

# Final Design Review



Super-Mileage Vehicle Drivetrain Design

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## **ABSTRACT**

The current Cal Poly Supermileage team has faced issues regarding the efficiency and durability of their SMV vehicle's drivetrain. After conducting research to solve their current issues, we developed a final drivetrain configuration that will improve the performance and life of the vehicle. This report outlines some of the completed research including: a table of designs used by other teams, a table of patents that can be applied to our design, and a list of technical literature we can use to better our design. It also summarizes our goals and objectives, including a table of the engineering specifications of the drivetrain along with their target requirements and how we plan to achieve these targets. Also included, is the process we took to choose our final design starting with multiple different concepts and how we picked them, narrowing down the concepts to the best one by means of research and a decision matrix, choosing our final design, and analysis and risk factors. Based on this, we have chosen a single reduction chain driven drivetrain, very similar to the previous design, as our final design because it can result in the best efficiency while still being compatible with the other components of the drivetrain. We have decided to focus design on the rear hub and sprocket since they were the major factors in low efficiency and damage for the previous vehicle. We reverse engineered a hub as a base for our purpose-built hub, and we designed a new sprocket and axle. In this report, we cover how we produced the final design, manufactured the components, and tested design specifications to prove the viability of the design. Finally, future improvements and recommendations to improve the design for future iterations.

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# **INTRODUCTION**

The objective of this project is to design and manufacture a new drivetrain consisting of a clutch, transmission system, rear hub with brake mounts, and a mounting system for the Super-mileage Vehicle Team's 2020/2021 vehicle. The most important design specification we wish to improve is the efficiency of these components to increase the overall efficiency of the vehicle. Increased efficiency will produce a better MPG in competition and hopefully higher placement in competition. This report will cover the research done, the objectives / goals of the project, and the design specifications the project should meet. Also included in this report is our Concept Design, which consists of all the concepts considered to meet the design criteria and the final design which justifies our design decisions. Finally, we cover the final designs of each component, manufacturing plans, safety hazards / risk assessment, the analysis ran on each component, Design Verification Plan, and project planning. By the end of this report, we hope to establish a sense of confidence in our design and the future improvements that can be made on the next iteration of this project.

# **BACKGROUND**

This section consists of research done on different components of the drivetrain and what the customer requires. The research includes other school's designs, patent searches, and technical documents.

## **A. CUSTOMER REQUIREMENTS**

Based on meetings with the members of the SMV, input from Dr. Mello, and results of our research, a list of what the customer needs and a list of what the customer wants was created. These can be found in Table 1 below.


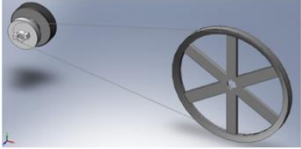
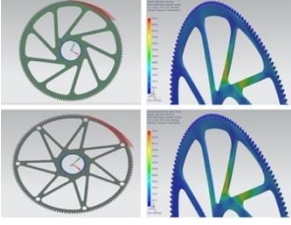


**Table 1.** List of Customer Needs and Wants for the Drivetrain

Customer Needs	Customer Wants
-Total budget cost ~\$600 -Assembly covered and protected for safety -Total size fits inside vehicle -Compatible with engine from SMV Engine Team	-Total Efficiency ~85% -Manufacturing time < 150 hours -Adjustable final drive gear ratio -Mass < 8.0 lbs -Lifespan > 2 years -Less Drag on hub and clutch -Decrease warpage of rear sprocket -Better alignment of sprockets -List of potential spare parts to bring

## B. EXISTING DESIGN TABLE

Below is a table consisting of existing designs from other universities and the previous Cal Poly SMV team, along with a photo and description.

**Table 2.** Existing Drivetrain Designs

Team Name	Photo	Description
Calvin College Team 16		Single gear reduction, chain and sprocket, reduction 12-18
Northern Arizona		Single gear reduction, composite v-belt, centrifugal clutch, aluminum drive sheave
University Laval Quebec		Single gear reduction, 125-150 teeth on the sprocket. Optimized sprocket design to reduce weight. Top speed 25mpg, 1.96 horsepower
Dalhousie University		2 step gear reduction, roller chain and sprockets, planetary gearbox w/ 20:1 reduction, ceramic ball bearings, centrifugal clutch
Cal Poly SMV		Single gear reduction, chain and sprocket, centrifugal clutch



## C. PATENT SEARCH TABLE

Below is a table of patents, acquired from a patent search, that relate to our problem. The purpose of this research is to come up with ideas and methods that may aid us in designing, manufacturing, and assembling the drivetrain.

**Table 3.** List of Relevant Patents and Their Descriptions

Patent Title	Patent Number	Description/Relativity
Self-Aligning Sprocket	US3597988A	An adjustable sprocket with a spherical head that can align itself with the chain and other sprocket. May be useful in designing a method to assure the best alignment of the sprockets for high efficiency.
Water Jet Sprocket Fabrication	US5933955	A method developed for fabricating a drive sprocket for a US Army M113 TCV using a water jet that may more than double the life of the sprocket. May be useful for strengthening sprocket and increasing its life span.
Resin-based Friction Material for Low Drag Hubs	US5478642	A friction material and the process of making it to be applied to a hub or clutch which can keep temperatures and friction effects low. Can be helpful in designing a more efficient hub.
High-Performance Sprag Clutch Assembly	US6902046	A high performance sprag clutch assembly for maximum torque applications. The assembly features reduced race eccentricity under load from interlocking stator caps. Could be useful for rear hub selection.
Multiple tension reducing sprockets in a chain and sprocket system	US8430775	A system including multiple sprockets to avoid resonance frequencies in a high chain tension setup. The sequence of sprockets allow each individual sprocket to cancel the other sprocket's resonance frequencies out. This is extremely useful for designing to avoid resonance frequencies.

## D. TECHNICAL LITERATURE

- a. Effects of Frictional Loss on Bicycle Chain Drive Efficiency [1]
  - i. Study frictional energy loss mechanisms associated with chain drive system. Chain tension and sprocket size had the largest effect on the efficiency of the drivetrain.
- b. Planetary Helical Gear System [2]
  - i. Gearbox is very compact, power-weight ratio, and efficient. Gears have high contact ratio and operates relatively quietly. Carrier, planet, and sun gears. Sun acts as driven gear with planet at driver.
- c. Purpose of Hub Assembly [3]
  - i. The purpose of the hub is to prevent excessive deflections from bending and torsion. Deflections can result in fatigue in both the hub and other components, as well as toe changes. Slight changes in toe can negatively impact a car's steering ability.

- d. Fundamentals of Sprocket Design and Reverse Engineering of Rear Sprocket of a Yamaha CY80 Motorcycle [4]
  - i. Discusses dimensioning, drafting, chemical composition, material selection, choice of manufacturing process, heat treatment, surface finish and packaging as the steps that need to be followed for manufacturing a hardened sprocket.

## **E. SHELL ECO/ SMV RULES**

Based on research done on the Shell-Eco Marathon Rules and the Super-Mileage Vehicle 2019 rules, a list of rules relating to the drivetrain was compiled. The most important ones are:

- The transmission and/or clutch must be designed to be able to disconnect the engine from the wheel so the vehicle can be stationary while the engine is running.
- Guards and shields must be used to cover any moving drivetrain components to protect damage to any fuel carrying components and to prevent any injuries to the driver.
- Vehicle must have a clutch. [5]
- For centrifugal/automatic clutches, the starter motor speed must always be below the engagement speed of the clutch. [5]
- For manual clutches, the starter motor must not be operable with the clutch engaged. An interlock is required to facilitate this functionality. [6]

## **F. CONCEPT DESIGN RESEARCH**

Multiple concepts were considered for the design of the drivetrain. This section contains some research of the concepts we were considering but ultimately did not choose and the positives and negatives of each one.

### ***Planetary Gearbox***

A planetary gearbox is a gearbox in which there is one or more gears orbiting about the central axis of the train. The positives of a planetary gearbox are that it has high efficiency for heavy load and rpm purposes, and it will allow for a smaller rear sprocket thanks to a gear reduction [7]. The negatives are that it takes up space outside the motor shaft, which, from the dimensions given, we cannot do. Also, it would require moving the rear axle, which cannot be done. Finally, Planetary Gearbox are expensive, and cannot fit it in the budget.

### ***Belt Driven***

A belt driven drivetrain transmits motion from one shaft to another with the help of a thin inextensible band that runs over two pulleys. Some positive aspects of the belt drive are that they are cost efficient, simple to use, low maintenance, and low noise. However, they take up a lot of space, have a limited speed, low life cycle, and can only operate at lower temperatures [8]. Overall, for this application the belt is not idea compared to a chain.

## **OBJECTIVES**

The task for this project is to redesign the IC Drivetrain for the SMV team to maximize efficiency and performance for upcoming races in the Shell Eco Marathon and SMV competitions. The drivetrain includes all the components necessary to deliver power from the IC engine to the rear wheel. Specifically, this includes specifying a new clutch, transmission system, and rear hub with brake mounts.

From our understanding, the Cal Poly SMV team is aiming to increase its mpg to 1,200 or more. Efficiency, durability, and reliability are critical for success in the competition as well as ease of installment for modifying final drive ratios. The drivetrain must last at least two years of competition assuming two races per year, have an efficiency of 85% or more, and have no critical failures. Our team's QFD is attached in appendix A, which helped develop the design specifications for this project. We used previous drivetrain senior projects to guide the development of these specifications, and each was reviewed to highlight important attributes. Our list of specifications can be seen on the following page in Table 4, with their respective target values and acceptable tolerances. Also included in this table is the anticipated risk level, which rates how challenging we expect it will be to meet each specification target. The last column, labeled "Compliance", describes the general methods in which we will determine whether our design meets each specification. The letters in this column, T, A, I, and S, stand for Test, Analysis, Inspection, and Similarity to the SMV's existing drivetrain, respectively.

**Table 4.** Design Engineering Specifications

Specification	Specification Description	Requirement or Target	Tolerance	Risk	Compliance
1	Volume Occupied	8"x6"x10"	$\pm 1.0x$ $\pm 1.0x \pm 1.0$	L	S,I
2	Drive Ratio	8:1 - 14:1	Min/Max	L	I
3	Time to Build	150 hrs	Max	L	T
4	Time to Change Drive Ratio	15 min	$\pm 5$	M	T
5	Clutch Engagement Time	0.2s	$\pm .1$	M	T
6	Torque	17.50 lbf-ft	Max	M	T, A
7	Driveline Efficiency	85%	Min	H	T, A
8	Rear Hub Cost	\$300	Max	M	A
9	Sprocket and Chain Costs	\$400	Max	M	A
10	Offset Angle	1 degree	Max	H	I
11	# of Seasons	2 seasons	Min	M	T, I
12	Overall Weight	8lbs	Max	M	T

The methods that we will use to measure each specification are described below:

- 1. Volume Occupied:** Can be initially measured using a yardstick, and if the completed drivetrain fits inside the vehicle in a similar manner to the existing drivetrain, we will have met our target.
- 2. Drive Ratio:** This will be measured by counting the teeth in each sprocket.
- 3. Time to Build:** By keeping a log of all the hours spent on building the vehicle, we can determine if we've met our target build time.
- 4. Time to Change Drive Ratio:** This will be determined by timing several trials of changing the drive ratio with a stopwatch and averaging this number.
- 5. Clutch Engagement Time:** We will also use a stopwatch and average the clutch engagement time for several trials.
- 6. Torque:** This will be measured by using a dynamometer.

- 7. Driveline Efficiency:** By using a dynamometer we can measure the power output from the engine as well as the power that actually makes it to the wheels and transmits to the ground. Dividing the second power reading by the first will give us the driveline efficiency.
- 8. Rear Hub Cost:** We will keep track of the rear hub cost by keeping a log of each component and material purchased to manufacture the hub.
- 9. Sprocket and Chain Costs:** This will also be determined by keeping a log.
- 10. Offset Angle:** This will be calculated using trigonometry by placing a yardstick on the flat surfaces of both sprockets. They will be perfectly aligned if the yardstick rests on both faces evenly. If not, measurements will be taken between the sprockets to calculate the angle.
- 11. Number of Seasons:** We will estimate the number of seasons the driveline will last before becoming ineffective or failing, through stress and fatigue analysis. This will be confirmed once the vehicle actually fails.
- 12. Overall Weight:** The overall weight will be determined using a standard scale.

The three highest risk specifications we need to meet will be a driveline efficiency of at least 85%, a chain alignment offset angle no greater than 1 degree, and lifespan of at least two seasons. The driveline efficiency and lifespan will be a direct result of the effectiveness of each component put together, meaning that each component must be chosen and assembled carefully and with great attention to detail in order to maximize overall driveline efficiency. The chain alignment is extremely critical to the overall success of the vehicle, as even slight misalignment can cause sprocket warpage, chain tension issues, and stresses. Proper alignment will be difficult to achieve as the accepted tolerance of +/- 1 degree requires high precision and caution with installation, and slight adjustments can end up causing large problems.

# CONCEPT DESIGN

## IDEATION

After defining the project objectives and goals, the next step was to develop a concept to best satisfy each of the requirements listed above (see Objectives). Two major ideation sessions were conducted using the brainstorming and check list methods to produce numerous ideas to solve each of the individual requirements. Due to the nature of the project, each session focused on overall system design for the drivetrain as well as the subcomponents which included the clutch and rear hub. Documentation of the two sessions can be found in the appendix at the end of this report.

## DRIVETRAIN DESIGN CONCEPT MODELS

Following the brainstorming sessions, many of the ideas were then developed into concepts. The concepts are crude in this stage but were effective for combining ideas created in the ideation sessions. A few of the top overall concepts are included below and were selected based on our team's prediction on their ability to satisfy the specifications / metrics determined in the objectives.

### Concept 1: Single Stage Reduction – Chain + Sprocket

This concept resembles the drivetrain used in Cal Poly's current SMV vehicle utilizing a chain and sprocket. The idea is that the engine power will be directly applied to a permanent driving sprocket at the engine shaft and deliver power with a chain to the driven sprocket. The driven sprocket will be designed to be removable so that different final drive ratios can be varied depending on the conditions of the race. This will result in numerous sprockets being developed and will require high precision for chain alignment in order to prevent premature wear on the system.

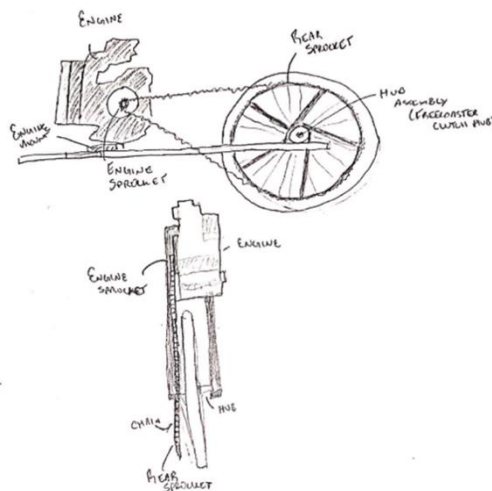


Figure 1. Single Stage Reduction-Chain + Sprocket

### Concept 2: Two Stage Reduction – Planetary Gearbox + Chain & Sprocket

This concept has resembled past SMV vehicle projects in which the final drive ratio is determined through two different reductions; one through a planetary gearbox, and then again reduced with a chain and sprocket. This design requires a less drastic change in sprocket size increasing chain efficiency. Purchasing gearbox would also be more reliable than a chain since there is less chance for misalignment. Space to fit the gearbox is a concern for this concept.

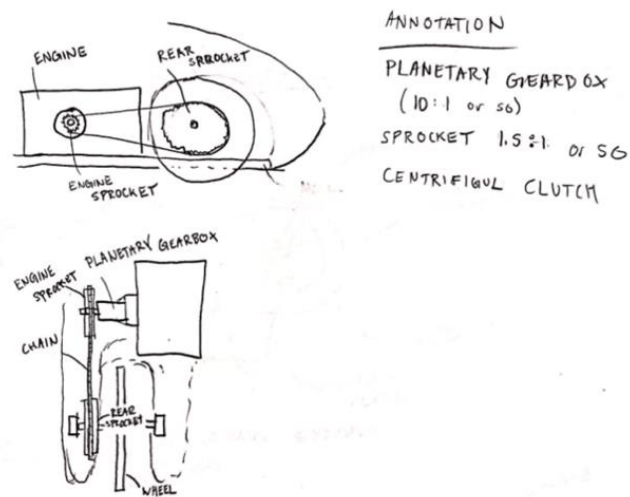


Figure 2. Two Stage Reduction – Planetary Gearbox + Chain & Sprocket

### Concept 3: Single Stage Reduction – Gearbox

This concept eliminates the need for a chain in the drivetrain and instead relies on a gearbox to complete the required drive reduction. Changing final drive ratio could be a significant problem, requires designing a driveshaft, and difficult to space in the vehicle but can be very reliable, efficient, and should not have major issues with alignment.

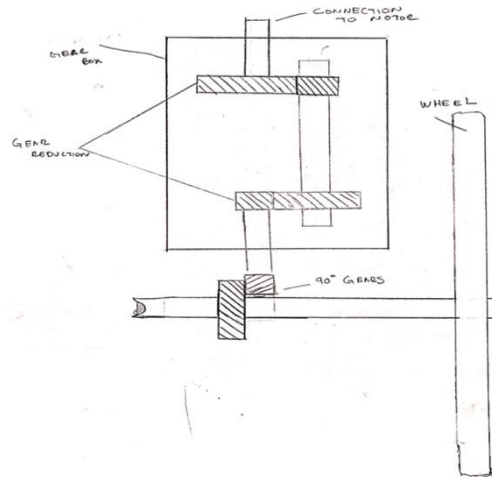


Figure 3. Single Stage Reduction – Gearbox

#### Concept 4: Single Stage Reduction – Belt Drive

The belt drive is designed very similarly to concept 1 with the exception of replacing the chain & sprocket with a belt drive. A belt drive would be easy to change drive ratio, reduce noise and vibration of the vehicle, require no lubricant, economical, and do require parallel shafts. The biggest concern with using a belt drive is efficiency and reliability.

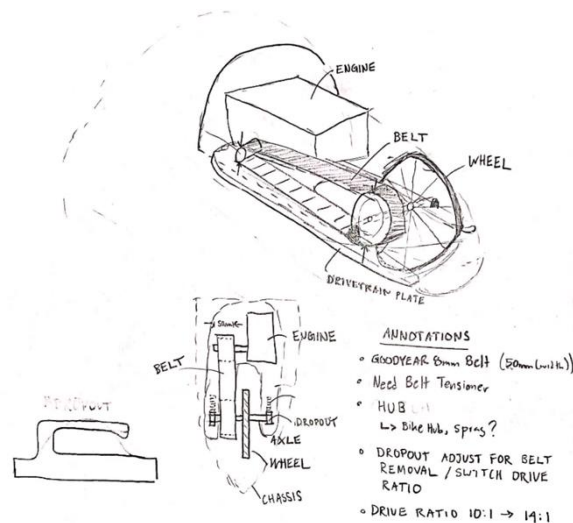


Figure 4. Single Stage Reduction – Belt Drive

#### Concept 5: Two Stage Reduction – Gearbox + Chain Drive

This concept is similar to concept two except that the planetary gearbox is replaced with slimmer gearbox running down the length of the vehicle. This will make better use of the extra length of the vehicle vs the width. The gearbox will have a reduction around 3:1 to reduce the size of the sprockets. The driver gear will pass through an idler and transmit power to a shaft delivering power to the chain drive.

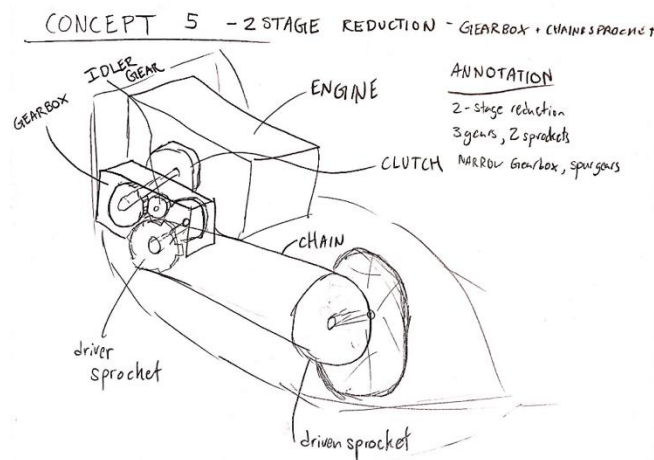


Figure 5. Two Stage Reduction – Gearbox + Chain Drive



In addition to developing these overall concepts, subsystem concepts were also developed. Because all the overall systems can incorporate the subsystem concepts, they were not included in the sketches.

## **EVALUATING LEADING CONCEPTS**

After developing several concepts for the overall and subsystems, Pugh matrices were developed to evaluate the strengths of these concepts against the requirements developed. In addition to the Pugh matrices, a morphological matrix was created to combine the strengths each concept and develop new concepts. Both the Pugh and morphological matrices can be found in Appendix C.

To determine the best final concept for the design, a weighted decision matrix and preliminary analysis was conducted to analyze the overall and subsystem concepts. Although many requirements of the design are difficult to measure in this stage of the design, preliminary analysis was used to roughly estimate certain metrics of the design. The analysis performed can be found in the appendix of this document. Efficiency, weight, precision, and space were roughly estimated for the 4 design concepts and helped influence the scores developed in the weighted decision matrix.

Efficiency for each of the drivetrain designs was estimated by using approximate max efficiencies for gears, belts, and chains and raising them to the power of the number of each component. Example: Efficiency (E) = .98 Number of Gears (N) = 4. Overall Efficiency =  $E^N = .98^4$ . Overall Efficiency = 0.922. If a drivetrain combines two different types of components, solve each efficiency separately and then multiply the component efficiencies together. Using this method, it was determined that all the concepts had the potential to satisfy our efficiency requirement, but the single stage chain drive concept had the highest potential efficiency at 92.2%.

After analyzing efficiency, estimated size of the concepts was analyzed. After contacting the SMV team, it was determined that our estimated space to place our drivetrain was approximately 8in (xdim), 6in (ydim), and 10in(zdim). These dimensions are based on the origin at the base of the engine shaft. It was determined that the only concept incapable of fitting within the chassis is the two-stage reduction with the planetary gearbox. Although initially this concept seemed to be a leading design, it does not seem possible to fit a clutch, gearbox, and sprocket from the engine shaft due to the tapering of the vehicle's body.

In addition to efficiency and size, vehicle complexity / precision was analyzed using the method of tolerance stacking. Tolerance stacking will base the accuracy of the drivetrain assembly on the worst possible scenario of parts. By using this method, it is possible to find which concepts present the most risk to achieving optimal precision. Precision drives manufacturing time and reliability of the entire drivetrain therefore it is crucial to find a design that minimizes the risk of misalignment. Having the sum of the parts be within 10 thou or so will be crucial for alignment and manufacturing.

The next criteria analyzed was the overall weight of the vehicle drivetrain. The goal of the project is to reduce the drivetrain weight by at least 20% from the current design. By reusing the same drivetrain plate, assuming similar weights for engine mounts, dropouts, chains etc., it was determined that it will be very difficult to reduce the weight of the drivetrain using these concepts. In the best-case scenario with the materials chosen, the maximum weight that can be reduced is about 10%. In order to reach the project goal, new materials will be evaluated, and various other options will be explored to save weight.

The last parameter our team analyzed was the overall cost to implement each drivetrain system. Using manufacturer retail prices, a cost table was constructed to estimate the building cost for each of the systems. After approximating each budget, it was determined that only single stage chain and belt drives were within our team’s budget. The cost analysis can be found in the appendix of the report.

After performing all the preliminary analysis, three decision matrices were constructed to reflect the information gathered in the analysis. The three decision matrices developed analyze overall system, clutch, and rear hub concepts. These can be found below.

**Table 5. Overall System Weighted Decision Matrix**

Weighted Decision Matrix: Overall System									
Criteria	Weighting	Chain Drive		2 Stage Reduction		Direct Gear Transmission		Belt Drive	
		Score	Total	Score	Total	Score	Total	Score	Total
Cost	4	4	16	2	8	2	8	4	16
Volume	3	3	9	2	6	2	6	3	9
Efficiency	5	3	15	4	20	4	20	2	10
Weight	3	3	9	2	6	2	6	4	12
Reliability	3	2	6	4	12	4	12	2	6
Change Drive Ratio	2	3	6	3	6	1	2	2	4
Life / Durability	2	3	6	4	8	3	6	2	4
Complexity / Ease of Use	2	3	6	2	4	2	4	2	4
	<b>Total</b>		73		70		64		65

**Table 6. Front Clutch Weighted Decision Matrix**

Weighted Decision Matrix: Front Clutch							
Criteria	Weighting	Centrifugal		Manual Cable Actuated		Manual Hydraulic Actuated	
		Score	Total	Score	Total	Score	Total
Cost	4	3	12	4	16	4	16
Drag	5	3	15	3	15	3	15
Weight	3	3	9	3	9	3	9
Reliability	3	3	9	4	12	4	12
Complexity / Ease of Use	3	5	15	3	9	3	9
Adjustability	3	3	9	3	9	3	9
Time to Install	3	4	12	2	6	2	6
Life / Durability	3	3	9	3	9	3	9
	<b>Total</b>		90		85		85

**Table 7.** Rear Hub Weighted Decision Matrix

Weighted Decision Matrix: Rear Hub					
Criteria	Weighting	Freecoaster		Cassette	
		Score	Total	Score	Total
Cost	5	2	10	4	20
Drag	5	5	25	2	10
Noise	1	5	5	2	2
Weight	4	2	8	4	16
Reliability	4	2	8	4	16
Engagement Time	4	2	8	4	16
Life / Durability	4	2	8	4	16
Maneuverability	2	5	10	2	4
Alignment Reliability	4	4	16	3	12
	<b>Total</b>		98		112

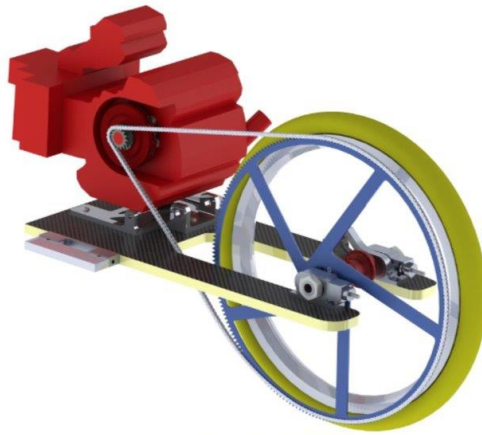
## REAR HUB

At first, we planned to purchase a new rear hub based on extensive research about which hubs on the market would be an improvement over the previous Odyssey Freecoaster that was used. A decision matrix was constructed above in Table 7 comparing a typical cassette hub to a typical freecoaster hub, and it was ultimately determined that given a limited budget for purchasing a new hub, the standard cassette hub would be the most practical choice. While a freecoaster would essentially eliminate all rolling drag, its most desirable trait, due to their advanced technology they are much more expensive, heavier, less durable, and less reliable. Their incredibly delayed engagement time and their fragility is what we believe caused the SMV’s current hub to fail. This is because the torque being created from the motor is significantly higher than that of a cyclist’s pedal-which is what these hubs are designed to handle, and slow engagement allows the impact on the freecoaster’s pawls to be much greater than with the faster engagement seen in cassette hubs.

However, after learning about the cost of freecoasting hubs, we decided that instead of redesigning the entire drivetrain, we would just continue to use the existing clutch and concentrate on improving the sprocket and rear hub since their malfunction is what ultimately caused the vehicle to fail. Since we will now be mainly focusing on only two aspects of the drivetrain, we decided that it would be more cost-effective to manufacture our own hub, and it would allow us the freedom to design it to our needs.

## SELECTED CONCEPT

After finalizing the decision matrices, it was determined that a drivetrain that is single-stage chain-driven and uses a centrifugal clutch and cassette rear hub or custom hub will best satisfy the above requirements moving forward. Included below is the concept model including some of the most important features of the design.



**Figure 6.** Finalized CAD-generated drivetrain concept

In this concept, power will be transmitted through the engine shaft to the driver sprocket. On the same shaft, a centrifugal clutch will be used instead of the proposed manual brake. The centrifugal clutch will be reused from the previous drivetrain model with replaced friction pads to save on cost. The driver sprocket will be manufactured and mounted by the team. An ANSI 25 chain will transmit power from the driver sprocket to the rear sprocket. The rear sprocket will be manufactured by the team in 2-3 different final drive ratios. The material of the sprockets was narrowed down to two materials, carbon fiber and steel, with a few different configurations in mind. One configuration was a two-part system, where we have an inner disk made carbon fiber and an outer ring with the teeth be made of steel. This design quickly became too difficult to manufacture and was therefore infeasible. The second option to save weight was a sprocket made completely of carbon fiber. However, laying carbon fiber sheets and machining it was both difficult and hazardous. In addition, carbon fiber is more much expensive than steel. The final option was to make a completely steel sprocket. Since it was the most feasible and cheapest option while still meeting all the safety requirements, steel was the chosen material. To mount the rear sprocket, two separate methods are in development. A custom rear hub will be designed and manufactured by the team with custom mounts to the sprocket and brake disk. Drawings of the final design of the sprocket, custom hub, mounts, and axle are completed and can be found in Appendix F. We designed it based off of a BMX Ultra SSD rear hub, manufactured by Onyx Racing Products, that features a sprag clutch system allowing for frictionless coasting as well as instantaneous engagement time. Along with those qualities we will also design with the following parameters in mind: weight, durability, ease of alignment, and disc-brake and sprocket mounts. If

the hub we manufacture were to fail, we would encourage the SMV team to purchase the Onyx hub pictured in figure 7 below.



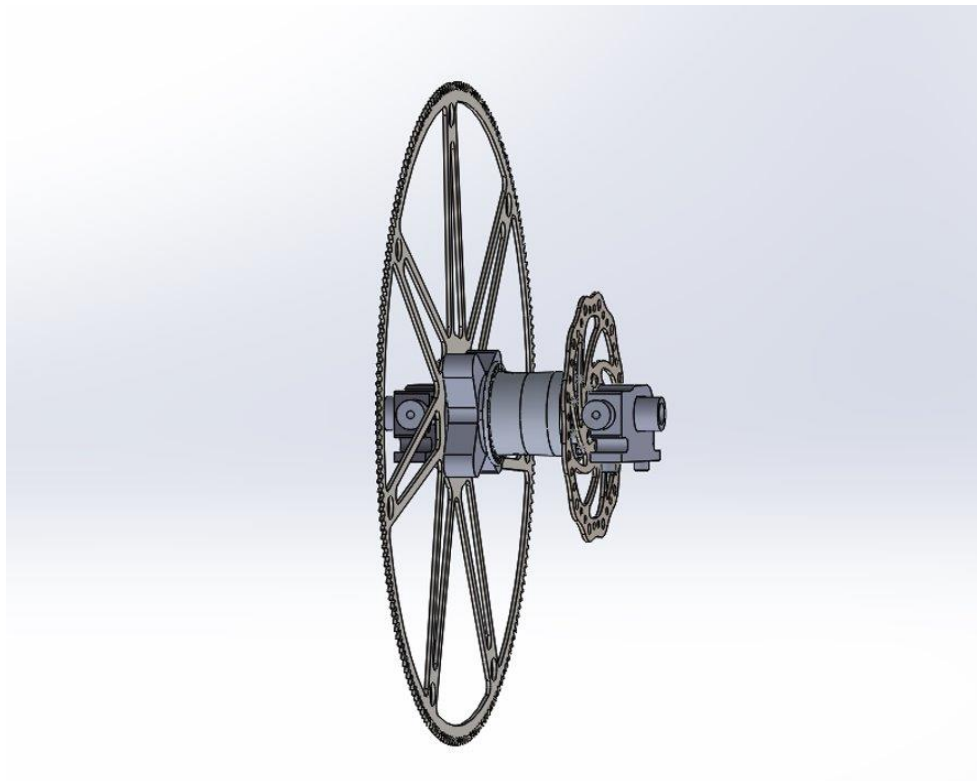
**Figure 7.** Onyx BMX Ultra SSD ISO OX-110/15mm thru Rear Hub

## **RISKS, CHALLENGES, UNKNOWNNS**

The chosen design has its risks, challenges, and unknowns. The biggest challenge of this project will be designing and manufacturing our own hub. With little to no experience with designing hubs, it will require a lot of research and practice to perfect the manufacturing process for all the components of the hub. With that being said, it is a very feasible task and we will be able to accomplish it. On a positive note, there is some experience in our group in designing and manufacturing sprockets. Though it will still be challenge, the sprocket will be an easier task to accomplish. The biggest risk we have with our design would be the failure of components like the hub or sprocket, as well as possibly the front clutch since we are reusing it from the previous vehicle, meaning it will have some wear on it. Another risk of our design is the incorrectly manufacturing the sprocket or hub in a way that it can't be undone, and we have wasted the materials purchased. Aside from all these risks, challenges, and unknowns, we are confident in our planning and research enough to successfully build our design and meet our goals.

## FINAL DESIGN

After careful analysis, the final proposed design is a single-stage reduction chain and sprocket drivetrain with a custom hub and water-jet steel sprocket. This proposed design highly resembles the current design but further emphasizes hub reliability and performance of the sprocket. The concept builds upon the design selected in the concept design phase with expanded dimensions, functionality, and safety considerations. The team made the decision to keep the single-stage reduction chain and sprocket drive because of the previously discussed advantages as well as no major safety concerns inhibiting the design. A figure of the final design can be seen below.

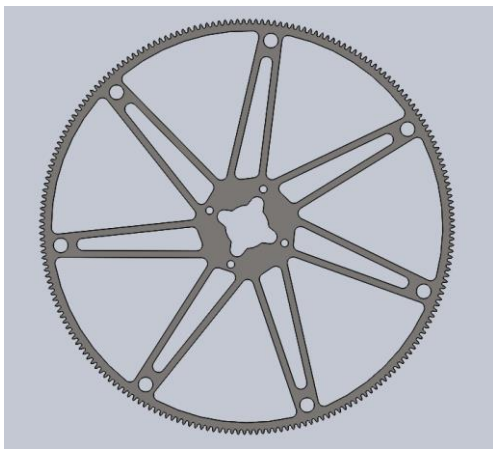


**Figure 8.** CAD of Final Design

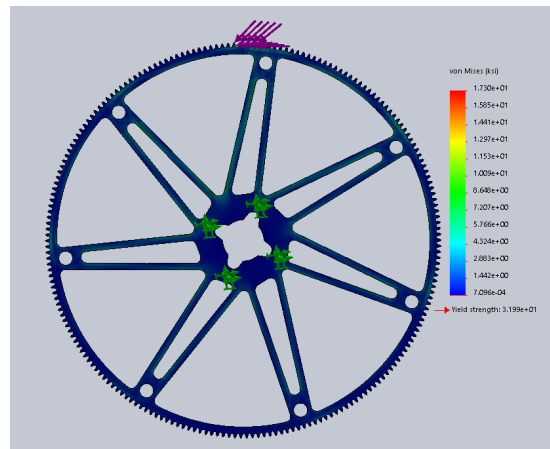
### **Sprocket**

The sprocket of our final design takes a different form which aims to decrease deflection, increase precision, and reduce weight. The proposed sprocket design has a 7-way star pattern with 14 spokes in comparison to the 5 spoke pattern on the previous design. The 12 spoke pattern increases the number of pathways for loads to travel throughout the sprocket, decreasing deflection and the chance of failure. The sprocket has circular holes at the end of the spoke pattern closest to the teeth to decrease the weight far from the axis of rotation. This will decrease the shear stress put on the fasteners and reduce the chance of the bolts failing in shear. The fasteners on the interior part of

the sprocket are placed in a circular bolt pattern and contains 4 M8x1.0 fasteners. A helicoil kit was purchased to prevent fastener stripping. The helicoils are installed in the sprocket mount which will be discussed in later sections. The sprocket contains 195 teeth with a ratio of 15:1 until the desired ratio is determined. While the vehicle is coasting, the sprocket will remain idle and have no loads applied. When the engine shaft begins running, the sprocket will engage approximately 5 teeth and produce a torque on the wheel. The teeth engagement was modeled in FEA based on the analysis of other team sprockets. In the first load case, a 17.5 lbf load is applied at each of the teeth. In the second load case, a 17.5 lbf load is applied to each of the 5 engaged teeth as well as a lateral load to simulate a 1 degree offset between the driver and driven sprocket. The results of the FEA can be seen below.



**Figure 9a.** Sprocket Design



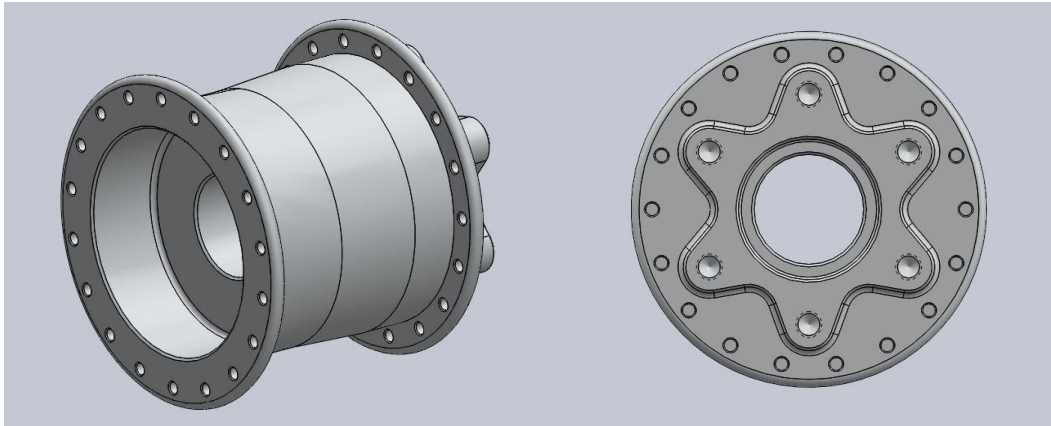
**Figure 9b.** Sprocket FEA

**Figure 9.** Custom Designed Sprocket

The location of the most stress is at the teeth where the loads are being applied. The factor of safety for the von mises stress & deflections was determined to be 1.8~2.0. Hand calculations for the sprocket were used to verify the FEA calculations are legitimate. These calculations can be found in Appendix J. To stay compliant with Shell Eco Marathon rules, the existing chain guard used by the team in the previous years will be reused to prevent significant injury to members of the team.

### Hub Shell

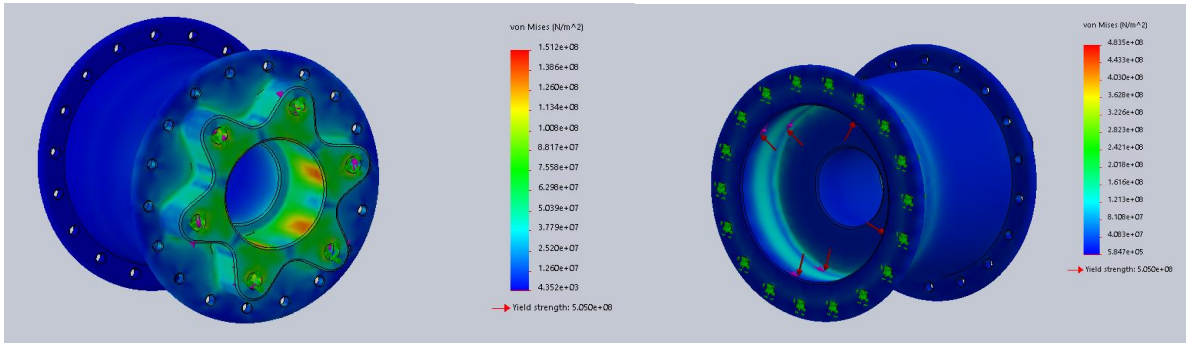
The final hub design is modeled as a custom freecoaster hub using a sprag clutch bearing to simulate the coasting effect. The freecoaster hub shell is designed for a 36 spoke rim and contains a custom disk brake rotor mount. When the clutch engages, the shell will rotate synchronously with the rear wheel rim thus driving the vehicle. When the vehicle is coasting on the track, the clutch will allow the hub to continue to freely rotate with minimal drag. The shape of the shell closely resembles the shape of an Onyx freecoaster hub. The shape of the hub can't be modified too much in order to integrate the existing / standard parts of the vehicle, but thicknesses of the shell were optimized to minimize weight.



**Figure 10.** Custom Designed Hub with Brake Mount

The original design consisted of a three-piece shell: 1 hub shell, 1 sprocket mount, and 1 brake rotor mount. The final design takes the overall shape of those three pieces and combines them into two parts. The first part is the hub shell + brake mount and the second part is the sprocket mount. The sprocket mount design will be further analyzed in the following section. The original design of the brake mount had it fastened to the hub shell using a 6-bolt pattern. Helicoil kits were also purchased to protect the hub from stripping when the fasteners are installed / unscrewed for maintenance. Due to concerns over the amount of shear stress applied to the fasteners, the mount and shell was combined into one piece to reduce the stress concentrations, risk for failure of the components, and reduce additional pieces in the design. The hub will be made out of 7075 Aluminum instead of carbon steel to reduce overall weight. Switching from carbon steel to aluminum will reduce the overall weight by 177%. This helps our team reach our goal of reducing weight and should increase the performance of the vehicle. In the large cavity, the sprag bearing will be installed using a shrink fit technique. Description of the process can read in later sections. On the other side of the hub, a ball bearing will be installed to take axial and radial loads of the vehicle. This bearing will be installed using a hydraulic press. To accommodate the replacement of the hub, the dimensions of the shell continue to resemble those of the previously selected Onyx freecoaster hub.

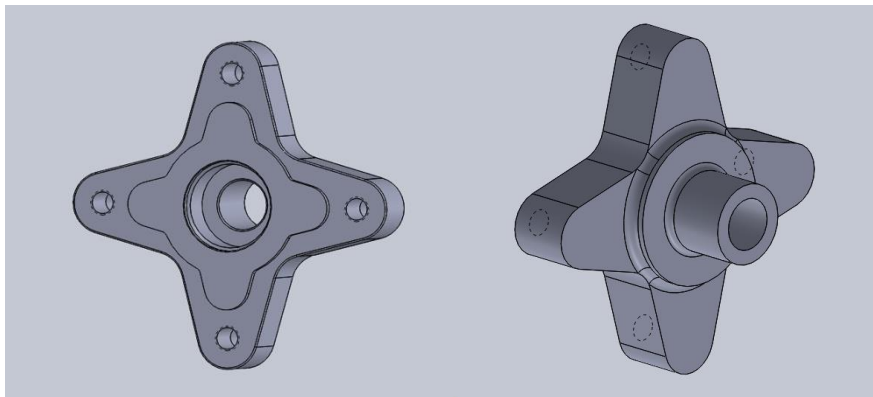




**Figure 11. Hub FEA**

To ensure that the hub will not need replacement, loading calculations were performed by hand and analyzed using FEA to calculate the factors of safety for each load conditions. The most significant cases were loads due to impact, braking, and the torque while the clutch engages. The results of the FEA can be seen below, the hand calculations can be found in Appendix J.

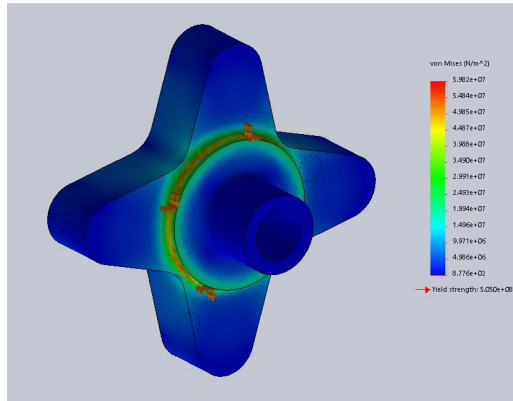
### **Sprocket Mount**



**Figure 12. Custom Designed Sprocket Mount**

The final sprocket mount design has a similar design to what was presented in the PDR with minor changes to ensure functionality for the system. The sprocket mount will continue to incorporate a 4-bolt pattern to accommodate the sprocket, but now has a through hole to feed the axle through the part. A small extrusion was placed on the fastener surface to have more surface in contact with the sprocket. This extrusion is used to assist with sprocket alignment and to reduce shear forces on the fasteners. In addition, a cavity is cut to insert another radial bearing into the part to align the sprocket and a circular extrusion comes out of the back side. Unlike the brake mount, the sprocket mount could not be attached to the hub shell and is directly due to functionality. The circular

extrusion is press fit into the sprag clutch bearing. When sprocket is rotating due to direct engine torque, it will cause the sprag clutch to engage causing the sprocket to drive the wheel. If the mount was directly attached to the hub shell, any rotation by the hub shell will cause the chain to drag resulting in reduced efficiency. Therefore, it was crucial that this mount remain separate from hub shell and rotate separately from the hub shell. On the sprocket side, a SMR2718-2R S/W7C SRI-2 radial bearing will be press fit into the cavity using a hydraulic press.



**Figure 13. Sprocket Mount FEA**

The most significant load case that the mount will likely endure is the engine torque case. The torque is applied at the bolt pattern with a fixed end where the sprag first engages at stall torque. Hand calculations and FEA were conducted to verify the design. The factor of safety was approximately 8.0 which is adequate for design. Hand calculations can be found in Appendix J.

### **Sprag Clutch Bearing**



**Figure 14. Boca Bearings CSK6005(X) One-way Sprag Clutch Bearing**

In the interior of the hub shell, a CSK6005(X) one-way sprag clutch bearing was chosen to transmit the torque in the vehicle. The sprag bearing works by allowing the hub shell to rotate freely while the engine is not applying torque to the sprocket. When the engine begins transmitting torque, the

internal parts engage allowing torque from drivetrain to apply to the hub/wheel. The dimensions and catalog rating of the bearing can be found in Appendix H. The sprag bearing engages very quickly and has a low friction value of 1.3 (N-cm), satisfying our engagement time requirement and reduced drag. In order to confirm that the bearing engages quickly, simple tests were conducted to measure the amount of rotation the bearing will undergo before engaging. From the simple tests, it was determined that the bearing engaged within 1-2 degrees. Further tests may be conducted to confirm the engagement strength and perhaps more accurate readings. The bearing torque rating will have a factor of safety of 4.5 which should account for any dynamic forces applied to the rear wheel. A torque wrench test was to be conducted in the future to test the reliability of the bearing. Results of the torque-wrench test can be found in the testing section later in the report. In addition, a coast down test is conducted on the sprag bearing to estimate drag torque. This will be useful for measuring friction and efficiency. The results of the test can be seen in later sections of the report. Hand calculations can be found in Appendix J to confirm our results. The sprag clutch will be inserted into the hub cavity using a hydraulic press and will lock in using an interference fit.

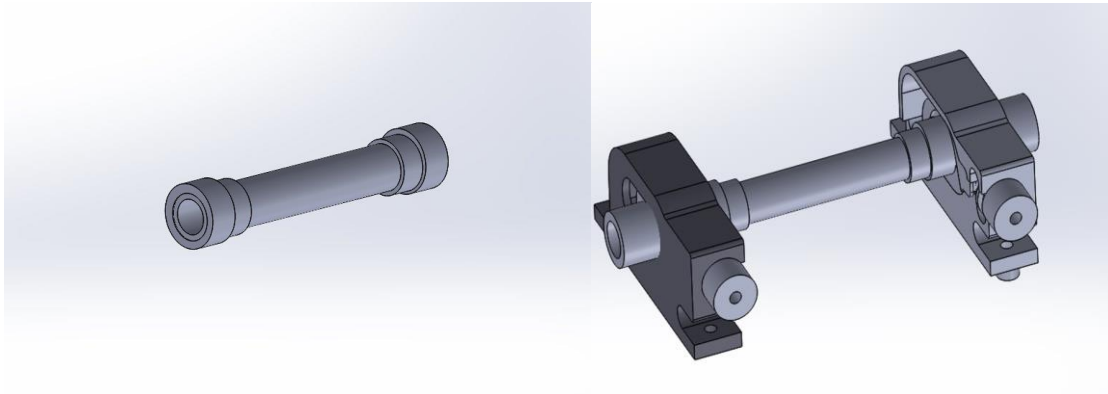
### **Ball Bearing**



**Figure 15.** Boca Bearings SMR2718-2R S/W7C SRI-2

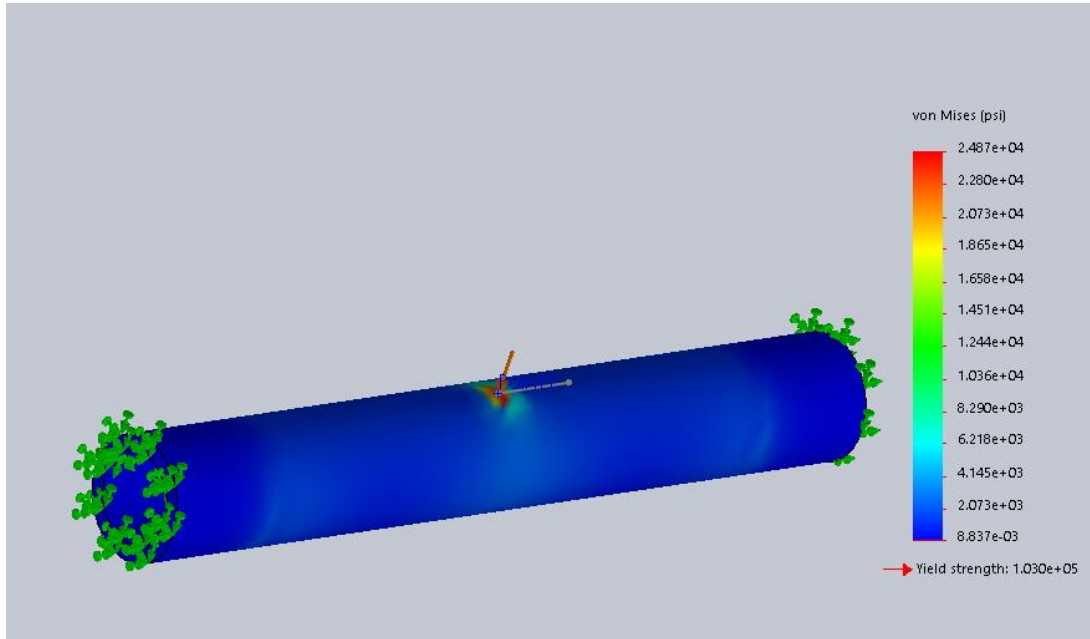
The other bearing chosen in the drivetrain design is a SMR2718-2R S/W7C SRI-2 ball bearing. The ball bearing accounts for any axial and radial loads applied to the rear wheel, which may occur during cornering and any normal driving conditions. It does not contribute to vehicle performance but is necessary to prevent failure of the hub. The catalog rating for the proposed bearing can be found in Appendix H. Hand calculations based on a cornering load case can be found in Appendix J. This bearing will be inserted into the hub cavity and sprocket mount cavity using a hydraulic press and will lock in by using an interference fit.

## Axle



**Figure 16.** Custom Designed Axle with Dropout Mounts

The axle is a 16 mm internal axle that will provide support for the rear assembly and help hold all the components in place. The length is approximately 125 mm but should be remeasured as the wheel mounting is constantly changing. This allows it to fit in between the current drop out brackets. Both ends of the axle will have tapped and threaded M14 holes. This allows for the system to be used with drop out brackets from the previous vehicle. It also allows for easy disassembly and quicker sprocket swapping. In addition to the axle, there will be two 20 mm spacers that fit on both ends of the axle. These spacers will locate the hub assembly between the dropout brackets as well as support the inner race of the ball bearings.



**Figure 17.** Axle FEA for Point Load

### Existing System Components

In addition to all the other components of the design. There are some components that will be reused from the current vehicle. The driver sprocket used to deliver power from the engine to the wheel will be used from the previous vehicle. Calculations will need to be done to confirm the sprocket has a long enough life to be reused. In addition, the engine plate & drivetrain plates will be reused to mount all the components to the vehicle. These do not need additional calculations. The dropouts located on the outside of the axle will also be reused from the previous vehicle. The right-side mount will have to be slightly modified by cutting away the inner part to allow space for the brake rotor. The shim will be used to fill space if replacement hub used.

# **MANUFACTURING PLAN**

Because of the complexity of the components for the drivetrain, proper planning must be done for the manufacturing of individual parts. This will help streamline the process and ensure no mistakes are made, which can save the money and time on the project. Material procurement and manufacturing for each part will be outlined in this section.

## **Sprocket**

The current manufacturing plan for the sprocket begins with acquiring the material. Ideally, left over material from the club or another group should be utilized to undercut the project budget, but under the circumstance that free material isn't available, it will be purchased through McMaster Carr. The primary material that is being considered is carbon steel because of its strength and durability. Carbon fiber was considered because of its superior strength over steel and while having a lower overall density, but the high cost and difficulty to manufacture has prevented the design from going in that direction. Once the material is acquired, a 1"x18"x18" steel fixture of the negative of the sprocket must be made to help machine the sprocket (assuming the team wants to machine the teeth). To cut the sprocket, a blank will be water-jetted and put into the fixture to machine the teeth. Once the sprocket is complete it can be mounted to the sprocket mount in the assembly using M8x1.0 bolts.

## **Hub**

The hub will be made from a 3" block of aluminum 7075, which will be procured by a supplier if not through the club. It must be turned on a lathe and then run on a CNC mill. The part must be finished on a CNC Mill due to the contours for the rotor mount. Due to lack of experience on a lathe amongst group members, there is a chance that this operation will be outsourced. There is potential for the outsourcing to be free of at the least discounted, if the company is willing to help sponsor the project. Once the hub is complete and the bearings and axle are connected, the wheel can be attached by lacing the spokes through the drilled spoke holes. On the brake side of the hub, the disk brake will be attached to the hub using M5x0.8 bolts. On the sprocket side, the sprocket mount will sit in the inner race of the sprag bearing. This will allow for the hub to free coast, and the sprocket and sprocket mount will stay stationary relative to the hub.

## **Sprocket Mount**

The sprocket mount will be manufactured from a 5" block of 7075-T6 aluminum, which will hopefully be procured by a supplier if not through the club. The mount will need to be run on a CNC mill to give the mount its shape as well as the cavity / through hole of the mount. The geometry of the mount is simple; however, fixturing will need to be developed for workpiece holding. Once the machining for the mount is finished, the ball bearing will need to be pressed into the mount.

## **Axle**

The manufacturing of the axle should be fairly simple. We will take a 20 mm diameter 1144 carbon steel rod and turn it down to 16mm for the axle itself to the length necessary to fit correctly between the dropout mounts (~125mm). Then, each end of the axle will be tapped and threaded to match the 14mm bolts on the dropout brackets. For the spacers, they will be turned on a lathe and the inside 16 mm hole will be drilled. The length and measurements of the spacers should be adjusted for best fit alignment for the system.

## **Bearings**

There will be a total of 3 bearings used for the design of the hub. These bearings will be purchased through Boca Bearings. The primary bearing will be a sprag CSK6005X 25x47x14mm bearing. The brake-side bearing will be an F19-32-TP ball thrust bearing. These two bearings will be press fit into the hub shell using a hydraulic press. The final bearing will also be a ball bearing and will be connected to the sprocket mount to allow free coasting. No manufacturing will be required for bearings.

## **Drop Out Mounts**

The same dropout mounts from the previous vehicle will be utilized. However, on the previous vehicle the brake side mount has a machined in spacer since the brake was mounted at a different location. However, because this design required the brake to be mounted to the hub, the dropout mount on that side must be machined to allow for more space. The driver side mount will not be altered.

# **DESIGN VERIFICATION PLAN**

**Volume Occupied** is the volume of space that the designed drivetrain takes up. To ensure that this specification was met, the team worked with other teams and members of the club to make sure the design fit within the required space. Additionally, many of the dimensions were modeled based on the previous design to also assure the volume occupied would not be more than the chassis would allow.

**Drive Ratio** is the ratio between the driving (front) sprocket and the rear sprocket. The club required a range from 8:1 to 15:1. The team designed one with a 15:1 ratio as a maximum with the ability to scale the design down to the needed ratio should the club want to manufacture more sprockets. Final size determined by simulation team.

**Time to Build** is how long it will take for all the drivetrain components to be manufactured. It has not come into play yet as the building process has not yet begun. Estimations were made for how long each component would take to manufacture.

**Time to Change Drive Ratio** is how long it will take to change out the sprocket to a different drive ratio. With the current design, to change the sprocket the axles must be unbolted and the entire rear wheel system can then be removed. After that, the sprocket just

needs to be unbolted from the mount and replaced with the new sprocket. Then everything is replaced where it needs to be. This process should not take more than 15 minutes.

**Clutch Engagement Angle** is the degrees it takes for the clutch to engage when it is free coasting. Minimizing this would improve efficiency. To get this we will measure the degrees it takes for the clutch to engage.

**Torque** is the torque from the engine transmitted onto the sprocket. The given value was roughly 1.2 ft-lbs going through a 15:1 ratio, which results in a torque of 17.5 ft-lbs on the sprocket and hub. FEA was done to assure the components could handle the torque. Another method of testing could be to use a torque wrench and crank on the system and observe how high of a torque we can reach while simultaneously not damaging the system.

**Driveline Efficiency** is how efficient the drivetrain is at transmitting the power from the engine to the wheel. This will be a percentage of the actual power transmitted vs the expected power transmitted. To test the efficiency, we will run the vehicle on a dynamometer.

**Rear Hub Cost** is the total cost to purchase the materials for and manufacture the hub. To minimize this the group has been reaching out to companies to see if any of them can spare material or sponsor some of the manufacturing.

**Sprocket and Chain Costs** is the total cost to purchase materials for and manufacture the sprocket and chain. Just like the hub, the group has been reaching out to companies and clubs to help reduce costs.

**Offset Angle** is the angle between the front and rear sprocket. If this angle is too great the chain can slip and cause problem. To ensure being able to line up the sprockets the drop out mounts allow for left and right adjustment of the system.,

**Number of Seasons** is the amount of years the drivetrain can last. For this we focused on the bearings and did a life calculation of them and found that they can last well over two years. These calculations can be found in Appendix J.

**Overall Weight** of the drivetrain is important as it plays into the fuel efficiency of the vehicle. The components were all designed with this in mind, cutting weight where possible without sacrificing integrity or strength of the components. Goal weights were determined using the previous vehicles numbers and the components were designed to be equal to or lighter than these components.

## **PROJECT MANAGEMENT**

### **ROLES AND RESPONSIBILITIES**

Throughout this project, different roles and responsibilities have been delegated to the individuals in the group. These roles will help improve productivity and provide structure to the group. Although these are the relative roles, all teammates are expected to aid and work in all aspects of the project.



Team Roles:

Treasurer/Planner: Arya Mahdavian

- Maintain team's travel & materials budgets (planning & tracking)
- Organize/maintain project plan/tracking

Secretary & Editor: Griffin Kraemer

- Organize/maintain information repository for team (online storage)
- Ensure documentation is complete, well-written, and timely
- Main point of communication with sponsor, coordinate sponsor meetings

Manufacturing/Testing: Kai Meter

- Coordinate build activities; arrange materials/equipment
- Conduct test activities; arrange facilities/instruments
- Compare theoretical data from analysis to experimental results

## **APPROACH**

Throughout the many different milestones and aspects of this project, the focus is making improvements to the components that will directly improve the efficiency, reliability, and driver usability of the drivetrain. After exploring the focuses of the previous drivetrain design group's work, the team has noted several goals of the project. Our team decided that a single-stage reduction drivetrain had the most promise for achieving high efficiency, reliability, and driver usability. The advantage of the single-stage reduction is the reduction of parts, less contact friction, and easier maintenance. Components will be designed to mimic existing systems with improved functionality. The sprocket will be designed to reduce deflection as well as weight. The hub will have similar geometry but reduced weight and higher efficiency. Research will be done in material selection, manufacturing processes, and design for the fabricated mounting system. Emphasis will be placed on designing for manufacturing. Lastly, the system will be tested, and iterations will be made to improve on the design and locate issues for future improvements.

## **TIMELINE AND DELIVERABLES**

There are many tasks and deliverables that need to be organized to allow for a successful project. The Appendix consists of our team's progress up to this point, including concept designs and how the final design was reached, FEA analysis and hand calculations for this design, a drawing package of all the components we plan to manufacture, costs, safety, and the remaining timeline. The team has manufactured most of the components designed after purchasing materials. After this, the system was assembled and tested to determine efficiency of the drivetrain, and the effectiveness of the design project. Torque-wrench testing and coast down test were conducted to find improvements for future projects.

## **PLANNED ANALYSES**

As the team plans for the next stage of the project, component designs must be analyzed against the required specifications prior to manufacturing. The first component on the list is the manufactured hub assembly. It was determined that the sprag bearing could not take radial and axial loads. So, two precision ball bearings were be used on each side of the hub with a sprag bearing utilized within the hub. After this, FEA analysis was completed on the hub and mounts. Utilizing an analysis tool from ME 328 along with FEA, the team optimized dimensions and materials for the hub and mounts based on cost and safety factors. The next component that was designed was the rear sprocket. The previous senior project team utilized Fusion CAD to determine the best design for the sprocket; however, it has been shown to warp significantly under load. The new sprocket was designed by reverse engineering the winning team from Quebec's sprocket from the previous year's race.

Next, purchased components were tested against the team's requirements to ensure the best components are selected for this application. The sprag bearing was tested for drag through the application of a torque-wrench and coast down test. Qualitatively, the team will determine an effective method of comparing multiple vendor's sprag bearings based on drag. In addition to drag, the sprag bearings need to be tested for engagement time. This will be completed through the rotation slope prior to the sprags grabbing the axle. This will be measured in degrees of a rotation.

Lastly, the overall system design needs to be analyzed to ensure it meets the outline design requirements. Once the system has been designed and installed in the vehicle, testing on a dynamometer will be completed to ensure the overall efficiency goal was met. The horsepower and torque at the crankshaft will be determined and compared to the horsepower and torque at the rear wheel. The difference between these values will provide the overall system efficiency.

## **PLANNED PURCHASES**

Since our team plans on only focusing on designing and manufacturing a new rear sprocket and a new rear hub with brake and sprocket mounts, the planned purchases are exclusively for these components. The primary purchases for these parts include materials and a couple of off the shelf parts including bearings.

We were fortunate enough that the SMV team had leftover steel sheets for use on the sprocket. This will provide a flat sheet for water jetting prior to machining. The next planned purchases will be for the manufactured rear hub. 3" OD 6" long Aluminum Bar Stock will be purchased for machining the hub. 7075-T6 aluminum will be utilized for the machining of the hub. In addition to the hub, a sprocket mount will need to be manufactured out of a 5" OD 7075-T6 bar. The rear brake rotor mount will be manufactured into the hub. In addition to these components, several off the shelf bolts will need to be purchased for mount fastening as well as helicoil kits to prevent stripping. The last purchase for the manufactured rear hub will be the sprag and two ball bearings. Since Boca Bearings is a sponsor of the Supermileage vehicle, they are the primary choice for a vendor for hub bearings.

## **MANUFACTURING AND TESTING PLANS**

With the design done and manufacturing starting, we will have to test the drag and engagement time of the sprag bearing we purchased from Boca Bearings. If the drag is considerably higher than what is optimal, measures will be taken to reduce it by removing seals and cleaning grease off the sprags.

The hub will be machined out of a 5" 7075-T6 aluminum bar. It will first be turned on a lathe, either a CNC lathe or a manual lathe. Once the bar is turned, fixturing will be developed to finish the turned part on a Haas CNC Mill. Currently, a pocket jaw set up appears to be the easiest process for finishing the hub on a CNC mill. After the hub has been machined, the hub will be surface ground to ensure proper flatness and parallelism on the mounting surfaces. The sprocket and sprocket mounts will be machined on a CNC Haas Mill. Lastly, the sprocket has the most time intensive manufacturing process as it is one of the most intricate components. A rough profile of the sprocket will be cut on a waterjet from a blanchard ground steel sheet. The waterjet blank sprocket will then be machined on a Haas CNC Mill if it is deemed necessary. If the waterjet does a sufficient job in cutting the sprocket, machining it will not be done to save on time. For the components that will be machined on a vertical Haas mill, tooling and fixturing needs to be designed.

The last step of testing prior to assembly will include a final inspection of all manufactured parts. Features will be measured against a detailed drawing of the solid model. Flatness and parallelism will also be inspected with an appropriate metrology device. If the team can gain access to a CMM, coordinate measuring machine, that will be the best method for ensuring accuracy of all features on the components. Once the individual parts are assembled, and bearings are press fit into the hub, testing of drag and efficiency can be done on individual parts. Then, once the entire assembly is complete it can be tested for overall efficiency on a dynamometer.

### **Cost Analysis**

The initial budget for this project was given to be from \$500-600. To save on costs, we tried to cut back on spending by reusing materials from the club. The total amount our team spent on materials was around \$500. Sprocket cost was \$0, as material was acquired from the club. The sprocket could not be machined since the waterjet has not been functioning. The most expensive piece of material was the 5" diameter 7075 aluminum which was used for the sprocket mount. 3" diameter 7075 aluminum was also purchased and used for the hub shell before it went into the CNC. The bearings are relatively cheap at around 24\$ each, for a total of three bearings. However, because of errors during assembly, two bearings were damaged and had to be replaced, increasing the cost by roughly \$50. The Heli coil kits for threading the hub and sprocket mount were expensive at roughly \$100 for both. We recommend finding a cheaper threading option if possible. The steel for the axle and spacers was relatively cheap. Costs for additional pieces of equipment that may be required to manufacture parts have been included in the budget breakdown but do not factor into our teams cost. The full budget breakdown can be found in Appendix I.

## **Maintenance Considerations**

Many of the main considerations for maintaining the drivetrain can be found in Appendix O. In that section you can find instructions for the safe operation and maintenance of the drivetrain product. Specifically, it covers the adjustment / replacement of the drivetrain chain, replacing components within the dropouts, and replacing the sprocket. It is in the best interest of the drivetrain life to regularly inspect and / or replace parts after each race. Critical components such as the sprocket, hub, and mounts should be inspected each race to look for signs of fatigue or failure. Fasteners should be replaced regularly so spares should be kept on the team at all times. To learn more, please flip to the Drivetrain Operation and Maintenance section in appendix O.

If any unexpected maintenance is needed, all of the parts could be replaced using the CAD parts and G code to run CNC operations. These models should be kept in the team's CAD folder and archived if no longer used.

## **Safety Considerations**

As with all projects, safety while operating on the vehicle is of the utmost importance. The primary potential hazard associated with the drivetrain design is the failure of important components during a race, potentially injuring the driver. One of the most critical components is the failure of the brake mount because of its impact on the functionality of the rear brake, but the risk of it failing is quite low due to a high factor of safety for that load case. There are many other risks that were analyzed prior to the manufacturing of the drivetrain components and can be found in Appendix K & L. The check list and FMEA showed that there were no potential hazards that would require additional hazard assessment. In addition, thorough testing on the primary components will reveal any additional hazards not accounted for during final design and manufacturing.

## ***Product Realization & Manufacturing***

### **Sprocket**

Due to the many issues with the Cal Poly waterjet in Mustang 60, the sprocket was not able to be manufactured by the end of this project. For over 5 weeks, the waterjet was inoperable during key weeks of the manufacturing phase of this project. Although the sprocket has not materialized, the CAD file for the sprocket and steel sheet have been handed over to the team. If results from the simulation team change the drivetrain ratio, the sprocket can be adjusted accordingly. The sprocket part file and steel sheet will be handed over to the shop technicians and machined when the waterjet is back up and running. The process should take an hour or so to complete.

## **Sprocket Mount**

The material of the sprocket mount was 7075-T6 aluminum. The particular material for this component was 5" round bar stock. Utilizing a hydraulic programmable bandsaw, a 3" piece was cut from the stock material. This completed the stock preparation part of the manufacturing process.

For the machining portion of the manufacturing, the CAM programming was completed in Mastercam. This part required two operations on a standard 3-axis Haas Mill. The fixture solid was toolpathed, and then each operation was toolpathed. An aluminum pocket jaw fixture was chosen for both operations to allow easy workpiece holding. Due to the large diameter of the stock material, two 2.5"x5" jaws were squared up in a Kurt vice, and a light skim pass was made to ensure the jaws were square. Center of jaw was found using a touch probe. A 5" diameter cylindrical pocket was machined into the jaws. After this, the sprocket side of the sprocket mount was first machined on OP-1. 3/8" and 1/4" end mills were used to mill the geometry of the part and interpolate the bearing counterbore and axle bore. After running the first operation of the part program, dimensions of the part were inspected prior to being pulled out of the vice. Once the part was determined to be true dimensionally, the part was pulled out of the vice. The jaws were flipped over, a light skim pass was made, and the touch probe was again utilized to set z-zero. For OP-2, the perimeter geometry of the sprocket mount was utilized to cut another pocket in the jaw. The part was loaded sprocket side down into the jaw. A 3/8" bullnose with .030" corner radius end mill was utilized to circle mill the boss. To machine the flange at the bottom of the boss with the proper corner radius, a 5/8" bullnose with .1875" corner radius end mill was utilized. The axle bore was then finished with a 1/4" 4FL long flute end mill. After the second operation was complete, and the dimensions were checked against the detailed drawing, the part was pulled. A hand deburring tool was utilized to remove any burrs from the part. This completed the machining portion of the manufacturing.

Finally, hand finishing was needed to complete the part. To remove any residual burrs and machining marks, the part was placed into an aluminum vibratory finisher. This tumbling in stones greatly improved the surface finish of the part. The last step for this part was to install helicoils. Utilizing the M8x1.0 helicoil kit, an STI tap was run into the holes on the sprocket mount using a t-handle. Once the holes were tapped, the helicoil tool was utilized to install the helicoils into the tapped holes.

## **Hub**

The material of the sprocket mount was 7075-T6 aluminum. The particular material for this component was 3" round barstock. A 6" long bar was purchased from McMaster-Carr.

For the machining portion of the manufacturing, two different material removal methods were needed due to the complex geometry of the part. First, the part was machined on a lathe. The bar was first faced to length. Then, the middle portion of the hub was turned to the final diameter. Finally, the spoke flanges and rotor mount flange were turned. The final part off the lathe consisted of four concentric cylinders. After this, the lathe part was machined in a similar manner as the sprocket mount. This part required two operations on a standard 3-axis Haas Mill post lathe operations. An aluminum pocket jaw fixture was again chosen for both operations to allow easy workpiece holding. Two 1"x5" jaws were squared up in a Kurt vice, and a light skim pass was made to ensure the jaws were square. Center of jaw was found using a touch probe. A 2.24" diameter cylindrical pocket was machined into the jaws. After this, the sprag side of the hub was first machined on OP-1. The spoke holes were center drilled, then drilled they were drilled with a .0938 carbide drill. The counterbore was interpolated with a 1/2" 3FL end mill. After running the first operation of the part program, dimensions of the part were inspected prior to being pulled out of the vice. Once the part was determined to be true dimensionally, the part was pulled out of the vice. The jaws were flipped over, a light skim pass was made, and the touch probe was again utilized to set z-zero. For OP-2, a 3" diameter cylindrical pocket was utilized to cut another pocket in the jaw. The part was loaded sprag side down into the jaw. The rotor mount was milled with a 3/8" 3FL end mill. The spoke holes were again center drilled and drilled with a .0938" drill. After the second operation was complete, and the dimensions were checked against the detailed drawing, the part was pulled. A hand deburring tool was utilized to remove any burrs from the part. This completed the machining portion of the manufacturing.

Finally, hand finishing was needed to complete the part. To remove any residual burrs and machining marks, the part was placed into an aluminum vibratory finisher. This tumbling in stones greatly improved the surface finish of the part. The last step for this part was to install helicoils. Utilizing the M6x0.8 helicoil kit, an STI tap was run into the holes on the sprocket mount using a t-handle. Once the holes were tapped, the helicoil tool was utilized to install the helicoils into the tapped holes.

## **Axle and Spacers**

To make the axle, the steel rod was placed into a manual lathe. One end of the rod was faced down to a flat surface. Then the rod was turned down to 16mm a total length slightly larger than the length that the axle needs to be. A center drill was used to drill the 12mm inner hole through the length of the axle and then the axle was parted from the rest of the steel rod as close to the exact length of the axle. During manufacturing, the surface finish of the axle came out pretty rough. It is recommended that a high feed speed and auto feed be used for a nice surface finish. The spacers should be manufactured very similarly but with their own respective measurements. Make sure final length of axle is correct and fits within the vehicle dropout mounts before manufacturing the axle.

## **Assembly**

After most of the components for the drivetrain were manufactured, the drivetrain was assembled. Unfortunately, not all of the components were completed by the end of this project but instructions on the installation of these parts have been included. Items such as the sprocket and spacers were not complete due to issues with the waterjet and the spacers need to be calibrated for alignment following the installation of the engine and rear brakes. Once the sprocket mount/ hub components are assembled, they were issued for testing. This subassembly is much easier to test the functionality of the system. Steps for assembling the entire drivetrain as well as testing have been included in the appendix of this report.

## **Design Verification & Testing**

### ***Torque Wrench Test***

The first and most important test to be done is a torque test. The torque test will tell us if the sprag bearing inside the hub can stand to the max torque of the engine without slipping or failing. If it does fail, a stronger bearing or better method of fixturing the bearing to the hub must be found. To conduct the test, you must utilize a torque wrench, custom torque wrench fixture, and a vise. A full step by step breakdown of the test can be found in the user manual in Appendix Q. When conducting this test, our team noticed that the hub was slipping a bit out of the vise. To fix this, we clamped the hub by the brake mount within the vis. While testing we noticed that the structure of the hub was beginning to deform slightly but did not yield. When we completed this test, we found that the hub with the sprag bearing and sprocket mount was able to withstand a torque load of 35.5 ft-lb, which is the estimated max dynamic load assuming an engine torque output of 1hp. Therefore, we have confidence that the hub will work as it was designed.

### ***Coast Down Testing Procedure***

The second test to consider is a coast down test. This test can be used to measure the friction factor of the hub and sprocket mount assembly. By measuring how many rotations the assembly goes through as it slows from one RPM to second set RPM, you can see the effects of friction/drag that the assembly undergoes. To conduct this test you need a vise, a tachometer, and a camera with slow motion. The full step by step breakdown of the test can be found in the user manual in Appendix Q. Unfortunately, due to the COVID-19 outbreak shops and labs were closed making us unable to finish conducting this test. Using this test, the drag torque of this assembly can be found and compared to the manufacturing data and other hubs to directly compare drag at least until the dynamometer is completed.

### ***Additional Testing***

Another test to consider doing that would be useful data to have is an efficiency test on a dynamometer. Because the current dynamometer is not yet complete, along with the final assembly of our drivetrain, we could not perform this test. However, once both the dyno and the assembly

are completed, this test will help show if this prototype design is able to reach high enough efficiencies.

### Specification Verification Checklist

Specification	Specification Description	Requirement or Target	Test Results	Pass/Fail
1	Volume Occupied	8"x6"x10"	8"x6"x10"	Pass
2	Drive Ratio	8:1 – 14:1	14:1	Pass
3	Time to Build	150 hrs	200 hrs	Fail
4	Time to Change Drive Ratio	15 min	TBD	TBD
5	Clutch Engagement Time	0.2s	TBD	TBD
6	Torque	17.5 lbf-ft	35.2 lbf-ft	Pass
7	Driveline Efficiency	85%	TBD	TBD
8	Rear Hub Cost	\$300	\$100	Pass
9	Sprocket and Chain Costs	\$400	\$0	Pass
10	Offset Angle	1 degree	TBD	TBD
11	# of Seasons	2 seasons	TBD	TBD
12	Overall Weight	8lbs	TBD	TBD



Because the entire assembly was not complete, the dynamometer was not finished, and the club vehicle was not assembled, many of the tests our team hoped to run could not be done. The system did fit within the vehicle so that specification was met. The sprocket was designed to be adjustable for different drive ratios and the hub/sprocket mount and sprag assembly was able to withstand twice the required torque load meaning those specifications were also met. The cost specifications were met as well because we were able to get material from the club. The only specification that failed at this time was the time to build. It took us over the expected 150 hours to build most of the parts. However, this is due to our minimal shop experience and other problems we ran into. The rest of the specifications can be checked once the entire assembly is completed. The weight of the components appears to be heavier than anticipated, meaning the overall weight would likely have been more than 8 lbs. Our team highly recommends optimizing the components for weight reduction in the future.

## **CONCLUSION**

The goal of the Supermileage Vehicle Drivetrain Project is to design and manufacture a more efficient, reliable drivetrain for the 2020/2021 Supermileage vehicle. A need was established by the Supermileage Vehicle Club, due to problems with the existing drivetrain that suffered from reliability issues, ultimately failing at Sonoma in April 2019. In addition to the reliability issues, the drivetrain's overall efficiency can be improved significantly. Comparing the losses associated with the drivetrain to the theoretical maximum single reduction drive train from *Mechanical Engineering Design* by Shigley, there is ample room to improve. The Supermileage Vehicle Club originally asked us to design and manufacture a new drivetrain consisting of a clutch, transmission system, rear hub with brake mounts, and a mounting system. However, we will be focusing mainly on the rear hub and sprocket, with the decision being to design and manufacture a new hub with an internal sprag clutch system and a new sprocket because these were what caused the greatest issues for the team. We will be reusing the teams centrifugal clutch and front sprocket and buying a new chain. The sprocket we designed was reverse-engineered from the previous year's leading team's design and customized to work with our system. A custom hub was also reverse-engineered from an onyx bike hub and integrated with a brake mount. In addition to these components, our team also designed a sprocket mount to attach the sprocket to the hub, and a custom axle that will allow our design to mount to the team's dropout brackets with a little modification. This report outlines the project goals, along with a complete timeline of the project. The sponsor's project goals, along with the team's project goals, are displayed in the attached QFD. The Appendices includes preliminary analyses, a bill of materials and the drawing package for our design, our projects budget, a Failure Modes and Effects Analysis, a Design Hazard Checklist, Manufacturing Plan and finally an updated Gantt Chart outlining the next and final steps of the project. Following the completion of the updated Gantt Chart, the drivetrain components were manufactured and tested against the target specifications. The manufacturing process was a fairly rough process as many unexpected hurdles impacted project schedule. There were numerous issues with the

bearings and press fits due to slight errors during the manufacturing process. Recommendations to improve this process and the components themselves can be viewed in the section below. Testing results can also be found in the appendices. Overall, the drivetrain assembly is functioning, but additional improvements should be made prior to competition next spring.

## **Lessons Learned and Future Improvements**

There are many improvements that can be made to improve the functionality and manufacturing process within the drivetrain components of the vehicle. In terms of functionality, the most significant improvements that can be made to manufactured components is reducing weight of the sprocket mount and hub. Both components were made to resist component failure but in turn excess material was left on the parts adding weight. Using the CAD models of the existing components, FEA should be conducted to locate areas where additional material can be cut away. During this process though, careful consideration should be made to ensure the improvements can actually be manufactured. In addition, the future design should investigate solutions that can allow the bearings to be easily removed in the event of bearing failure or replacement. The current method for removing bearings involves machining out the bearing and is not an ideal method for bearing removal. One of the bigger suggestions our team has for future teams is to buy more available components if within the team's budget. Manufacturing custom components led to many issues down the road. Multiple bearings were replaced and errors due to manufacturing cost the team an additional 20% which prevented our team from coming way under budget.

In addition to improvements to the design, there are many suggestions or improvements that can be made to smoothen the manufacturing process. The first and most simple suggestion is to allot much more time for machining than anticipated. This will allow time for practicing toolpaths on practice/ scrap material. This will help identify issues with improvements and reduce headaches later in the manufacturing process. In terms of the bearings, shrink fit should be avoided. Using shrink fit on the sprag bearing melted the plastic retaining ring within the bearing and prevented the bearing from holding any torque. Therefore, press fits should be used on all the bearings. The press fit interference should be directly taken from the bearing supplier to prevent failure of the bearing or parts. The interference fits were calculated in the appendix but because parts were cut to be material safe, the interferences tended to run tight. Lastly, more research should be done to better fasten the components to the hub and sprocket. The helicoil kits purchase were very expensive and used about 20% of the overall budget. If a more cost-effective method is implemented, a lot of money can be saved securing the components together.

The last improvements that should be made to the drivetrain design verification would be to test the drivetrain on the team dynamometer. At the conclusion of this project, the dynamometer was not ready for active tests. Using the dynamometer, a better estimation of drivetrain efficiency can be concluded to verify our efficiency specification.

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## APPENDIX B: IDEATION SESSIONS

Ideation Session #1 - Brainstorming 4/28/19

- Gearbox
  - ↳ planetary gearbox
  - ↳ research pricing
  - efficiency big concern
  - weight
- Hub
  - ↳ check which hub broke
  - ↳ see if they still have it
  - ↳ check failure modes for vehicle
  - ashew, fatigue, etc
- Hardening/strengthening methods for sprocket
  - ↳ research
- Alignment of sprockets
- best adjustments for chain/sprocket
  - ↳ laser for alignment: research method
- need dimensions for back /
- decrease sprocket size
  - ↳ consider gear ratios e  $8:1 \rightarrow 14:1$
  - need
- developing instalment procedure
- key / chuck for adjustments to final drive ratio - makes small adjustments easier
- include procedure in scope of work
- axle mounts to easily remove sprockets
- min sprocket sizes?
- chain - need tensioning method
- just change sprocket size @ wheel
  - ↳ slide to adjust?
- need multiple chains
  - ↳ therefore standard chains may be better.

◦ sprag vs centrifugal clutch

→

- CVT
  - ↳ cost?
  - ↳ efficient?
- 

TASKS → KAI - PROJECT MANAGE  
 - clutch - CONCLUSION  
 - 2 PATENTS (clutch)  
 - GIANTT  
 MICK - Bullet spec list  
 - Add QFD  
 - Hub Research  
 GRIFF - PLANETARY GEAR Research

ARYA - Abstract  
 - SPROCKET HARDENING

Figure 19. Ideation Session 1

Week 5  
 ↳ SOW  
 ↳ Ideation

Week 6  
 ↳ concept modeling / Refinement

Week 7  
 ↳ concept selection  
 ↳ preliminary analysis

10 CONCEPTS  
 ↳ evolve 4 concepts  
 ↳ assess using statement of work

NEEDS TO BE OBJECTIVE!

Week 8  
 Refine selected concept.

Week 9  
 • PDR  
 • PDR - Review - Report

4/30/19

Ideation Session #2 - Check List

Physical Conditions

size tbd - more vertical room than horizontal room  
 - size of chassis will affect size of drivetrain

weight - emphasize attribute

- ↳ steel / titanium
  - ↳ hard to machine
  - ↳ magnesium? ~~stiff~~ stiff but brittle
- find stock titanium

shapes - narrow, high vertical occupation

PAUSE ||

SPROCKET - Research Ratio (K/A1)

- ↳ Titanium
  - ↳ expensive
  - ↳ strong
  - ↳ stiff

Aluminum Hub & outer Steel?  
 ↳ consider warpage?  
 ↳ attaching two pieces?

- Steel
  - ↳ cheap
  - ↳ easy to manufacture
  - ↳ potential warping

• Waterjet vs Machine Stock

- Aluminum
  - ↳ soft metal
  - ↳ easy to manufacture
  - ↳ cheap-ish

CHAINS (GK)

- ↳ ORING etc.

CLUTCHES - REAR & FRONT

GENTRIFUGAL GK

FRONT (ARYA)

- ↳ CENTRIFUGAL ]
- ↳ MANUAL
  - ↳ Hydraulic
  - ↳ cable activated
  - ↳ pneumatic

- ↳ CVT
- ↳ VORTEX

REAR Hub (MICK)

~~GENTRIFUGAL~~ GK

- Sprag hub
- 1-way freewheel hub
- spring activated

Figure 20. Ideation Session 2

## APPENDIX C: PUGH AND MORPHOLOGICAL MATRICES

**Table 8:** Pugh Matrix-Overall System Design (Old Design)

Pugh Matrix				
Overall System				
<i>Criteria</i>	SMV Team 2018 Design	2 Stage Reduction	Direct Gear Transmission	Belt Drive
Cost Efficient		-	-	-
Volume Occupied	D	-	-	S
System Efficiency	A	+	+	-
Minimal Weight	T	-	-	+
Reliability	U	+	+	-
Time to Change Drive Ratio	M	S	-	+
Life / Durability		+	+	-
Complexity / Ease of Use		S	S	S
	$\Sigma+$	3	3	2
	$\Sigma-$	3	4	4
	$\Sigma S$	2	1	2

**Table 9:** Pugh Matrix-Front Clutch Design (Existing)

Pugh Matrix			
Front Clutch			
<i>Criteria</i>	Centrifugal	Cable Actuated Manual Clutch	Hydraulic Actuated Manual Clutch
Cost Efficient		+	+
Drag	D	+	+
Min Weight	A	+	+
Reliability	T	+	+
Complexity / Ease of Use	U	-	-
Adjustability	M	-	-
Time to Install		-	-
Life / Durability		+	+
	$\Sigma+$	5	5
	$\Sigma-$	3	3
	$\Sigma S$	0	0

**Table 10: Pugh Matrix-Rear Hub Design (Existing)**

Pugh Matrix						
Rear Hub						
Criteria	Conical	Ratchet and Pawl	Sprag	Freewheel	Cam Plate Design	Star Ratchet
Cost		+	S	+	S	S
Noise	D	-	+	S	+	+
Drag	A	-	+	-	-	+
Minimal Weight	T	S	S	S	+	S
Reliability	U	-	+	-	-	+
Engagement Time	M	+	+	-	-	+
Life / Durability		S	S	-	-	S
	$\Sigma+$	2	4	1	2	4
	$\Sigma-$	3	0	4	4	0
	$\Sigma S$	2	3	2	1	3

**Table 11: Morphological Matrix with Most Feasible designs**

	1	2	3	4	5	6
Overall	1 Stage Reduction	2 Stage Reduction	Direct Gear Transmission	Belt Drive		
Front Clutch	Centrifugal	Hydraulic Manual	Cable Actuated Manual	-		
Rear Hub	Conical	Ratchet and Pawl	Sprag	Cam Plate	Star Ratchet	Roller Bearing

**Table 12: Concept Morphs**

Concept Morphs			
	Overall	Front Clutch	Rear Hub
Concept 1	1 Stage Reduction	Centrifugal	Conical
Concept 2	1 Stage Reduction	Hydraulic Manual	Sprag
Concept 3	1 Stage Reduction	Cable Actuated Manual	Star Ratchet
Concept 4	2 Stage Reduction	Centrifugal	Conical
Concept 5	2 Stage Reduction	Centrifugal	Star Ratchet
Concept 6	Direct Gear Transmission	Centrifugal	Conical
Concept 7	Direct Gear Transmission	Hydraulic Manual	Sprag
Concept 8	Belt Drive	Centrifugal	Conical
Concept 9	Belt Drive	Hydraulic Manual	Sprag



## APPENDIX D: WEIGHTED DESIGN MATRICES

**Table 13: Weighted Design Matrix-Maximum Efficiency Analysis**

Efficiency Analysis		Estimated Efficiency per Component			Number of Components			Overall Efficiency
Concept #	Concept Name	Gears	Belts	Sprockets	Gears	Belts	Sprockets	(Highlight highest Efficiency)
Concept 1	Single Stage Chain + Sprocket	0.98	0.94	0.96	0	0	2	0.922
Concept 2	2 Stage Planetary	0.98	0.94	0.96	3	0	2	0.867
Concept 3	Gearbox w/ Driveshaft	0.98	0.94	0.96	6	0	0	0.886
Concept 4	Belt Drive	0.98	0.94	0.96	0	2	0	0.884
Concept 5	Gearbox w/ Chain + Sprocket	0.98	0.94	0.96	3	0	2	0.867

**Table 14: Weighted Design Matrix-Maximum Size Analysis**

Size Calculations		Size Constraints Xmax = 6in Ymax = 8in Zmax = 10in			
Concept #	Concept Name	Xdim	Ydim	Zdim	Pass?
Concept 1	Single Stage Chain + Sprocket	6	8	10	Pass
Concept 2	2 Stage Planetary	9	7	8	Fail
Concept 3	Gearbox w/ Driveshaft	6	8	6	Pass
Concept 4	Belt Drive	5	8	8	Pass
Concept 5	Gearbox w/ Chain + Sprocket	6	8	6	Pass

**Table 15: Weighted Design Matrix-Potential Weight Reduction**

Weight Calculation				
Concept #	Concept Name	Total	OLD SMV Weight	% Decrease
Concept 1	Single Stage Chain + Sprocket	8.245	8.5	3.0
Concept 2	2 Stage Planetary	8.705	8.5	-2.4
Concept 3	Gearbox w/ Driveshaft	9.505	8.5	-11.8
Concept 4	Belt Drive	7.745	8.5	8.9
Concept 5	Gearbox w/ Chain + Sprocket	9.765	8.5	-14.9

**Table 16:** Estimated Cost Analysis

<b>Concept 1</b>	<b>Single Stage Chain + Sprocket</b>	<b>Cost</b>
	Front Sprocket	20
	Rear Sprocket	300
	Clutch	350
	Chain	20
	<b>Total</b>	<b>690</b>
<b>Concept 2</b>	<b>2 Stage Planetary</b>	<b>Cost</b>
	Front Sprocket	20
	Rear Sprocket	100
	Clutch	350
	Chain	20
	Planetary Gearbox	300
	<b>Total</b>	<b>790</b>
<b>Concept 3</b>	<b>Gearbox w/ Driveshaft</b>	<b>Cost</b>
	Clutch	350
	Bevel Gears	200
	Gearbox	300
	Driveshaft	100
	<b>Total</b>	<b>950</b>
<b>Concept 4</b>	<b>Belt Drive</b>	<b>Cost</b>
	Belt	40
	Belt Drive Sprockets	200
	Clutch	350
	<b>Total</b>	<b>590</b>
<b>Concept 5</b>	<b>Gearbox w/ Chain + Sprocket</b>	<b>Cost</b>
	Clutch	350
	Idler Gear	200
	Gearbox	300
	Rear Sprocket	100
	Front Sprocket	20
	Chain	100
	<b>Total</b>	<b>950</b>

# APPENDIX E: PRELIMINARY ANALYSIS

5/19/19 PRELIMINARY ANALYSIS

Efficiency Calculations

CONCEPTS	NAME	# Gears	# Sprockets	Efficiency Est
1	Single-Stage CHAIN+SPROCKET	0	2	0.96
2	2 stage Planetary	3	2	0.90
3	Gearbox w/driveshaft	6	0	0.94
4	BELT DRIVE	0	2	0.88
5	Gearbox + Chain + sprocket + idler gear	3	2	0.90

Based on efficiency of above concepts, the single stage chain drive has the highest potential to satisfy our efficiency requirement.

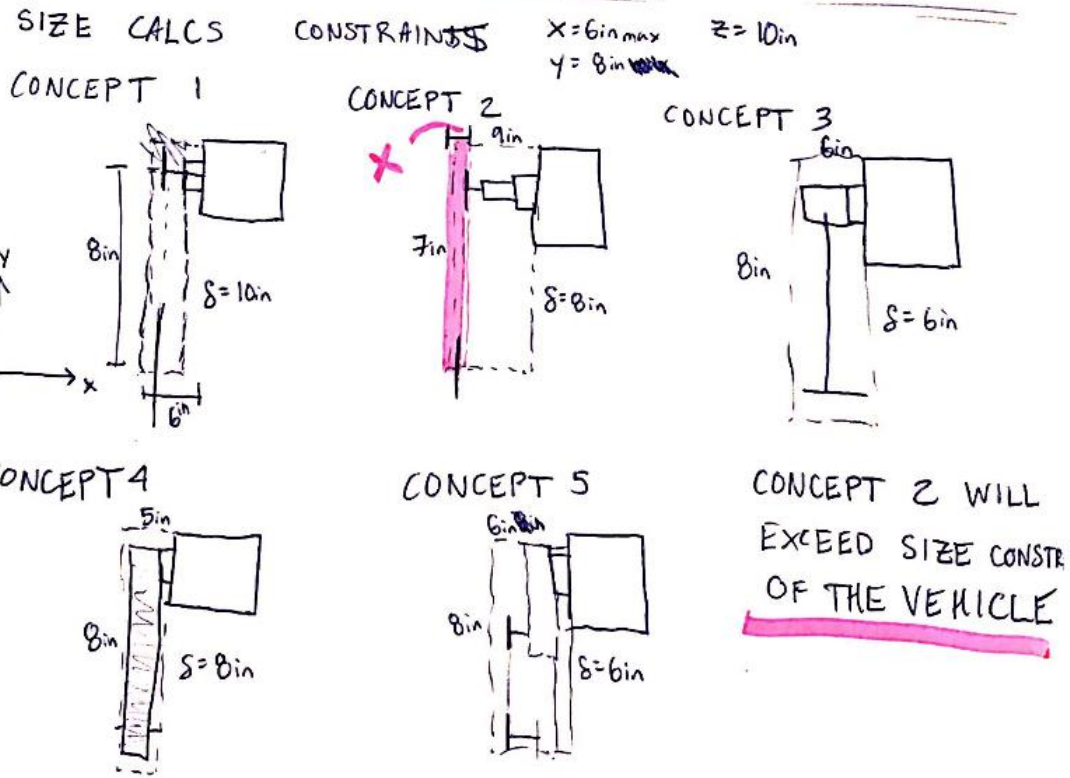


Figure 21. Preliminary Analysis: Efficiency and Size Calculations

# Precision Preliminary Analysis

5/29/2019

Concept #1 only

	TOLERANCE	#
14mm SHAFT <del>SHAFTS</del>	-0.027 mm	× 2
Waterjet Sprocket + Machine Grinding	$\pm \frac{0.005 \text{ mm}}{0.025 \text{ mm}}$	× 2
<del>Machine Grinding</del>	<del>± 0.005</del>	<del>× 2</del>
<del>Custom Hub Bearings</del>	<del>± 22 μm</del>	<del>× 2</del>

Min →  $-0.027 \text{ mm} + -0.005 \text{ mm} + -0.022 \text{ mm} = 0.054 \text{ mm} \sim 2.12 \text{ thou}$

Max →  $0 \text{ mm} + 0.005 \text{ mm} + 0.022 \text{ mm} \rightarrow 0.027 \text{ mm} \sim 1.06 \text{ thou}$

Precision should not be an issue for this application as long as installation done accurately.

Figure 22. Preliminary Analysis-Precision Calcs

PRELIMINARY ANALYSIS

Weight Analysis (lb)

	Rear Hub	CHAIN	#Gears	Gears	#Shafts	SHAFTS	#Bearings	Bearings	#SPROCKETS	SPROCKET	BELTS	Engine Mount	Mounting Plate	Proprietary	TOTAL	% reduction
Concept 1	1.125	0.1	0	0	2	0.54	0	0	2	1.4	0	0.97	3.08	1.03	8.245	3
Concept 2	1.125	0.1	3	1	1	0.1	0	0	2	1	0	0.97	3.08	1.03	8.765	-2.1
Concept 3	1.125	0	6	0.9	3	1.2	6	1.2	0	0	0	0.97	3.08	1.03	9.565	-11.8
Concept 4	1.125	0	0	0	2	0.54	0	0	0	0	1	0.97	3.08	1.03	7.745	8.9
Concept 5	1.125	0.1	3	0.95	3	0.81	6	1.2	2	1	0	0.97	3.08	1.03	9.765	-14.9

Rear Hub - weight estimated using leading Rear Hub concept  
 CHAIN - weight based on 10 ft of chain  
 CONCEPT #2 - Based on leading Planetary Gearbox weight  
 SHAFT weight based on steel pipe 14mm in diameter from steel stock re-biler  
 #Bearing weight from manufacturer (Boston centerless)  
 Belt weight based on manufacturer for 10 ft  
 Engine Mount weight based on previous SMV project  
 Mounting Plate  
 Proprietary

Not many of the designs have a significant weight decrease if any

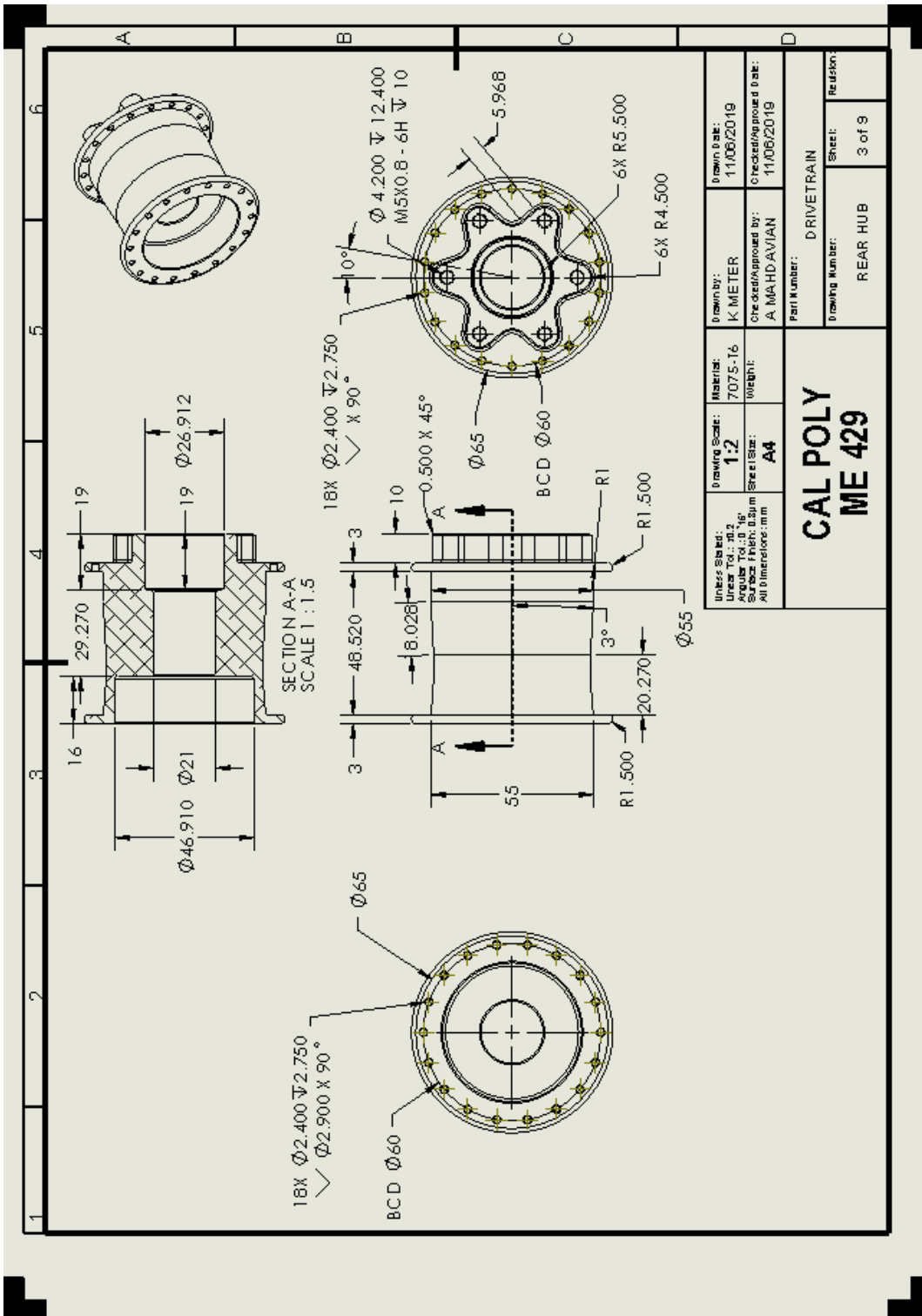
Figure 23. Preliminary Analysis-Weight

# APPENDIX F: BILL OF MATERIALS

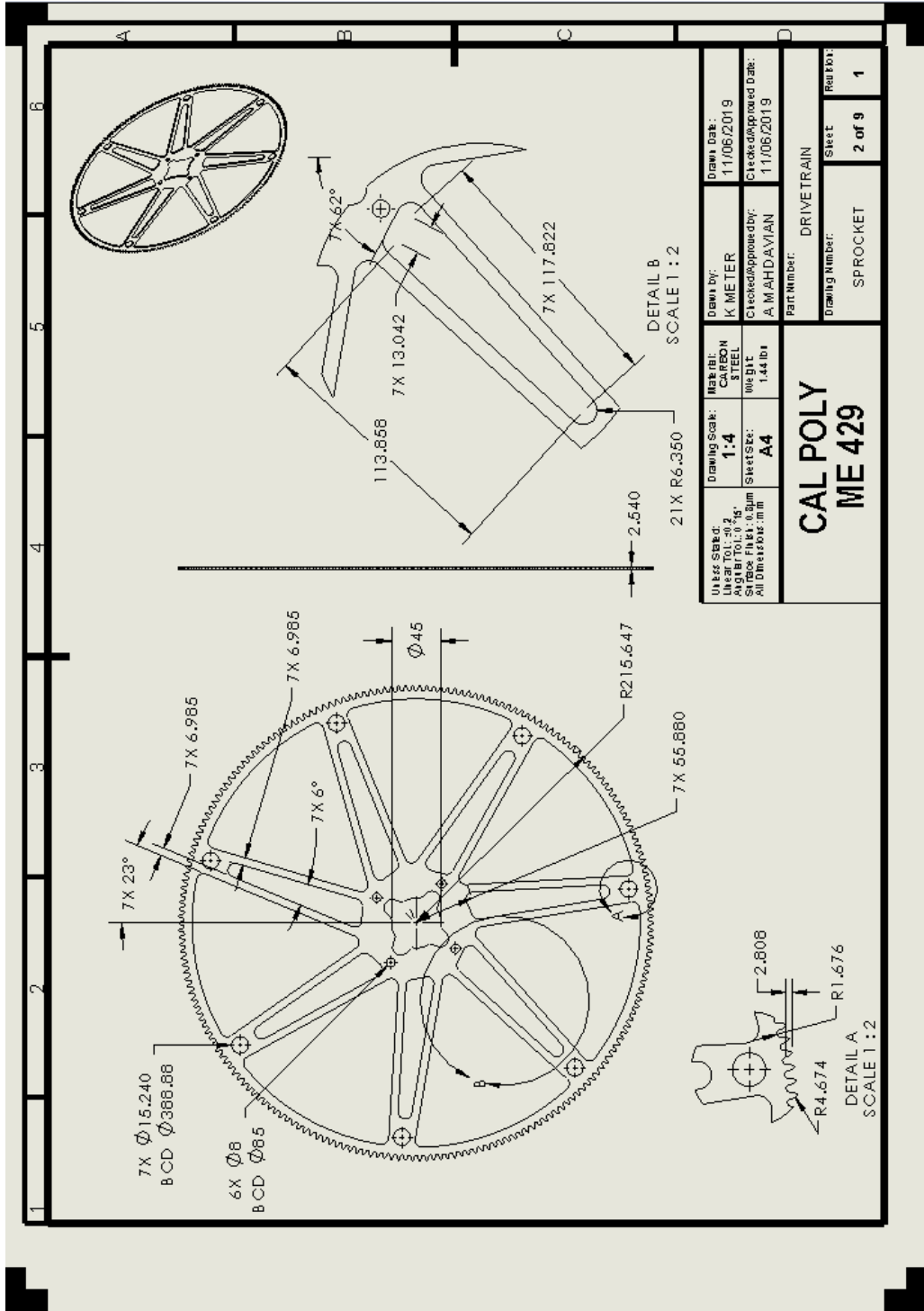
MEMO NO.	PART NUMBER	QTY.
1	Dropout_Adjustment_screw_Re design	2
2	Dropout_Assembly_Brakeside	1
3	Dropout_Assembly_Driveside	1
4	Sprocket_Mount	1
5	Sprocket	1
6	disc_brake_rotor_sw12	1
7	Csk6005(X)_Sprag	1
8	91352A151	4
9	91352A131	6
10	Hub	1
11	Spacer_Driveside	1
12	spacer_Brakeside	1
13	Axle	1
14	SMR2718_2RS_W7.stp	2

Unless Specd: Linear TOL: ±0.2 Angular TOL: 0°15' Surface Fx 63: 0.03µm All Dimensions in mm	Drawing Scale: 1:12 Sheet Size: A4	Material: weight:	Drawn by: K.METER Checked/Approved by: A.MAHD AVIAN	Drawn Date: 11/06/2019 Checked/Approved Date: 11/06/2019
<b>CAL POLY ME 429</b>			Part Number: DRIVETRAIN	Sheet: 1 of 9
			Drawing Number: BOM	Revision:

# APPENDIX G: DRAWING PACKAGE

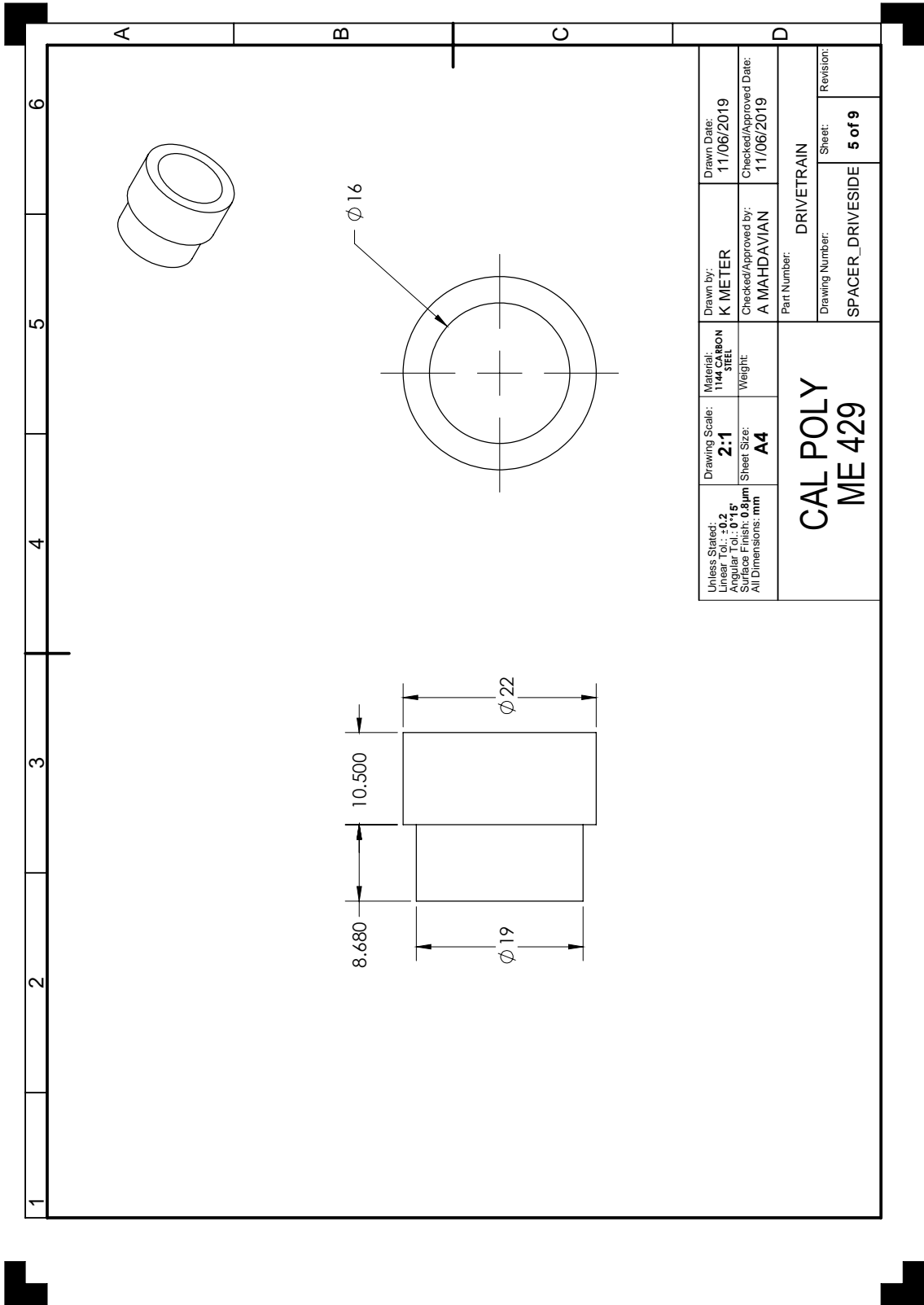




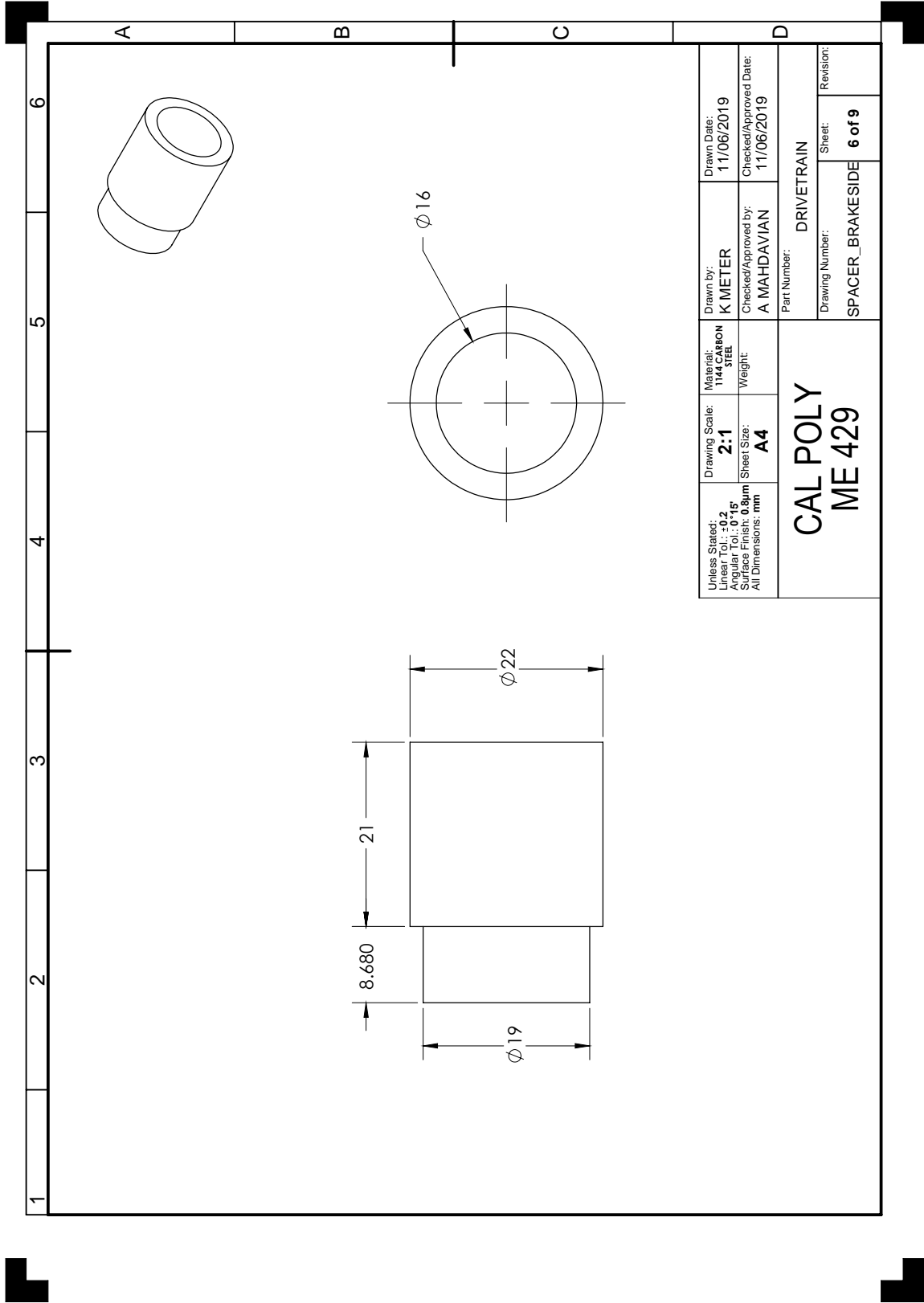




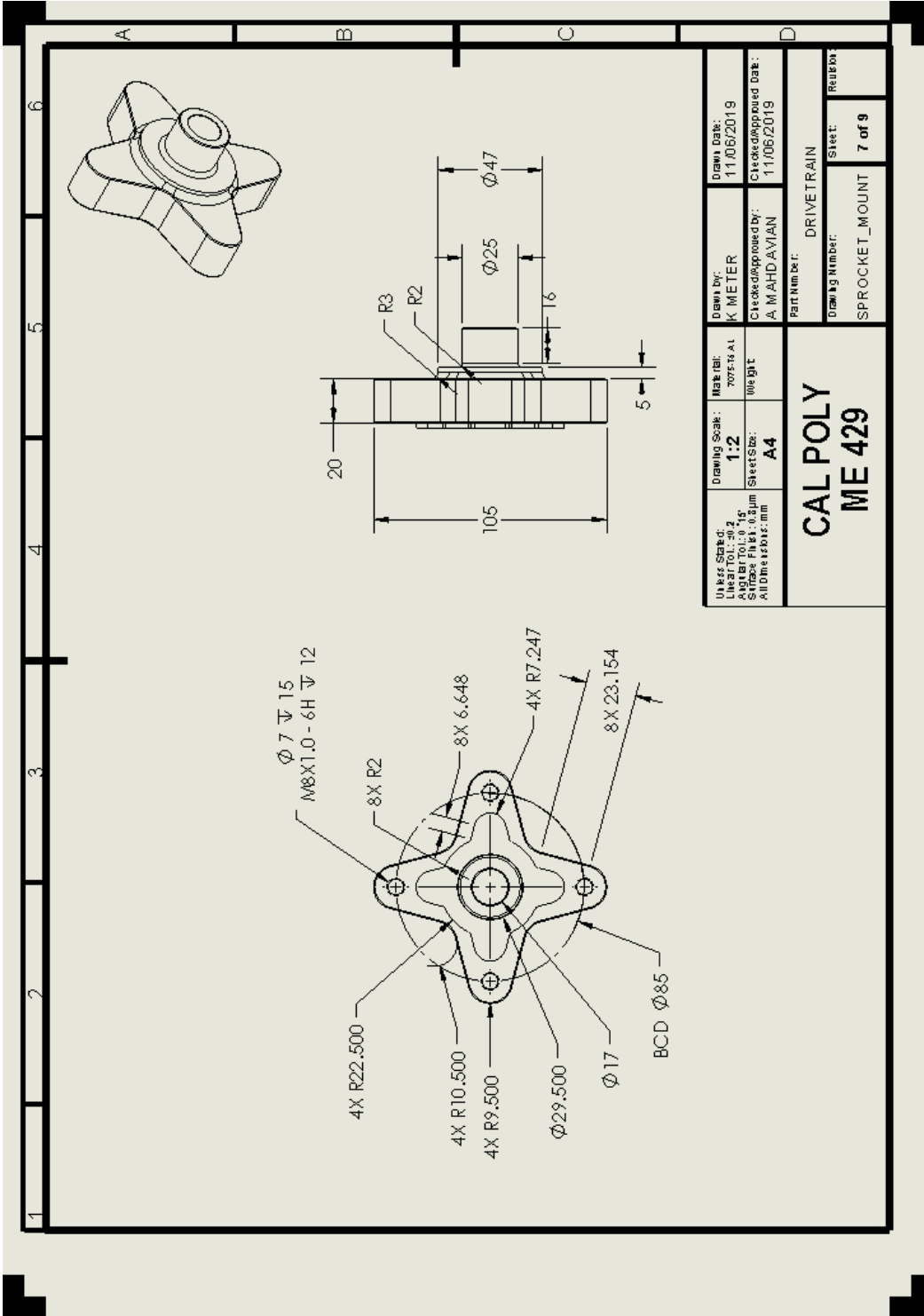




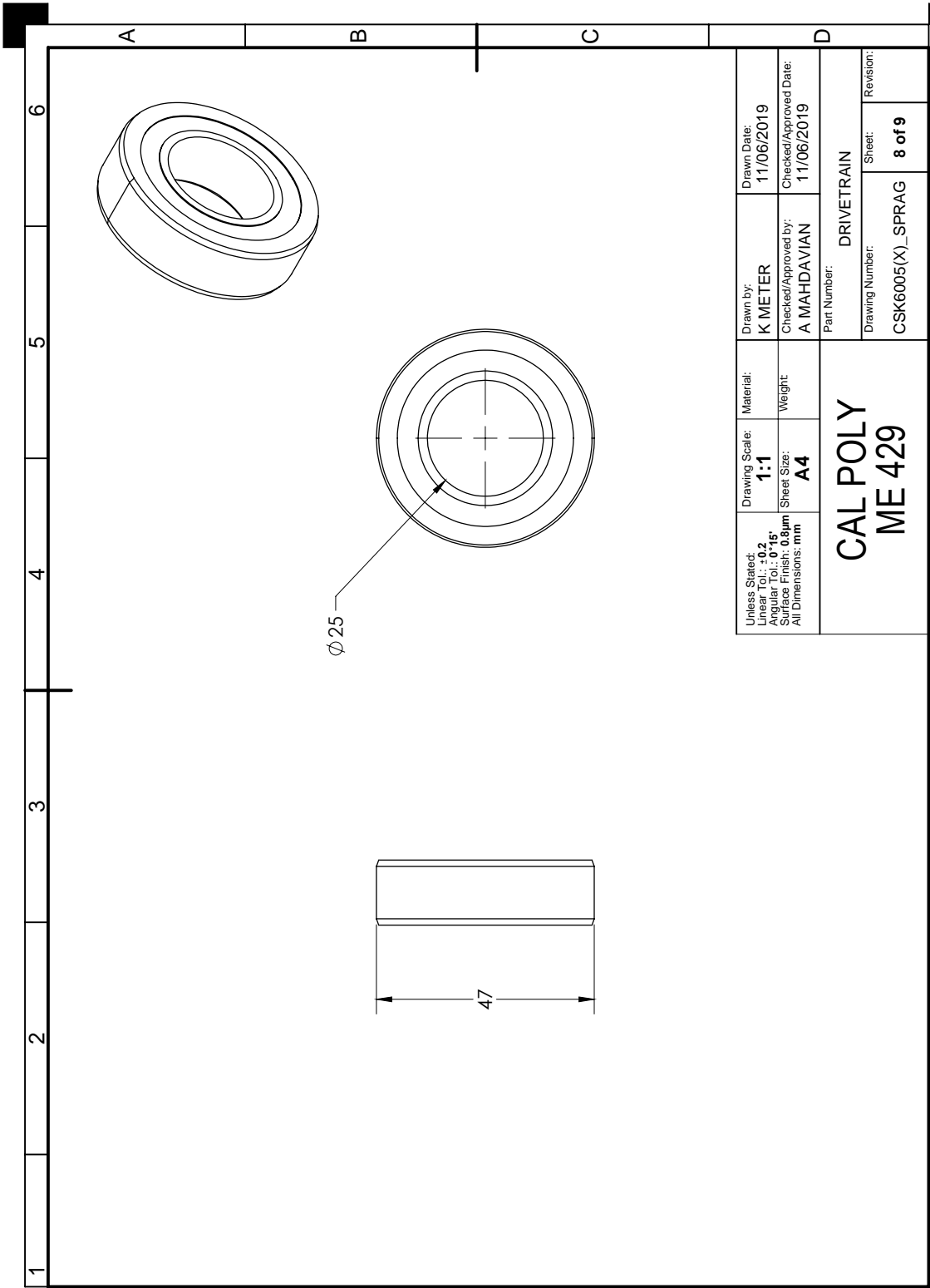
Unless Stated: Linear Tol: $\pm 0.2$ Angular Tol: $0.15^\circ$ Surface Finish: $0.8\mu\text{m}$ All Dimensions: mm	Drawing Scale: <b>2:1</b> Sheet Size: <b>A4</b>	Material: <b>1144 CARBON STEEL</b> Weight:	Drawn by: <b>K METER</b> Checked/Approved by: <b>A MAHDAVIAN</b>	Drawn Date: <b>11/06/2019</b> Checked/Approved Date: <b>11/06/2019</b>
<b>CAL POLY ME 429</b>			Part Number: <b>DRIVETRAIN</b>	
			Drawing Number: <b>SPACER_DRIVESIDE</b>	Revision: <b>5 of 9</b>



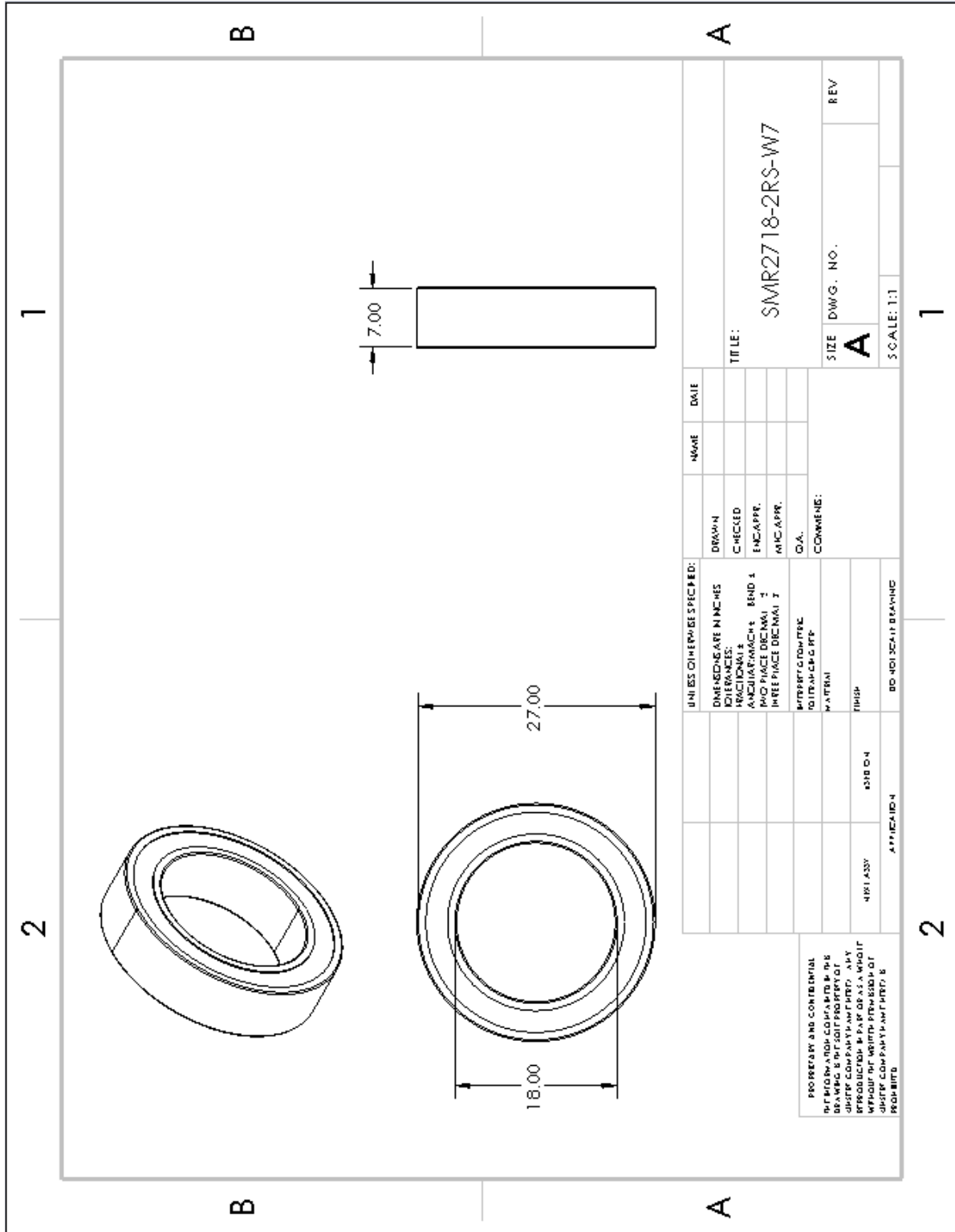
Unless Stated: Linear Tolerance: $\pm 0.15$ Surface Finish: 0.8um All Dimensions: mm	Drawing Scale: <b>2:1</b>	Material: <b>1144 CARBON STEEL</b>	Drawn by: <b>K METER</b>	Drawn Date: <b>11/06/2019</b>
	Sheet Size: <b>A4</b>	Weight:	Checked/Approved by: <b>A MAHDAVIAN</b>	Checked/Approved Date: <b>11/06/2019</b>
<b>CAL POLY ME 429</b>			Part Number: <b>DRIVETRAIN</b>	
			Drawing Number: <b>SPACER_BRAKESIDE</b>	Revision: <b>6 of 9</b>



Units Scale: Linear: 1:2 Angular: 15 Radial: 1500:1	Drawing Scale: 1:2 Sheet Size: A4	Material: 7075-T6 AL Weight	Drawn by: K METER	Draw Date: 11/06/2019
Checked/Approved by: A MAHDAVIAN	Checked/Approved Date: 11/06/2019	Part Number: DRIVE TRAIN	Drawing Number: SPROCKET_MOUNT	Sheet: 7 of 9
Revision:				



Unless Stated: Linear Tol.: <b>±0.2</b> Angular Tol.: <b>0°15'</b> Surface Finish: <b>0.8µm</b> All Dimensions: mm	Drawing Scale: <b>1:1</b>	Material:	Drawn by: <b>K METER</b>	Drawn Date: <b>11/06/2019</b>
	Sheet Size: <b>A4</b>	Weight:	Checked/Approved by: <b>A MAHDAVIAN</b>	Checked/Approved Date: <b>11/06/2019</b>
<b>CAL POLY ME 429</b>			Part Number: <b>DRIVETRAIN</b>	
			Drawing Number: <b>CSK6005(X)_SPRAG</b>	Revision: <b>8 of 9</b>



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 FORM OR BY ANY MEANS, ELECTRONIC OR  
 MECHANICAL, WITHOUT THE WRITTEN  
 PERMISSION OF THE COMPANY.

UNITS OTHER THAN SPECIFIED:	UNITS ARE IN INCHES	DRW'N	NAME	DATE
DIMENSIONS ARE IN INCHES		CHECKED		
DECIMALS TO FIVE PLACES		ENC/APP.		
ANGLES TO NEAREST 15 MINUTES		INC/APP.		
FINISH TO REMAIN UNLESS OTHERWISE SPECIFIED		Q.A.		
ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED		COMMENTS:		
4X1 ASSY	0318 0-4			
APPROVED:				
DATE:				
BY:				
SCALE: 1:1				

TITLE: SMR2718-2RS-W7  
 SIZE DWG. NO. A  
 REV

## APPENDIX H: PRODUCT LITERATURE

### Bearings

One-way sprag bearing: CSK6005X

[https://www.bocabearings.com/products/ck6005\(x\)-23082](https://www.bocabearings.com/products/ck6005(x)-23082)

Sprag Bearing Catalog

<https://www.bocabearings.com/Files/Images/drawings/One-Way-Bearing-Catalog.pdf>

Thrust Bearings: FP-19-32

<https://www.bocabearings.com/products/smr2718-2rs-w7c-sri-2-14200>

### Sprocket

Steel Sheet: 18"x18"x¼"

<https://www.mcmaster.com/1388k175>

### Sprocket Mount

5" Diam x ½' Aluminum Rod

<https://www.midweststeelsupply.com/store/7075aluminumroundbar>

### Hub

<https://www.mcmaster.com/standard-aluminum-rods/high-strength-7075-aluminum-rods-and-discs-7/>

### Axle

20mm Diam Rod by 1ft length

<https://www.mcmaster.com/standard-steel-rods>

### Fasteners

M8.0 Fasteners

<https://www.homedepot.com/p/M8-1-0-x-25-mm-Class-8-8-Zinc-Plated-Hex-Bolt-813548/204273570>

M5x0.8 Fasteners

<https://www.homedepot.com/p/Everbilt-M5-0-8-x-40-mm-Class-8-8-Zinc-Plated-Hex-Bolt-801408/204273659>

M14x1.5 Fasteners

<https://www.homedepot.com/p/Everbilt-M14-2-0-x-40-mm-Class-8-8-Zinc-Plated-Hex-Bolt-802018/204779250>

### Helicoil Kits

<https://www.oreillyauto.com/detail/b/heli-coil-3878/tools---equipment-16488/hand-tools-16814/cutting---drilling-tools-16542/thread-repair-16906/heli-coil-inserts-19596/ec39e02ab378/heli-coil-m5-0-80-metric-thread-repair-kit/55465/4368747?q=HeliCoil+m5&pos=1>

<https://www.oreillyauto.com/detail/b/heli-coil-3878/tools---equipment-16488/hand-tools-16814/cutting---drilling-tools-16542/thread-repair-16906/heli-coil-inserts-19596/ec39e02ab378/heli-coil-m8-1-0-metric-thread-repair-kit/55428/4368732?q=HeliCoil+m8&pos=4>

# APPENDIX I: PROJECT BUDGET

SMV Drivetrain Bill of Materials												
Assembly	Part	LVL 0	LVL 1	LVL 2	LVL 3	Description	LVL 4	Vendor	Quantity	Cost	Tax+Shipping	Total Cost
												\$507.86
0	Final Assembly											
1			Sprocket									
2				Driven Sprocket								
3					18"x18"x0.25" Steel Sheet			McMasterCarr	0	\$ 160.00	\$ -	\$ 0.00
3					18"x18"x0.25" Carbon Fiber Sheet			McMasterCarr	0	\$ 605.00	\$ -	\$ 0.00
2				Sprocket Fixture								
3					18"x18"x0.75" Steel Sheet			McMasterCarr	0	\$ 285.90	\$ -	\$ 0.00
2				Driver Sprocket								
3					Carbon Steel			SMV Club	1	\$ -	\$ -	\$ 0.00
2				Chain								
3					ANSI 25 Chain - 4ft			SDR	0	\$ 28.80	\$ -	\$ 0.00
1			Hub									
				Shell								
					3" Aluminum 7075 1/2 ft long			McMasterCarr	1	\$ 69.82	\$ 11.87	\$ 81.69
2				Sprocket Mount								
3					5" Diam, 6" Long 7075 Aluminum Barstock			Widwest Steel	1	\$ 117.86	\$ 20.04	\$ 137.90
				HeliCoil Kits								
					M5x0.8 HeliCoil Kit 5546-5			O'Reillys	1	\$ 59.66	\$ 10.14	\$ 69.80
					M8x1.0 HeliCoil Kit 5542-8			O'Reillys	1	\$ 39.99	\$ 6.80	\$ 46.79
2				Fasteners								
3					M8x1.0 Steel Screws			Home Depot	0	\$ 0.82	\$ -	\$ 0.00
3					M5x0.8 Steel Screws			Home Depot	0	\$ 0.85	\$ -	\$ 0.00
2				Bearings								
3					One-way Sprag Clutch (CSK6005(X))			Boca Bearings	2	\$ 24.19	\$ 8.22	\$ 56.60
3					Radial Bearing ( )			Boca Bearings	3	\$ 24.12	\$ 12.30	\$ 84.66
3					Bearing internal keys				4	\$ -	\$ -	\$ 0.00
4					6mmx2mmx1' Steel Bar			Scrap		\$ -	\$ -	\$ 0.00
				Axle								
					20mm Dia. 12" Carbon Steel Rod			McMasterCarr	1	\$ 26.00	\$ 4.42	\$ 30.42
				Fasteners								
					M14x1.5 Bolts			Home Depot	0	\$ 2.00	\$ -	\$ 0.00

## APPENDIX J: HAND CALCULATIONS / ANALYSIS

9/29

WJWRS GK

SPROCKET DESIGN

DRIVEN SPROCKET - 195 TEETH, DRIVER = 13 teeth  
RATIO - 15:1

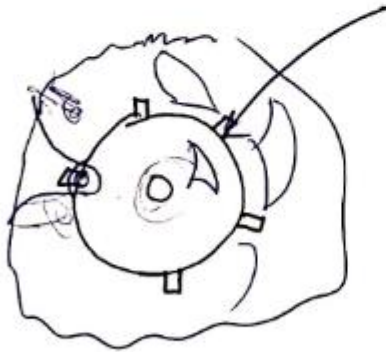
NEW RATIO  $\rightarrow$  ~~12:1~~ 14:1

NEW DRIVEN SPROCKET TEETH  $\rightarrow$  182

$$\sin \frac{\gamma}{2} = \frac{P/2}{D/2}$$

$$D = \frac{P}{\sin(\frac{\gamma}{2})}, \text{ pitch} =$$

~~pitch angle = 1.978°~~  
pitch angle =  $360^\circ / 182^{\text{teeth}}$   
 $= 1.978^\circ$



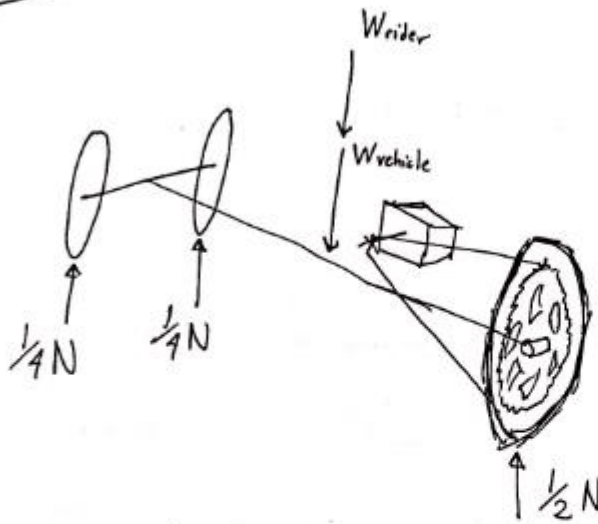
This calculation is performed to determine the number of teeth on driven sprocket if ratio changed. Will also help to determine engine torque load.



10/5/2019

## Hub Design - Load Paths

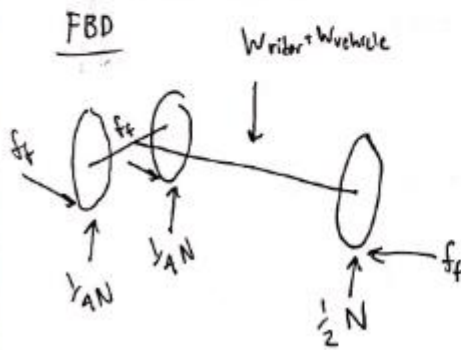
### STATIC



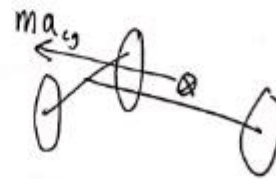
### Assumptions

- 1.) Weight evenly distrib throughout vehicle
- 2.)

### Dynamic - Longitudinal



### MAD

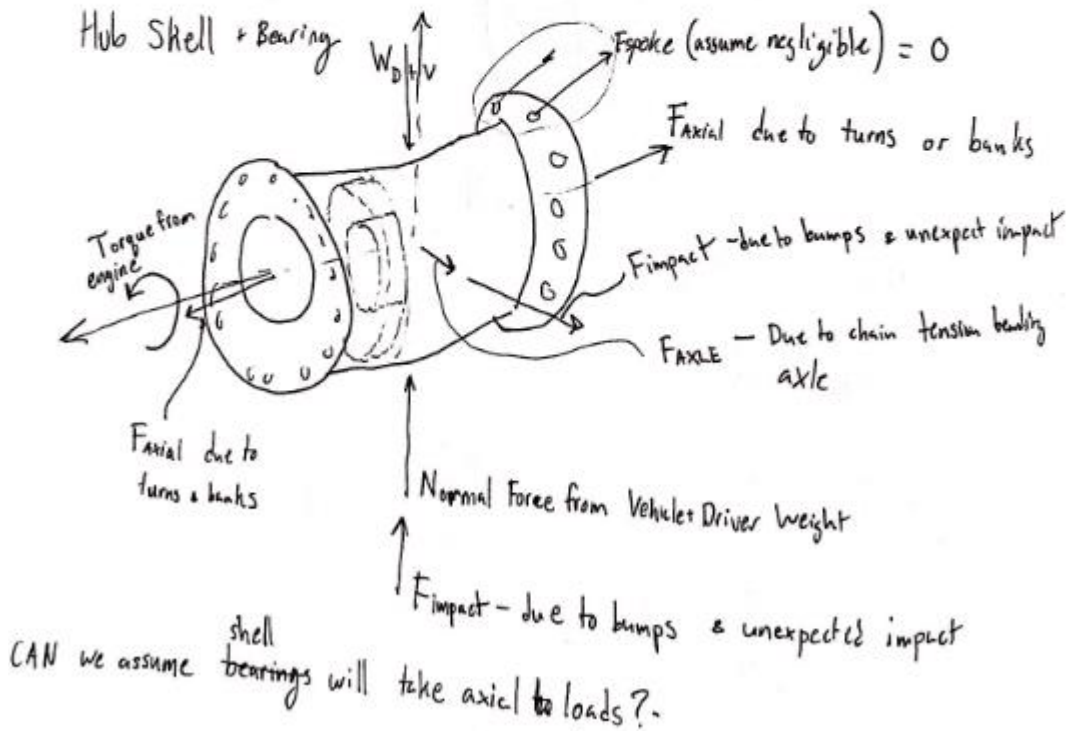
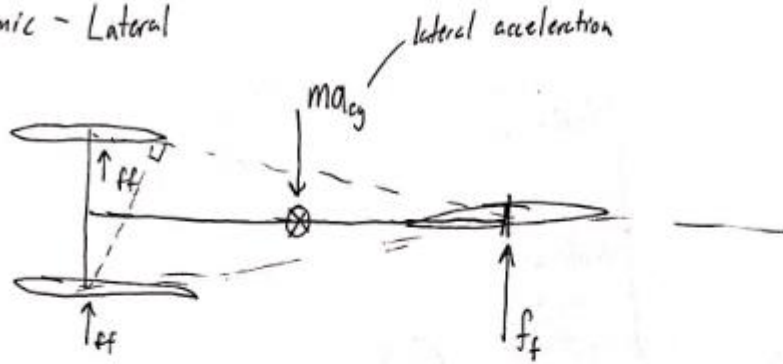


This hand calculation is performed to determine the kind of loads that would be transferred throughout the drivetrain design. These were specifically helpful to determine the impact load case performed on the hub shell and axle.

10/5/2019

Hub Load Design Cont.

Dynamic - Lateral

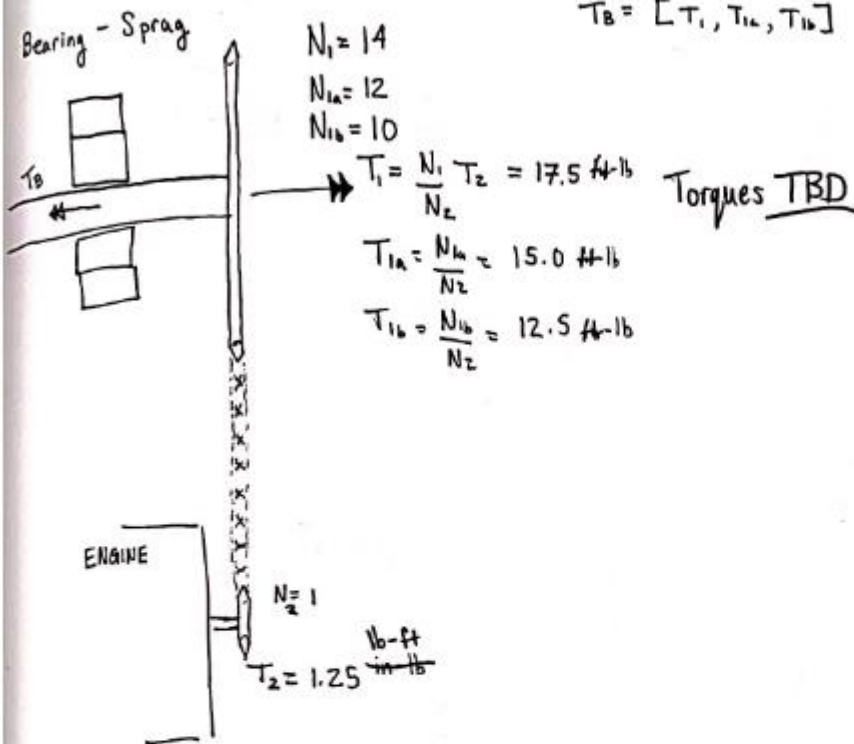


→ will make it necessary to buy bearings that take axial load

These are a continuation of the previous calculations.

10/8/2017

HAND CALCULATIONS CONT



Bearing Catalog Values - CSK202P-2RS

Metric	Torque	RPM	Dynamic Load	Static Load	Weight	Drag Torque
15 x 35 x 16	17 N-m	8400	7400	Load - 3420	70 g	4.0 N-cm

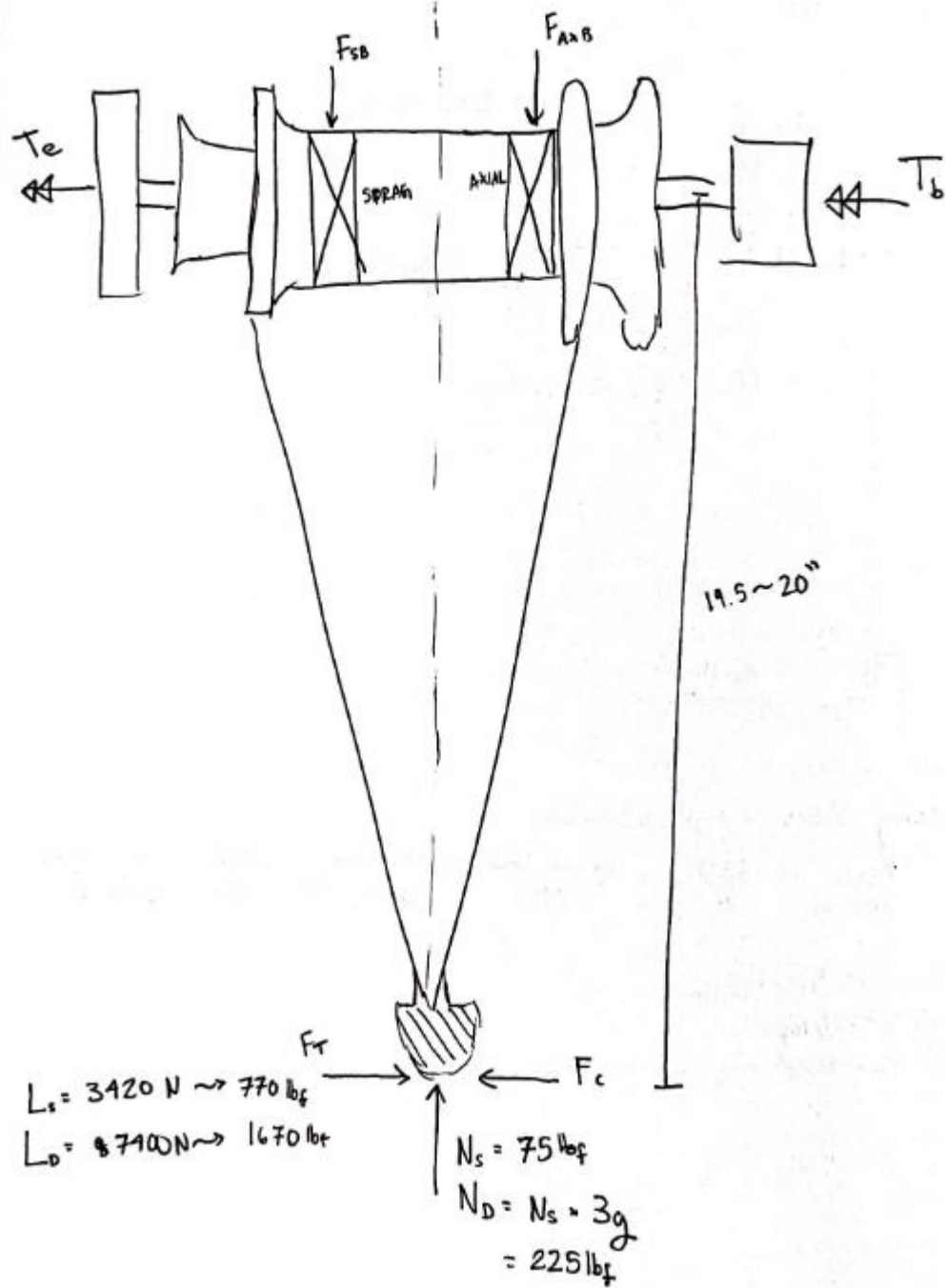
wheel diameter - 19.5 in ~ 20 in

Approximate weight - 200 lbs

Weight Distribution - 100 lbs front, 75 lbs back

The calculation performed above was helpful for determining the engine torque load that was later applied to the sprocket mount, sprocket, bearings, and hub housing. Included at the bottom were ratings for a previous bearing, but were helpful to guide future calculations.

10/8/20 K1



Bearing load calculations which were used to determine cornering loads as well as impact loads. These values were compared to catalog rated values to justify use in design.

10/10/2019

Bearing Life Calc.

Assume bearing life  $\sim 1,000,000$  rotations

Wheel diameter [D = 20in]

$$\begin{aligned} \text{Distance per rotation} &\rightarrow \pi D \\ &= \pi(20\text{in}) \\ &= \frac{20\pi \text{ in}}{12\text{in}} \\ &= 5.23 \text{ ft/rotation} \end{aligned}$$

$$1 \text{ mi} = 5,280 \text{ ft}$$

$$1 \text{ Race} \approx 7^{10} \text{ mi (conservative)}$$

4 Races / year

4 years

$$4 \text{ years} \times \frac{4 \text{ races}}{1 \text{ yr}} \times \frac{10 \text{ mi}}{1 \text{ Race}} \times \frac{5280 \text{ ft}}{1 \text{ mi}} \times \frac{1 \text{ rotation}}{5.23 \text{ ft}} = 161.3 \times 10^3 \text{ rotations}$$

Bearing life > Racing Life

$$\cancel{161.3 \times 10^3 \text{ rotations}}$$

~~1000 rotations~~

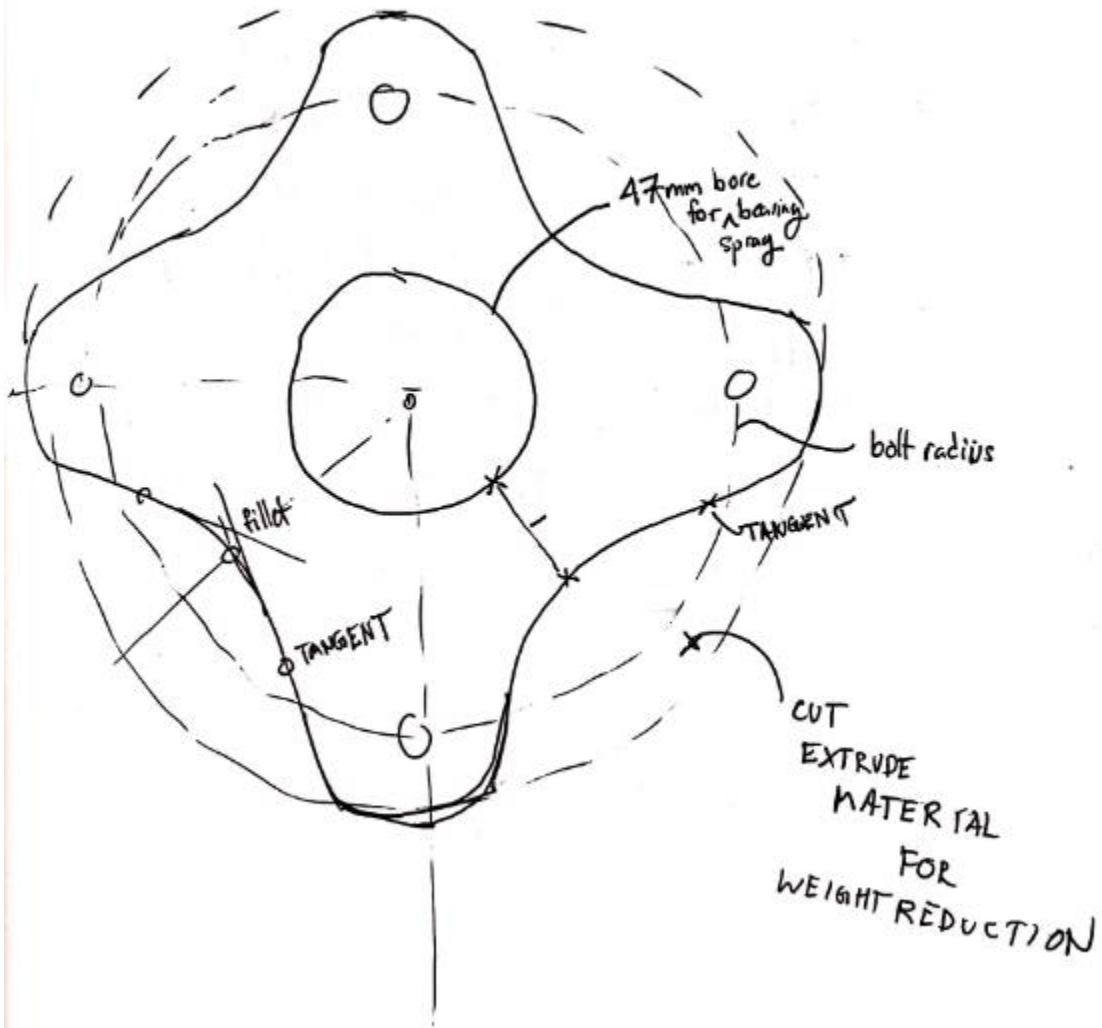
$$1000 \times 10^3 \text{ rotations} > 161.3 \times 10^3 \text{ rotations} \quad \checkmark$$

Bearing will have plenty of life to last 4 competition years.

Racing life calculations vs bearing life calculations. This calculation verified that the bearings chosen had a higher life than the expected race life verifying our target specification of 2-4 years.

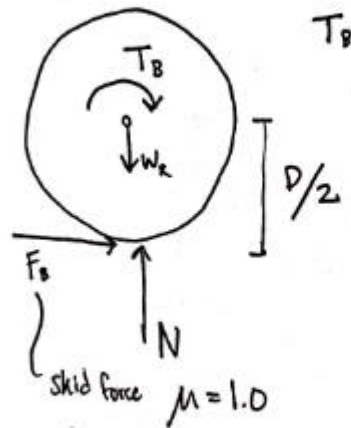
10/17

# SPROCKET MOUNT DESIGN



This drawing illustrates a preliminary design for the sprocket mount used to transfer torque from the sprocket to the wheel. The design was cut to reduce material and have simple shape to reduce the difficulty during manufacturing.

10/17  
Braking Torque Calculation (Load)

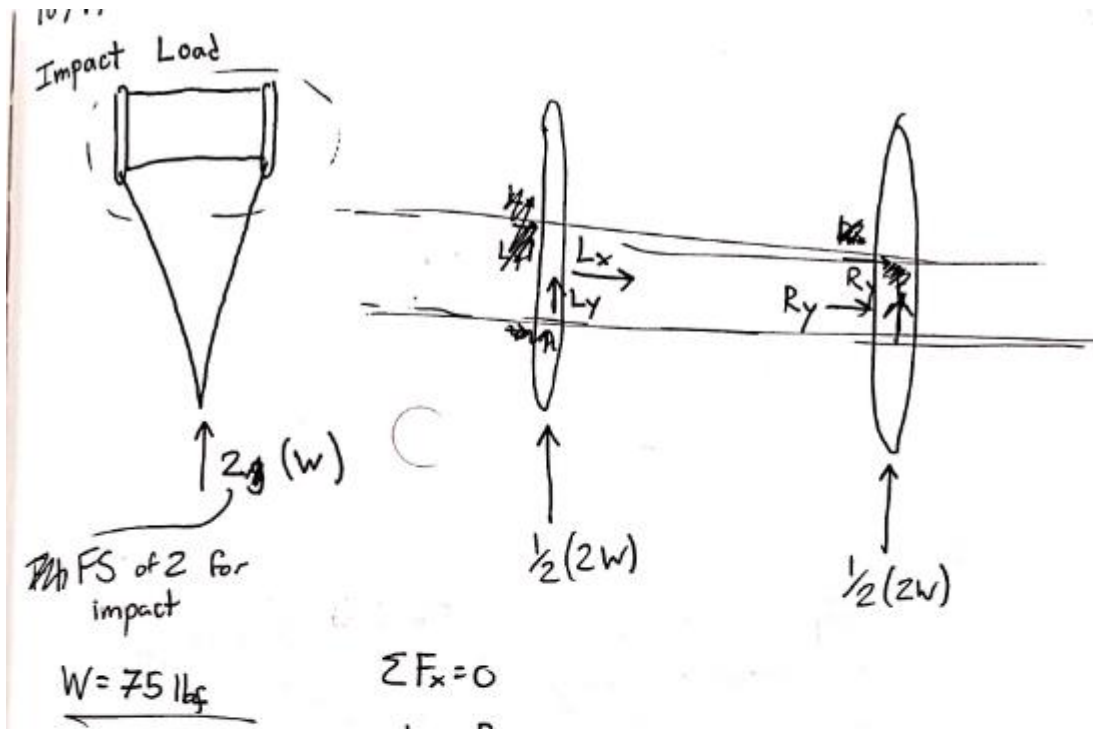


$$\begin{aligned}
 T_B &= F_B \left(\frac{D}{2}\right) F_s \\
 &= \mu N \left(\frac{D}{2}\right) F_s \\
 &= \mu W_R \left(\frac{D}{2}\right) F_s \\
 &= 1.0 (75 \text{ lbf}) \left(\frac{20 \text{ in}}{2}\right) F_s \\
 &= 750 \text{ lbf-in} (F_s)
 \end{aligned}$$

$F_s \sim 3?$  (must be high since critical to safety)

$$T_B = \underline{2250 \text{ lbf-in}}$$

Braking torque load calculation. Using estimated loads on the vehicle, the approximate braking torque that would be applied to the vehicle was determined. The load will then be applied to the hub shell and will also be used in future hand calculations to verify FEA.



$$\sum F_x = 0$$

$$L_x = R_x$$

$$\sum F_y = 0$$

$$L_y + R_y + \frac{1}{2}(2w) + \frac{1}{2}(2w) = 0$$

Note:  $L_y = R_y$  due to symmetry,

$$2L_y = 2w$$

$$L_y = w$$

$$L_y = 75 \text{ lbf}$$

$$R_y = 75 \text{ lbf}$$

Impact load calculation w/ load path through bearings. Used in hand calculations and to verify FEA.

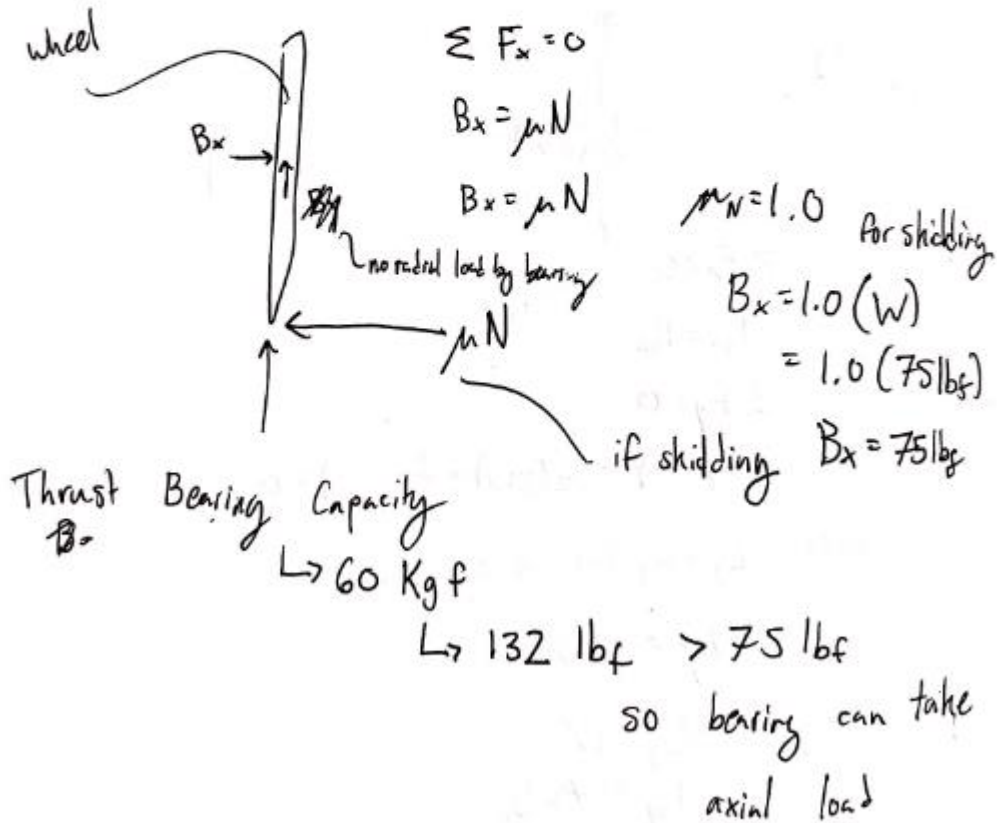


10/17

## Bearing Axial Load

Thrust bearing to absorb axial loads

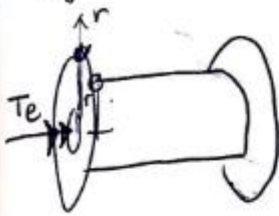
Load on a turn



Thrust bearing cornering load verification calculation. As shown, the thrust bearing will be able to take the axial loads applied during cornering.

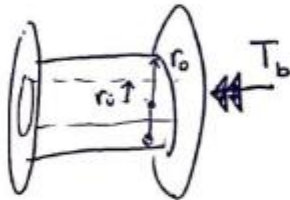
### Hub Shear Stress

#### Engine Load Case



$$\begin{aligned}
 T_{max} &= \frac{T_e r}{J} \\
 &= \frac{17.5 \text{ lbf-ft}}{J} \cdot 2.0 \\
 &= \frac{T_e (1.05) (12 \text{ in})}{\frac{\pi}{32} (2.1 \text{ in} - 0.9 \text{ in})^4} \text{ FS} \\
 &= 2166 \text{ lb/in}^2
 \end{aligned}$$

#### Braking Load Case



$$\begin{aligned}
 T_{max} &= \frac{T_b r}{J} \\
 &= \frac{62.5}{\frac{\pi}{32} (2.1 - 0.9 \text{ in})^4} \\
 &= 13400 \text{ psi}
 \end{aligned}$$

assume negligible

$$\begin{aligned}
 \sigma_{v \text{ engine}} &= \sqrt{\sigma_x^2 + 3\tau_{xy}^2} \\
 &= \sqrt{3\tau_{xy}^2} \\
 &= \sqrt{3(2166)^2} \\
 &= 3.75 \times 10^3 \text{ psi}
 \end{aligned}$$

$$\sigma_{v \text{ brake}} = \sqrt{3(13400)^2}$$

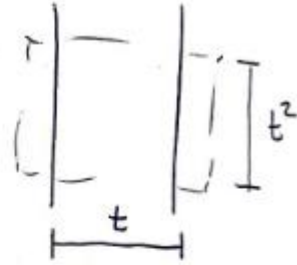
$$\sigma_{v \text{ brake}} = 2.3 \times 10^4 \text{ psi}$$

both ~~are~~ the same magnitude at locations, can assume FEA good estimation of loads

Engine and brake load cases to verify FEA. Using the primary force in each load case, a von mises stress is calculated at a specific location with simplified geometry. The hub shell was modeled as a hollow cylinder to simplify the equations. The stress found each of the cases were in similar orders of magnitude as the stresses found in FEA verifying the FEA models can be used to approximate locations of high stress and factors of safety.

10/23

Impact Load Case



$$\sigma = \frac{P}{A} = \frac{W}{(t^2)} = \frac{75\text{lbf}}{(0.1\text{in})^2} = 7500\text{psi}$$

Load Area applied to arc so Area can be infinitely small. using  $t^2$  which may be large.

$$\sigma_v = \sqrt{\sigma^2 + 3\tau_{xy}^2}$$

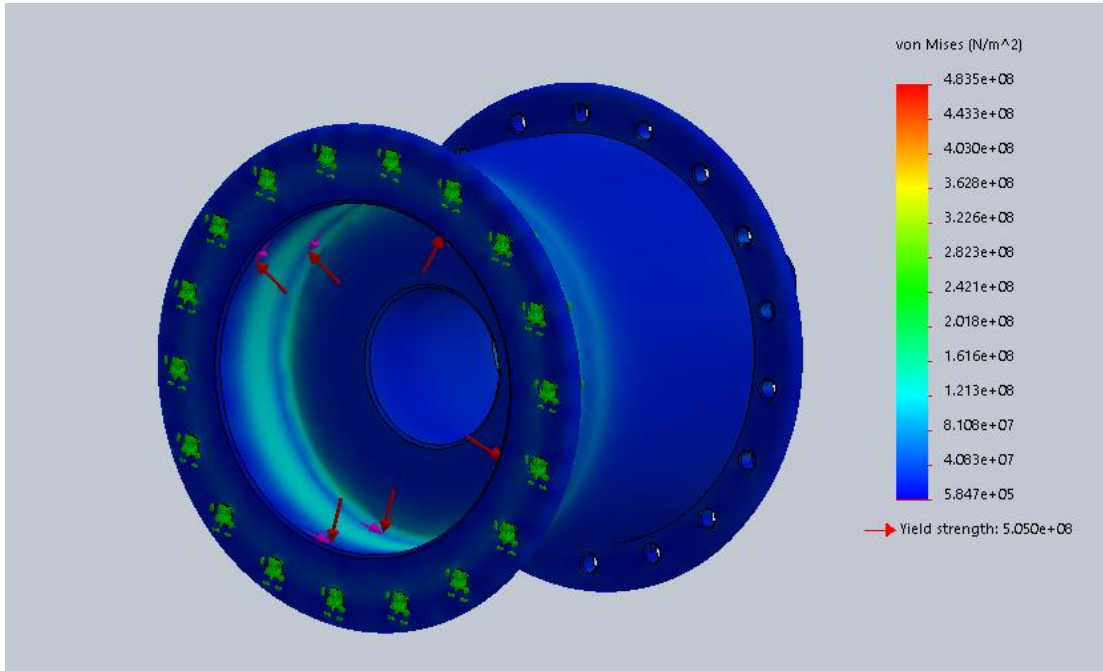
assume negligible

$$\begin{aligned}\sigma_v &= \sigma \\ &= 7500 \\ &= 7.5 \times 10^3 \text{ psi}\end{aligned}$$

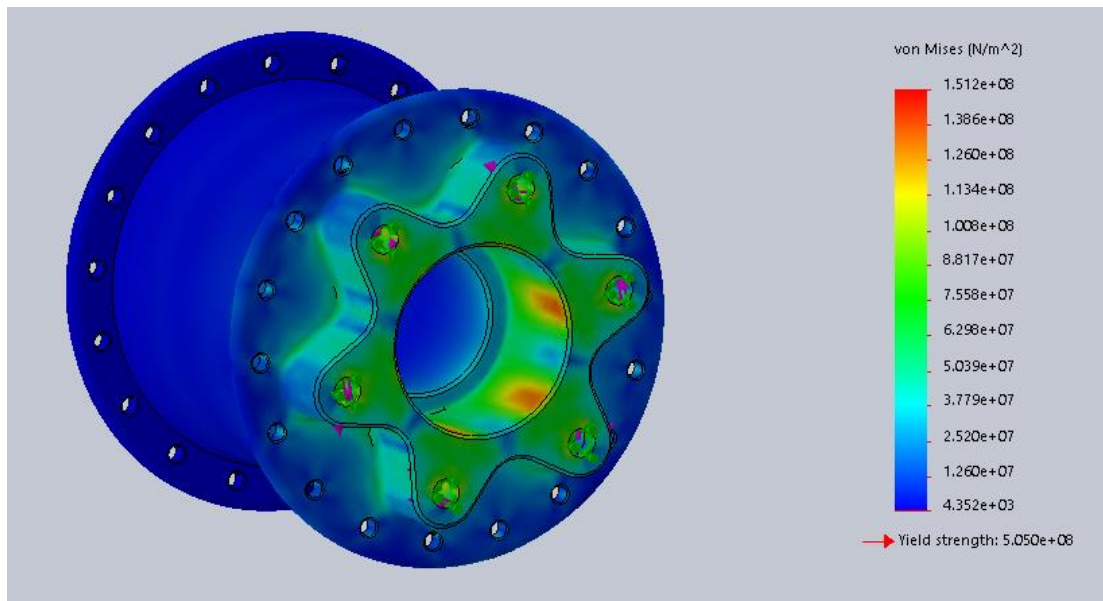
To be more conservative,  $A = \left(\frac{1}{2}t\right)^2$

$$\begin{aligned}\sigma &= \frac{75\text{lbf}}{\left(\frac{1}{2}(0.1)\right)^2} \\ &= 3 \times 10^4 \text{ psi}\end{aligned}$$

Impact load case to verify FEA. Using the primary dynamic force, a von mises stress is calculated at a specific location with simplified geometry. The stress was modeled as normal stress applied over a small area. The stress found in this case was similar in orders of magnitude as the stresses found in FEA verifying the FEA models can be used to approximate locations of high stress and factors of safety.

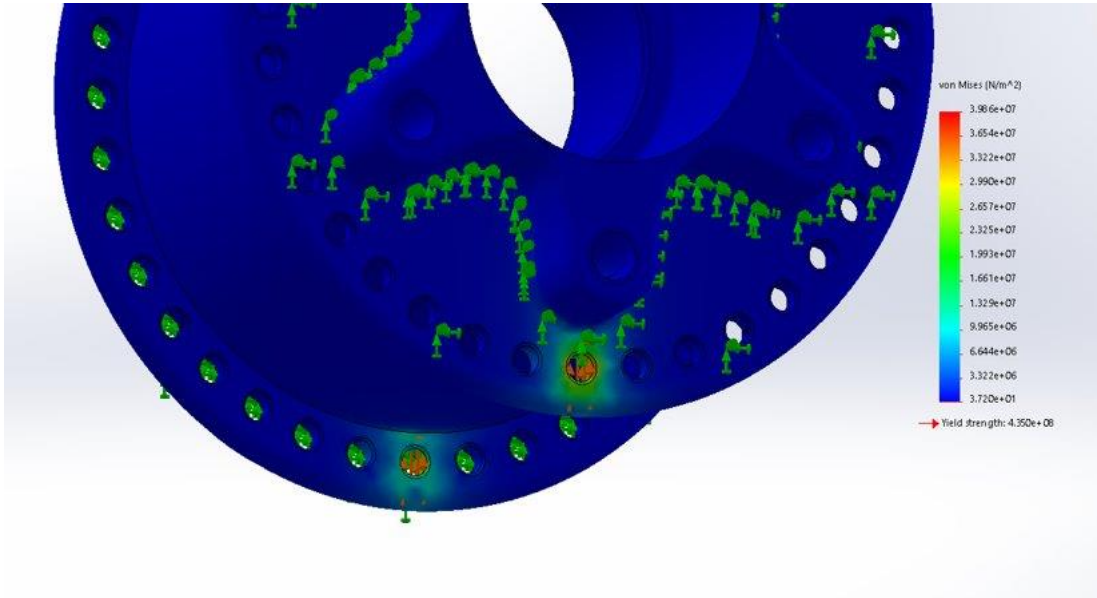


Hub FEA: Engine Torque Load



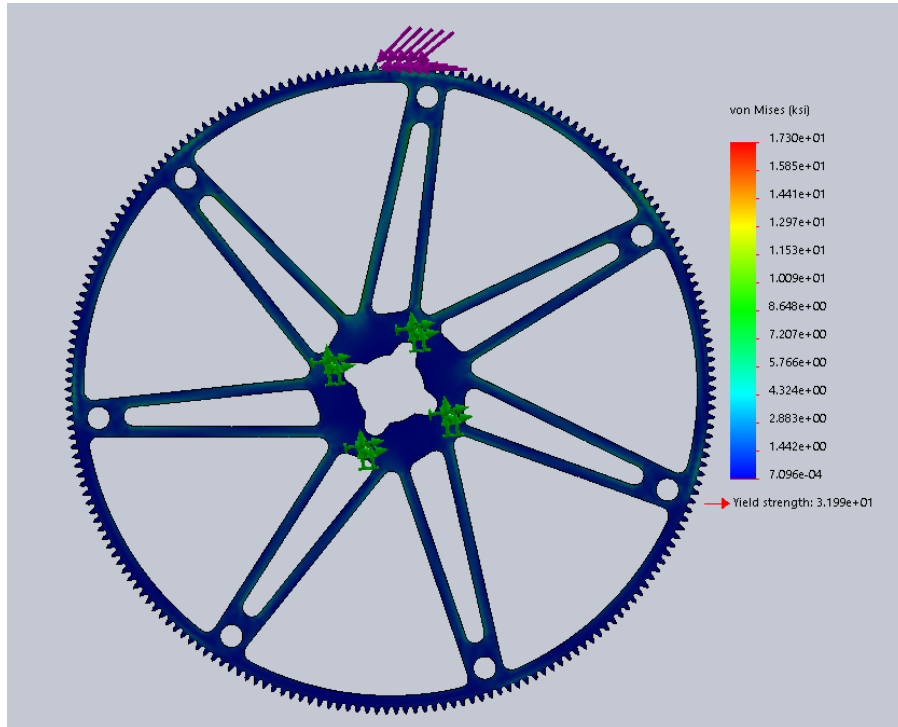
Hub FEA: Braking Torque Load

Load Case	Yield Strength (N/m <sup>2</sup> )	Max Stress (N/m <sup>2</sup> )	Factor of Safety
Engine Torque	5.05x10 <sup>8</sup>	2.421x10 <sup>8</sup>	2.09
Braking Torque	5.05x10 <sup>8</sup>	1.512x10 <sup>7</sup>	3.34

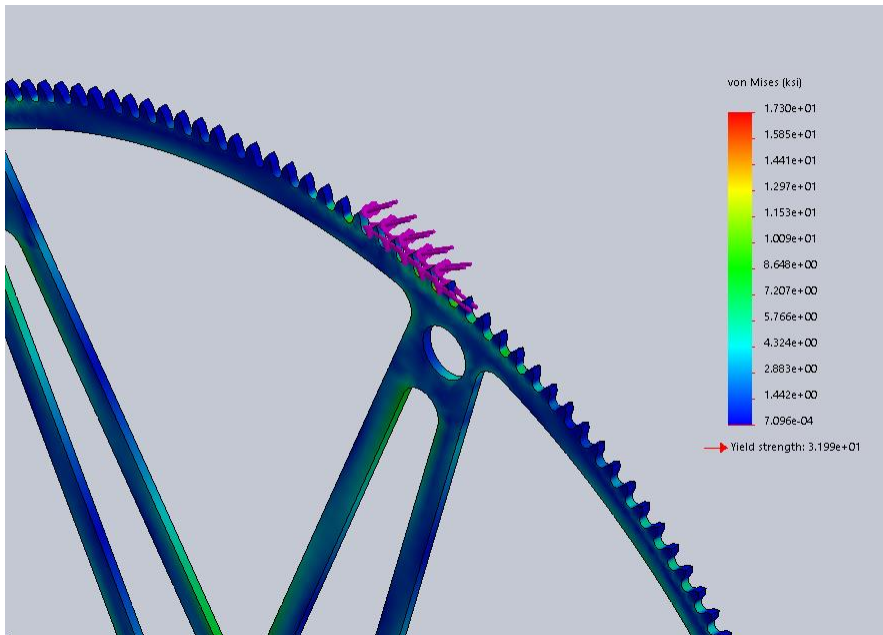


Hub FEA: Impact Load

Load Case	Yield Strength (N/m <sup>2</sup> )	Max Stress (N/m <sup>2</sup> )	Factor of Safety
Impact Load	4.35x10 <sup>8</sup>	3.98x10 <sup>7</sup>	10.9

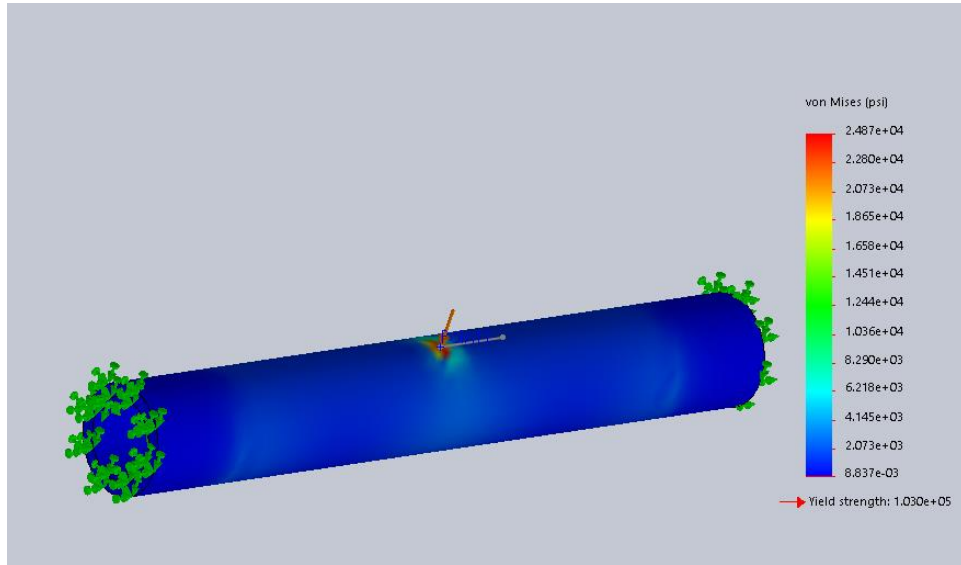


Sprocket FEA: Engine Load with 1-degree offset



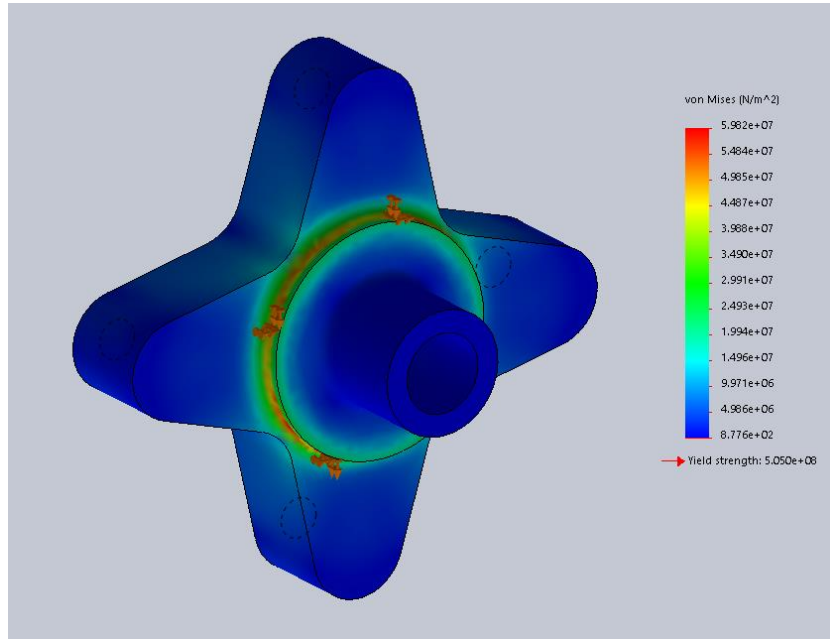
Sprocket FEA: Engine Load with 1-degree offset

Load Case	Yield Strength (N/m <sup>2</sup> )	Max Stress (N/m <sup>2</sup> )	Factor of Safety
Engine Load + Offset	3.199x10 <sup>8</sup>	1.730x10 <sup>8</sup>	1.85



Axle FEA: Point Load

Load Case	Yield Strength (psi)	Max Stress (psi)	Factor of Safety
Impact Load	100,000	24,070	4



Load Case	Yield Strength (N/m <sup>2</sup> )	Max Stress (N/m <sup>2</sup> )	Factor of Safety
Engine Torque	5.050x10 <sup>8</sup>	5.982x10 <sup>7</sup>	8.44



# Press Fit Calculations (pg 1 of 2)

## Press Fit Calculations

### Bearing Dimensions

Name	OD (mm)	OR (mm)	ID (mm)	IK (mm)	Depth (mm)	Material	Elastic Modulus, E (Pa)	Poisson's Ratio $\nu$
Sprag	47	23.5	25	12.5	14	Mild Steel	1.99948E+11	0.3
Thrust	32	16	19	9.5	8.68	Mild Steel	1.99948E+11	0.3
Mount Extrusion	25	12.5	20	10	14	7075 Aluminum	71705504000	0.33
Hub	52	26	47	23.5	14	7075 Aluminum	71705504000	0.33

Sprag-Hub Press Fit		Ideal Case	
Radial Interference (SI)	$\delta$	0.0655	mm
Radial Interference (FPS)	$\delta$	0.002578142	in
Radius (SI)	R	23.5	mm
Outer Radius	ro	26	mm
Inner Radius	ri	12.5	mm
Elastic Modulus Out	Eo	71705504000	Pa
Elastic Modulus In	Ei	1.99948E+11	Pa
Poisson's Out	vo	0.33	-
Poisson's In	vi	0.3	-
Press Fit Radial Pressure	p	18523928.08	Pa
Press Fit Radial Pressure	p	2686.67	psi

Sprag-Hub Press Fit		Loose Case	
Radial Interference (SI)	$\delta$	0.045	mm
Radial Interference (FPS)	$\delta$	0.001771655	in
Press Fit Radial Pressure	p	1845.81	psi

Sprag-Hub Press Fit		Tight Case	
Radial Interference (SI)	$\delta$	0.086	mm
Radial Interference (FPS)	$\delta$	0.00339	in
Press Fit Radial Pressure	p	3327.54	psi

Breakaway Torque		Loose Case	
Torque	T	1641.536484	lbf-in
Torque	T	136.794707	lbf-ft
Engine Torque (Dynamic)	Te	35	lbf-ft
Factor of Safety	Fs	3.908420199	-
Coefficient Friction	$\mu$	0.3	-

Loose Case Interference and tight cases based on Machinery's Handbook pg 654-655 for sprag hub fit & thrust. Based on preferred hole fit.

Loose Case Interference and tight cases based on Machinery's Handbook pg 658-659 for sprag mount. Based on preferred shaft fit.

### FEA Stress Results

Part Name	Load Case	Material	yield Strength	Safety	Factor of Safety
Hub	Engine	7075 Alum	5.05E+08	2.47E+08	2.045
Hub	Brake	7075 Alum	5.05E+08	2.89E+08	1.750
Sprocket Mount	Engine	7075 Alum	5.05E+08	2.54E+08	1.987

Thrust-Mount		Ideal Case	
Radial Interference (SI)	$\delta$	0.051	mm
Radial Interference (FPS)	$\delta$	0.00201	in
Radius (SI)	R	12.5	mm
Outer Radius	ro	23.5	mm
Inner Radius	ri	10	mm
Elastic Modulus Out	Eo	1.99948E+11	Pa
Elastic Modulus In	Ei	71705504000	Pa
Poisson's Out	vo	0.3	-
Poisson's In	vi	0.33	-
Press Fit Radial Pressure	p	58808499.05	Pa
Press Fit Radial Pressure	p	8529.47	psi

Thrust-Mount		Loose Case	
Radial Interference (SI)	$\delta$	0.027	mm
Radial Interference (FPS)	$\delta$	0.00106	in
Press Fit Radial Pressure	p	4515.60	psi

Thrust-Mount		Tight Case	
Radial Interference (SI)	$\delta$	0.061	mm
Radial Interference (FPS)	$\delta$	0.00240	in
Press Fit Radial Pressure	p	10201.91	psi

Breakaway Torque		Loose Case	
Torque	T	1136.224695	lbf-in
Torque	T	94.68539126	lbf-ft
Engine Torque (Dynamic)	Te	62.5	lbf-ft
Factor of Safety	Fs	1.51496626	-
Coefficient Friction	$\mu$	0.3	-

# Press Fit Calculations (pg 2 of 2)

Ideal Case		Assumption		Thrust-Hub		Ideal Case		Radial Interference	
0.044	mm	0.044	mm	$\delta$	0.044	$\delta$	0.044	$\delta$	0.051
0.00173	in	0.00173	in	Radial Interference (IPS)	0.00173	Radial Interference (IPS)	0.00173	$\delta$	0.00201
16	mm	16	mm	Radius (SI)	16	Radius (SI)	16	R	16
25	mm	26	mm	Outer Radius	26	Outer Radius	26	ro	26
9.5	mm	9.5	mm	Inner Radius	9.5	Inner Radius	9.5	ri	9.5
71705504000	Pa	71705504000	Pa	Elastic Modulus Out	71705504000	Elastic Modulus	7.17E+10	Eo	7.17E+10
1.99948E+11	Pa	1.99948E+11	Pa	Elastic Modulus In	1.99948E+11	Elastic Modulus	2E+11	Ei	2E+11
0.33	-	0.33	-	Poisson's Out	0.33	Poisson's Out	0.33	vo	0.33
0.3	-	0.3	-	Poisson's In	0.3	Poisson's In	0.3	vi	0.3
58703220.83	Pa	61803150.48	Pa	Press Fit Radial Pressure	61803150.48	Press Fit Radial Pressure	71635470	p	71635470
8514.20	psi	8963.81	psi	Press Fit Radial Pressure	8963.81	Press Fit Radial Pressure	10389.87	p	10389.87

Loose Case		Thrust-Hub		Loose Case	
0.027	mm	Radial Interference (SI)	$\delta$	0.027	mm
0.00106	in	Radial Interference (IPS)	$\delta$	0.00106	in
5224.62	psi	Press Fit Radial Pressure	p	5500.52	psi

Tight Case		Thrust-Hub		Tight Case	
0.061	mm	Radial Interference (SI)	$\delta$	0.061	mm
0.00240	in	Radial Interference (IPS)	$\delta$	0.00240	in
11803.77	psi	Press Fit Radial Pressure	p	12427.09	psi

# APPENDIX K: FAILURE MODE'S & EFFECTS ANALYSIS

## Design Failure Mode and Effects Analysis

Product: \_\_\_\_\_ Prepared by: \_\_\_\_\_ Date: \_\_\_\_\_ (orig)

Team: \_\_\_\_\_

Team Name: 1 Chainz  
 FMEA 10/3/19  
 SMV  
 Drivetrain

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results		
												Actions Taken	Severity	Occurrence
Sprocket / Durability	Sprocket fails / breaks	cannot complete race, expensive to replace, takes time to replace	4	1) Impact loads break sprocket 2) initial torque starting up high stress on teeth 3) high wear to sprocket	1) Test using FEA 2) Build prototype 3) Physical Testing	4	Regular Maintenance	4	64	Regularly inspect sprocket, replace after every few races. Design with a high factor of safety				
Sprocket / Deflection	Sprocket bends / not aligned. Chain falls off	a) sprocket becomes inefficient component b) can lead to sprocket breaking / warping	4	1) Misalignment between sprockets / axle / chain 2) low strength of intermediate components 4) fatigue strength	1) use CMM for alignment 2) treat sprocket material 3) stress analysis 4) fatigue strength	4	Regular Maintenance	3	48	Regularly inspect sprocket, replace after every few races. Design with a high factor of safety				
Sprocket Weight (heavy / light)	Poor vehicle performance	car runs at lower mileage, additional wear	2	1) Design not optimized for weight 2) additional torque on fasteners	1) FEA & Hand Calcs 2) fastener shear analysis	2	Computer aided design	2	8					
Sprocket / Aesthetics	Light sprocket prone to breaking visual dents / blemishes in sprocket	sprocket at risk for failure a) add stress concentrations	3	1) back doesn't fit user 2) seat has sharp edges 3) seat has hard spots 1) Difficulty manufacturing carbon / steel	1) FEA & Hand Calcs 2) fastener shear analysis 1) Inspect while manufacturing, 2) use good tools	2	Computer aided design	2	12					
Hub / Durability	Hub falls during race	cannot complete race, expensive to replace, takes time to replace	5	Bad design, too much stress on components of hub, large torque from engine	1) Test using FEA 2) Build prototype 3) Physical Testing	5	Regular Maintenance	5	125	Protect sprocket when traveling Regularly maintain hub, have backup at every race				
Hub / friction	poor vehicle performance	a) lead to part failure b) increase amount of regular maintenance	3	Poor bearing selection	Bearing testing	3	Prototype testing w/ bearings	3	27	Regularly inspect hub and replace bearings if necessary				
Hub / weight	Poor vehicle performance	car runs at lower mileage, additional wear	2	1) Design not optimized for weight 2) additional torque on fasteners	1) FEA & Hand Calcs 2) fastener shear analysis	2	Computer aided design	3	12					
Mount / Durability	sprocket / breaks do not work	a) disc break don't work b) no power delivered to wheels c) user is injured	5	Too much stress on fasteners, high stress concentrations	1) FEA & Hand Calcs 2) fastener shear analysis	3	FEA	3	45					
Mount / Weight	Poor vehicle performance	car runs at lower mileage, additional wear	2	1) Design not optimized for weight 2) additional torque on fasteners	1) FEA & Hand Calcs 2) fastener shear analysis	2	Computer aided design	3	12					

## Design Failure Mode and Effects Analysis

Product: \_\_\_\_\_ Prepared by: \_\_\_\_\_

Team: \_\_\_\_\_ Date: \_\_\_\_\_ (orig)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results		
												Actions Taken	Severity	Occurrence
General / hold parts together General / Maintain appearance	joints components separate	a) vehicle fails b) user is injured	3	1) high stress on joints from start up	FEA & Hand Calcs	3	Computer aided design	3	27	Regularly inspect fasteners and replace as necessary				
	surfaces get damaged	Parts may prematurely fail	2	normal use / wear	protect components when traveling	2	Visual inspection	2	8	regularly inspect components				

# APPENDIX L: DESIGN HAZARDS CHECKLIST

ME 428/429/430 Senior Design Project

2019

DESIGN HAZARD CHECKLIST	
Team:	<u>SMV Drivetrain</u> Faculty Coach: <u>Joseph Mello</u>
Y    N	
<input checked="" type="checkbox"/> <input type="checkbox"/>	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
<input checked="" type="checkbox"/> <input type="checkbox"/>	2. Can any part of the design undergo high accelerations/decelerations?
<input checked="" type="checkbox"/> <input type="checkbox"/>	3. Will the system have any large moving masses or large forces?
<input type="checkbox"/> <input checked="" type="checkbox"/>	4. Will the system produce a projectile?
<input type="checkbox"/> <input checked="" type="checkbox"/>	5. Would it be possible for the system to fall under gravity creating injury?
<input type="checkbox"/> <input checked="" type="checkbox"/>	6. Will a user be exposed to overhanging weights as part of the design?
<input checked="" type="checkbox"/> <input type="checkbox"/>	7. Will the system have any sharp edges?
<input type="checkbox"/> <input checked="" type="checkbox"/>	8. Will any part of the electrical systems not be grounded?
<input type="checkbox"/> <input checked="" type="checkbox"/>	9. Will there be any large batteries or electrical voltage in the system above 40 V?
<input type="checkbox"/> <input checked="" type="checkbox"/>	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
<input type="checkbox"/> <input checked="" type="checkbox"/>	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
<input checked="" type="checkbox"/> <input type="checkbox"/>	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
<input checked="" type="checkbox"/> <input type="checkbox"/>	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
<input type="checkbox"/> <input checked="" type="checkbox"/>	14. Can the system generate high levels of noise?
<input type="checkbox"/> <input checked="" type="checkbox"/>	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
<input checked="" type="checkbox"/> <input type="checkbox"/>	16. Is it possible for the system to be used in an unsafe manner?
<input type="checkbox"/> <input checked="" type="checkbox"/>	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.
<p>For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.</p>	

	Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
1	Sprockets spinning Chain revolving around Sprocket	<del>Sprockets</del> Chain cover will be added to cover chain + sprocket	WINTER 2020	TBD
2	Sprockets will rotate at high rpms	Sprockets will be in areas covered and away from driver	WINTER 2020	TBD
3	Sprocket has a high amount of Torque	Held in place with bolts and cover with chain cover	WINTER 2020	TBD
4	Sprocket teeth have sharp edges	will be covered and away from driver	WINTER 2020	TBD
5	Swapping/dissassembly of system may require abnormal effort	Designed to <del>disassemble</del> disassemble easily	FALL 2019	FALL 2019
6	Machining in shops produces chips that can be harmful	Follow safety protocols while working in shop. I.E Masks, glasses, etc.	WINTER 2020	TBD
7	Do not touch system when its running	Make sure system is enclosed when running	WINTER 2020	TBD

# APPENDIX M: MANUFACTURING ACTION PLAN

Manufacturing Action Plan		Subcomponent / Part	Plan (P.M.R)	Materials Needed	Equipment Used	Limitations
Lead Designer	Component / Part					
Kai Meier	Sprocket	-	Raw	Steel	Waterjet	Waterjet takes a lot of machining time and has relatively low precision. The jet has a taper, and does not cut square relative to the work piece.
	Dropouts	-	Modified	N/A	CNC Mill	Finishing to be determined for CNC Mill. Must cut soft jaws to workhold existing dropout bracket.
Griffin Kraemer	Hub Shell	-	Raw	7075 Aluminum	Lathe	Lathe work is preliminary machining for hub. Must leave stock to mill brake mount on turned hub. If manual lathe used, tolerances will not be as tight as CNC Lathe.
	Brake Mount	-	Raw	7075 Aluminum	CNC Mill	Stresses will be put into part during machining operation. Axiality tolerance is a limitation. Must machine brake mount on location.
Arya Mahdavian	Sprocket Mount	-	Raw	7075 Aluminum	CNC Mill	Finishing to be determined for CNC Mill. Geometry a bit complex which adds machining time and difficulty.
	Axle	-	Raw	1144 Carbon Steel	Lathe	Reducing the 20mm diameter down to 16mm on the Lathe will be difficult for the axle. A concern will be getting as close to 16mm accurately. Good threads on the tips are also important and must be done carefully.
	Brakeside Spacer	-	Raw	1144 Carbon Steel	Lathe	Creating a step on the spacers on the Lathe might have limitations.
	Driveside Spacer	-	Raw	1144 Carbon Steel	Lathe	Alignment of through holes is key for the spacers and must be done carefully as well.



## Appendix N – Drivetrain Assembly

This user's manual includes instructions for the assembly of this drivetrain product and important safety information. Read this section entirely including all safety warnings and cautions before assembling the product.

**Important:** This product is meant for the Cal Poly Supermileage Vehicle Club gas powered vehicle. Before using this product, the user should be familiar with the operation and safety risks involved with the product.

**Warning:** **Do not assemble the drivetrain components without supervision from club advisor or other team members**

Certain components of the design present safety hazards and therefore supervision is required in response to a potential emergency situation

The following instructions guide the safe assembly of the vehicle drivetrain.

### *Inserting bearings into custom hub*

Follow these instructions to insert one-way sprag bearing and radial bearing into custom hub.

1. First, lie hub on to the table of hydraulic press with the smaller cavity faced down. The side with the brake mount should be faced down.
2. Place the sprag bearing flush with the large cavity which is approximately the same size. Make sure that the bearing rotates counterclockwise and locks when turned clockwise. This simulates the freecoaster function. It should now be ready for pressing
3. Using a hydraulic press, force the sprag bearing into cavity by applying even pressure across the bearing. Make sure pressure is not all applied on the inner race of the bearing or the bearing will fail.
4. After the sprag bearing has been inserted, flip the hub over so that side is face down.
5. Using the same press method, place the radial bearing in the brake mount cavity and press.

### *Lacing the custom hub to rear wheel*

Follow these instructions to lace the custom hub to the rim of the rear wheel.

1. Follow the instructions on lacing the wheel using this website
  - a. <https://www.sheldonbrown.com/wheelbuild.html>

### *Inserting bearing into sprocket mount*

Follow these instructions to insert radial bearing into sprocket mount.

1. After lacing the wheel and hub together, put this assembly aside and take out the sprocket mount.
2. Place the sprocket mount with the extrusion face down. Allow the extrusion to pass through the table. Make sure bearing is lined up with cavity



3. Using a hydraulic press, force the radial bearing into cavity by applying even pressure across the bearing. Make sure pressure is not all applied on the inner race of the bearing or the bearing will fail.

#### ***Attaching hub to sprocket mount***

Follow these instructions to attach hub to sprocket mount.

1. Now that the bearings are pressed into both the hub and the sprocket mount, the hub and sprocket mount are ready to be pressed. Place the hub with the brake mount faced down.
2. Align the sprocket mount extrusion with the inner race of the sprag bearing
3. Using a hydraulic press, force the sprocket mount extrusion into the cavity of the sprag bearing. Now the components should be connected

**Note:** After the sprocket mount - hub assembly has been completed. Consider whether testing is required. If torque wrench test or coast down test is needed, skip to the testing procedure appendix. If testing is not required, continue with the rest of the procedure

#### ***Attaching sprocket to sprocket mount***

Follow these instructions to attach sprocket to sprocket mount.

1. Make sure that the sprocket mount has helicoil kit installed into each of the fastener holes on the sprocket mount.
2. Align the sprocket with the sprocket mount fastener holes, make sure that the sprocket is facing the direction of rotation. The sprocket holes should line up easily with the mount. Make sure that the sprocket is flush with the mount
3. Once the holes are aligned, use a screwdriver to secure the fasteners to attach sprocket. Make sure each of the fasteners are screwed in and secure.

#### ***Attaching brake rotor to brake mount***

Follow these instructions to attach brake rotor to sprocket mount.

1. Make sure that the brake mount on the hub has the helicoil kit inserted into each of the fastener holes
2. Align the brake rotor with the brake mount fastener holes, make sure the rotor is facing the direction of rotation.
3. Once holes are aligned, use fasteners to attach rotor. Make sure each of the fasteners are screwed in and secure.

#### ***Inserting spacers to axle***

Follow these instructions to insert spacers into assembly.

1. Insert spacers into the inner cavity of each of the radial bearings. Make sure that the larger spacer is inserted into the sprocket side and the shorter on the brake side.

#### ***Inserting axle into drivetrain assembly***

Follow these instructions to insert axle into drivetrain assembly.

**Note:** Make sure that chain is connected to driver sprocket and that both sprockets are aligned.

1. Take the axle and put it through the center hole of the hub – sprocket mount assembly. Make sure that axle goes through the chain so that the chain can be attached later.

#### ***Connecting drivetrain assembly to dropout mounts***

Follow these instructions to connect drivetrain assembly to dropout mounts.

1. Align the axle with the dropout sliders in the vehicle. Screw in the bolts to secure the axle to the vehicle.

*Attaching chain to the drivetrain assembly*

Follow these instructions to attach the chain to the drivetrain assembly.

1. Attach the chain with driven (larger) sprocket. Make sure the teeth align with the chain and that there is a little slack. Adjust the slider location to increase/ decrease chain tension.

## Appendix O – Drivetrain Operation and Maintenance

This user's manual includes instructions for the safe operation and maintenance of this drivetrain product and important safety information. Read this section entirely including all safety warnings and cautions before assembling the product.

**Important:** This product is meant for the Cal Poly Supermileage Vehicle Club gas powered vehicle. Before using this product, the user should be familiar with the operation and safety risks involved with the product.

**Warning:** **Do not operate on the drivetrain components without supervision from club advisor or other team members**

Certain components of the design present safety hazards and therefore supervision is required in response to a potential emergency situation

The following instructions guide the safe operation and maintenance of the vehicle drivetrain components.

### *Adjusting or replacing the drivetrain chain*

Follow these instructions to adjust the tension or replace the drivetrain chain.

**Caution:** The drivetrain assembly contains sharp components and therefore proper Personal Protection Equipment should be worn while operating on vehicle. Safety gloves and glasses should always be worn while operating on vehicle.

1. Use an Allen wrench to loosen dropout bolts running along the length of the vehicle. This will allow the axle location to be adjusted along the dropout cavity.
2. Slide dropout slide towards the driver seat to loosen chain. If adjusting the chain, move the slide around to desired position. Make sure chain has a little slack but remains taught. If adjusting chain, skip to step 5.
3. Remove chain carefully from the driver sprocket and then driven sprocket.
4. Replace chain by aligning driven sprocket with chain and then looping chain around the driver sprocket. Make sure there is a little bit of slack in the chain but remains taught.
5. After desired position is found, use Allen wrench to tighten dropout bolts and confirm that sliders are set and do not move.

### *Replacing drivetrain components within dropouts*

Follow these instructions to remove axle assembly from dropout mounts.

**Caution:** The drivetrain assembly contains sharp components and therefore proper Personal Protection Equipment should be worn while operating on vehicle. Safety gloves and glasses should always be worn while operating on vehicle.

1. Use an Allen wrench to remove bolts running through axle assembly. This will allow the axle assembly to be removed entirely from the vehicle. If the chain is still connected to assembly, follow the steps in the above section “Adjusting or replacing the drivetrain chain” prior to the removal of the axle.
2. After bolts are removed from the axle, lift assembly from vehicle. From this position, the sprocket, brake rotor, and other components can be accessed for maintenance. To replace sprocket mount or brake rotor, skip ahead to “
3. Once parts have been replaced or adjusted, align axle assembly with dropout sliders. Proceed to screw in dropout bolts to connect assembly.

### *Replacing driven sprocket*

Follow these instructions to remove and replace driven sprocket in drivetrain assembly.

**Caution:** The drivetrain assembly contains sharp components and therefore proper Personal Protection Equipment should be worn while operating on vehicle. Safety gloves and glasses should always be worn while operating on vehicle.

1. Follow the instructions of “Replacing drivetrain components within dropouts” first to remove axle assembly from the vehicle.
2. Remove screws holding sprocket to sprocket mount (4x) using screwdriver and release sprocket.
3. Take new sprocket and align fastener holes of the mount and sprocket.
4. Fasten the mount and sprocket using screws with screwdriver. Do this for all 4 holes of the mount. Ensure that the screws are tight but avoid stripping

## Appendix P – Manufacturing Procedures

### *Manufacturing drivetrain spacers*

Follow these instructions to manufacture the drivetrain spacers for the assembly using a manual lathe.

**Caution:** The manual lathe contains sharp rotating parts at high speed and therefore proper Personal Protection Equipment should be worn while operating the machine. Safety glasses, long pants, and closed-toe shoes *should always* be worn while operating on the lathe. Sleeves and hair should be tied back to avoid injury.

**Warning:** **Do not operate on the drivetrain components without supervision from club advisor, shop technician or other team members**

Certain aspects of the lathe present safety hazards and therefore supervision is required in response to a potential emergency.

1. Place steel rod into chuck of the lathe. Use cutting tool of the lathe to make sure that the center of the tool touches the center of the rod.
2. Set up the speed of the turning by using this equation: Since the material is steel the length of cut is 1mm, use a speed of approximately 400rpm.
3. Turn on the lathe and face the steel rod till flat. Turn off lathe and flip rod around to face other side. Make sure that this side is faced to length. Cut in small increments and measure frequently. The size of the spacer will affect the entire alignment of the assembly.
4. After cut to length, check to make sure the rod is centered in the chuck by making sure the center of the tool touches the center of the rod.
5. Turn on the lathe and turn down the spacer until the diameter is 18mm. Make sure you are only cutting the length to 20 mm of material from the end being cut and not the whole length of the spacer. Cut in 0.1mm increments to avoid taking off too much material at once.
6. After spacer is cut, remove from the chuck and clean up the workspace. Inspect the spacer and make sure it meets required dimensions.

## Appendix Q – Testing Procedures

### *Torque Wrench Testing Procedure*

Follow these instructions to conduct a torque wrench test on the drivetrain hub assembly.

**Caution:** The drivetrain assembly contains sharp components and therefore proper Personal Protection Equipment should be worn while operating on vehicle. Safety gloves and glasses should always be worn while operating on vehicle.

1. To conduct this testing procedure, remove the assembly from the vehicle by following Drivetrain Operation & Maintenance section of this manual. Use this section to also remove the sprocket from the sprocket mount. The hub and sprocket mount part of the assembly should be the parts isolated for this test.
2. Install the torque wrench fixture piece by aligning fixture with fastener holes. Use same bolts used to hold the sprocket to fasten the fixture.
3. Place the hub of the assembly into a soft-jaw vise with the sprocket mount able to spin freely. Make sure that the hub will not slip from the vise.
4. After the assembly is secured in the vise, take a ½" torque wrench and insert the head into the square opening of the torque wrench fixture.
5. Set up torque wrench to apply approximately torque at increments of 105 in-lbs until you reach 420 in-lbs (Max applied vehicle torque). Record if the sprag bearing begins to slip in the bearing or fails altogether. If the assembly fails, this indicates the assembly may fail in the event of a max torque scenario during races.
6. After conducting the test, release assembly from the vise. Then remove torque wrench fixture from assembly. Follow instructions from Operation & Maintenance section to attach assembly to overall drivetrain assembly. If the parts failed, further analysis must be conducted.

### *Coast Down Testing Procedure*

Follow these instructions to conduct a coast down test on the drivetrain hub assembly.

**Caution:** The drivetrain assembly contains sharp components and therefore proper Personal Protection Equipment should be worn while operating on vehicle. Safety gloves and glasses should always be worn while operating on vehicle.

**Warning:** **This testing procedure contains rotating parts at high speeds. Supervision is required in the event of a medical emergency.**

The rotating parts present safety hazards, therefore, PPE must always be worn. Pull sleeves and hair back to prevent them interfering with the components.

1. To conduct this experiment, you will need to check out a tachometer from Cal Poly's shop and a slow-motion feature on your phone/ camera.
2. To conduct this testing procedure, remove the assembly from the vehicle by following Drivetrain Operation & Maintenance section of this manual. Use this section to also remove the sprocket from the sprocket mount. The hub and sprocket mount part of the assembly should be the parts isolated for this test.
3. Place the hub of the assembly into a soft-jaw vise with the sprocket mount able to spin freely. Make sure that the hub will not slip from the vise.
4. Mark a section of the sprocket mount, this will be used as a datum for the experiment. This marker should have a large contrast to the sprocket mount in order to easily count the number of rotations.
5. Using the tachometer, align the laser with the marker but at a safe distance away. When turned on, the tachometer should be able to give real time speed of the drivetrain assembly.
6. Once this is all set up, get the assembly rotating at a high speed. This will allow more time to capture the experiment. Use the slow-motion camera to capture both the real time tachometer readings as well as the assembly. Set the start point at a time where the tachometer reading is easy to read e.g. 300rpm.
7. Once the tachometer has a reading at another easy reading, stop the video and analyze the frames to count the number of rotations it took to reach the final speed. Record the initial and final speeds as well as the number of full rotations. Repeat this step until there is sufficient statistical evidence.
8. After conducting the test, release assembly from the vise. Then remove torque wrench fixture from assembly. Follow instructions from Operation & Maintenance section to attach assembly to overall drivetrain assembly. If the parts failed, further analysis must be conducted.

9. Use the gathered data for initial RPMs, final RPMS, number of Rotations, and the moment of inertia of the sprocket mount to determine the friction torque of the system. The moment of inertia can be found using the Solidworks model. The equation to use is:

$$I\omega_1 - T_f\theta = I\omega_2$$



# APPENDIX R: PROJECT SCHEDULE



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