University of California, Davis

EME 185

Mechanical Engineering Systems Design Project

Formula Electric Drivetrain
Final Design Report

Michael Brown
Nicholas Hori
Jon Hromalik
Zac March
Bryce Yee

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Contents

1 Introduction

Formula Racing at UC Davis is a student design team challenged to design, build, and race a formula style electric vehicle for the 2013-2014 FSAE competition. Students are tasked with designing and fabricating a vehicle that can be sold to a manufacturing firm for mass production and targets the weekend autocross racer. The competition provides team members with the vital hand-on experience and skills necessary to succeed as engineers.

This project focused on the electric drivetrain of the vehicle consisting of a dual motor setup and a custom rear axle system that incorporated a student-developed torque vectoring system. It also integrated with the rest of the car including a sensor array network. All designs were made to meet SAE Formula Electric specifications described in the 2014 rulebook.

2 Layout Drawings

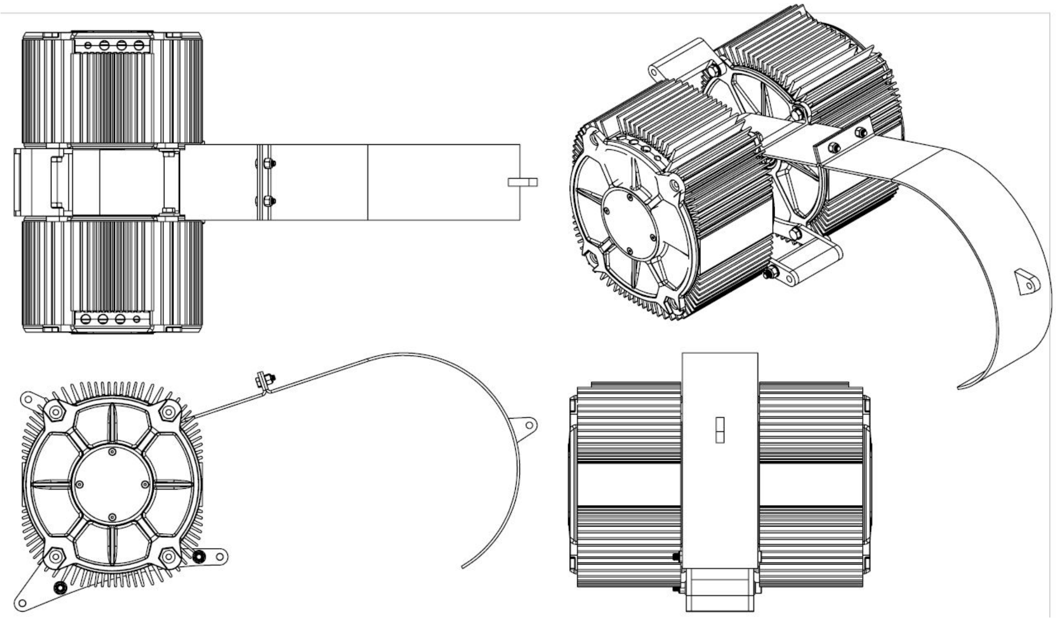


Figure 1: Motor Assembly

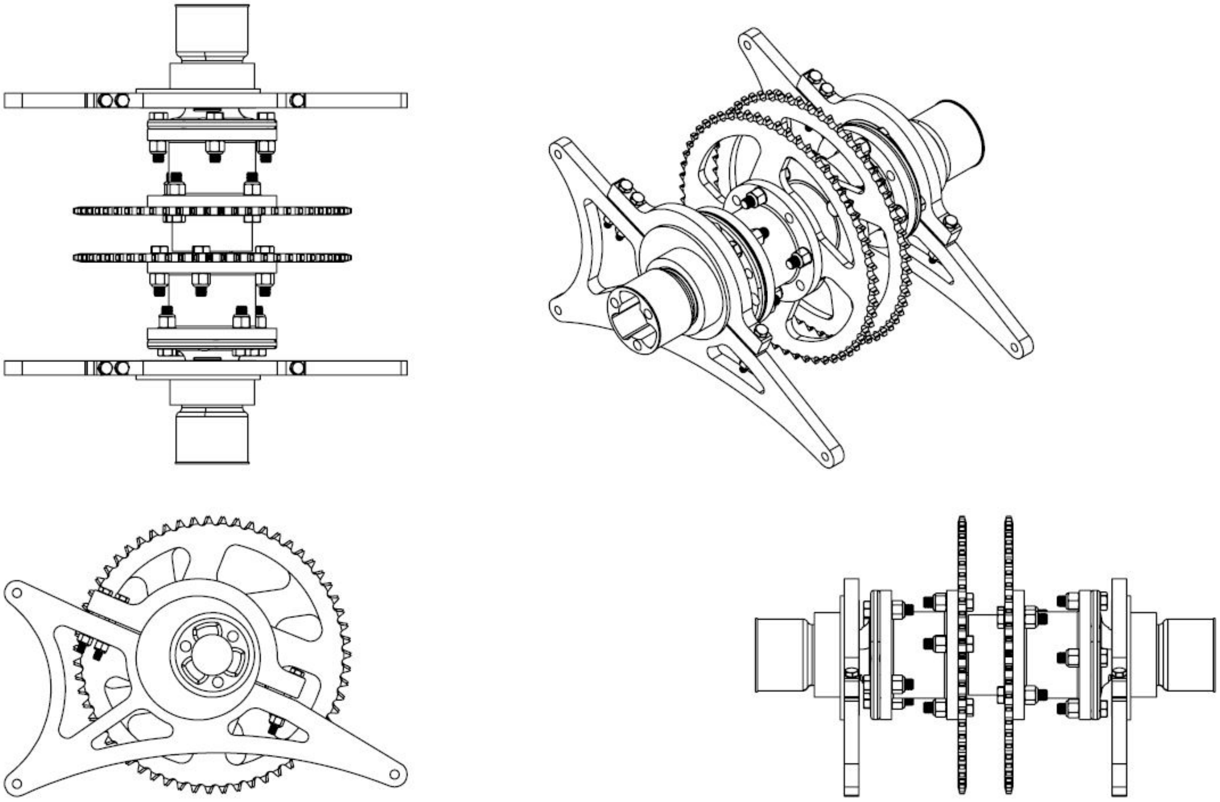


Figure 2: Axle Assembly

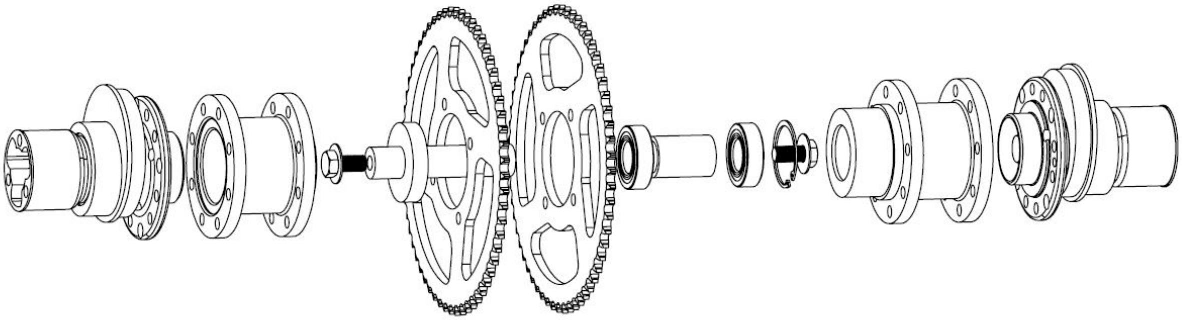


Figure 3: Exploded View: Axle

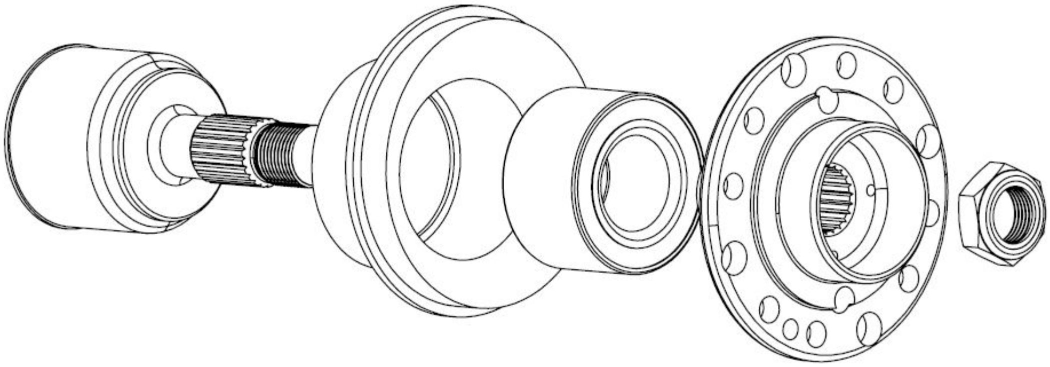


Figure 4: Exploded View: Half Axle

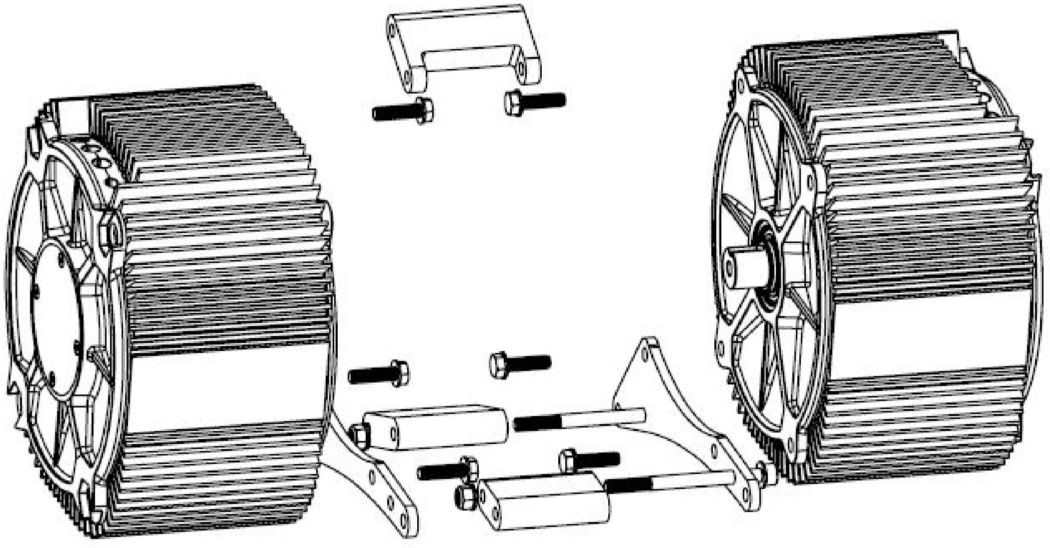


Figure 5: Exploded View: Motor Assembly

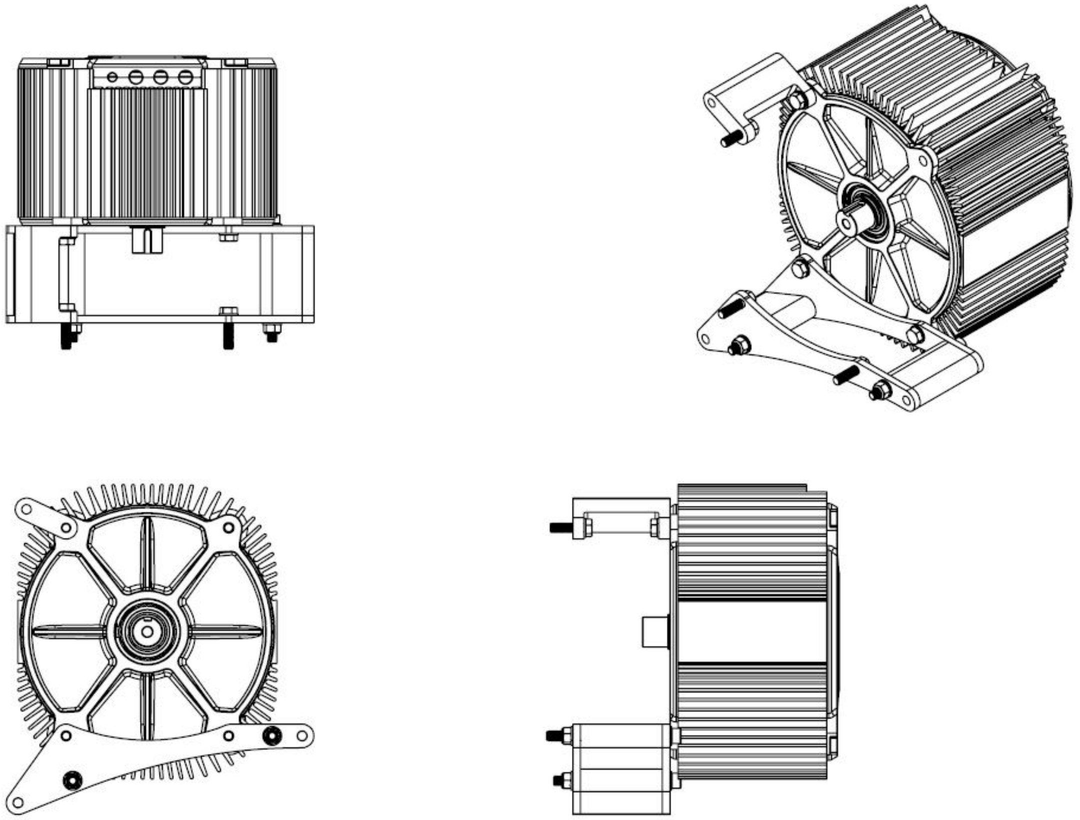


Figure 6: Assembly with Brackets

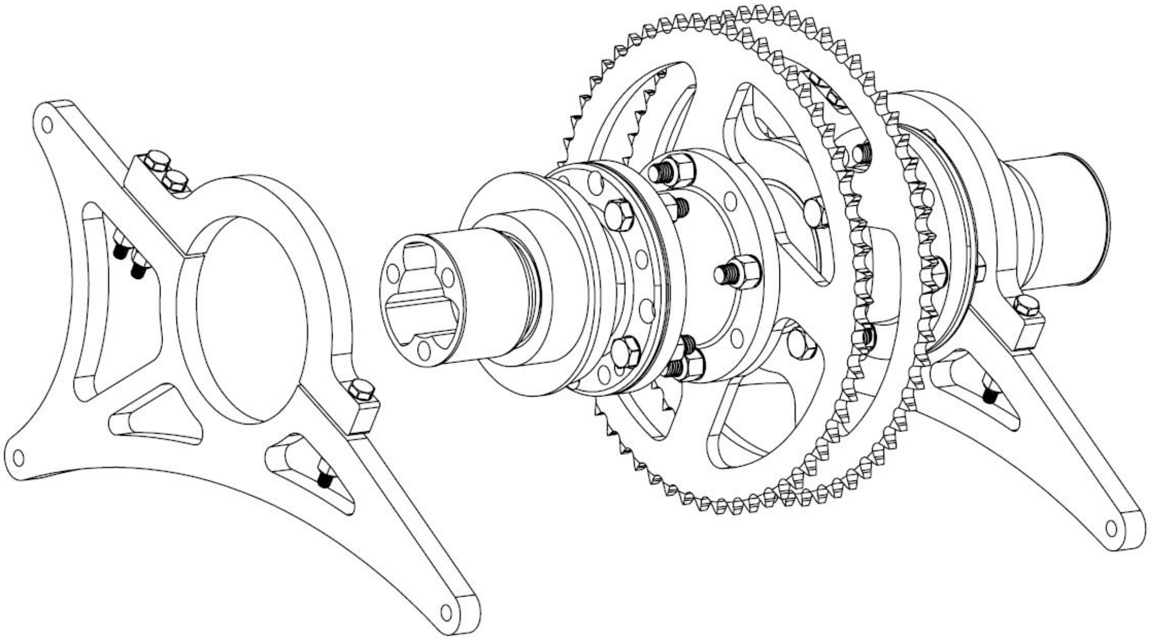


Figure 7: Exploded View: Whole Axle Supports

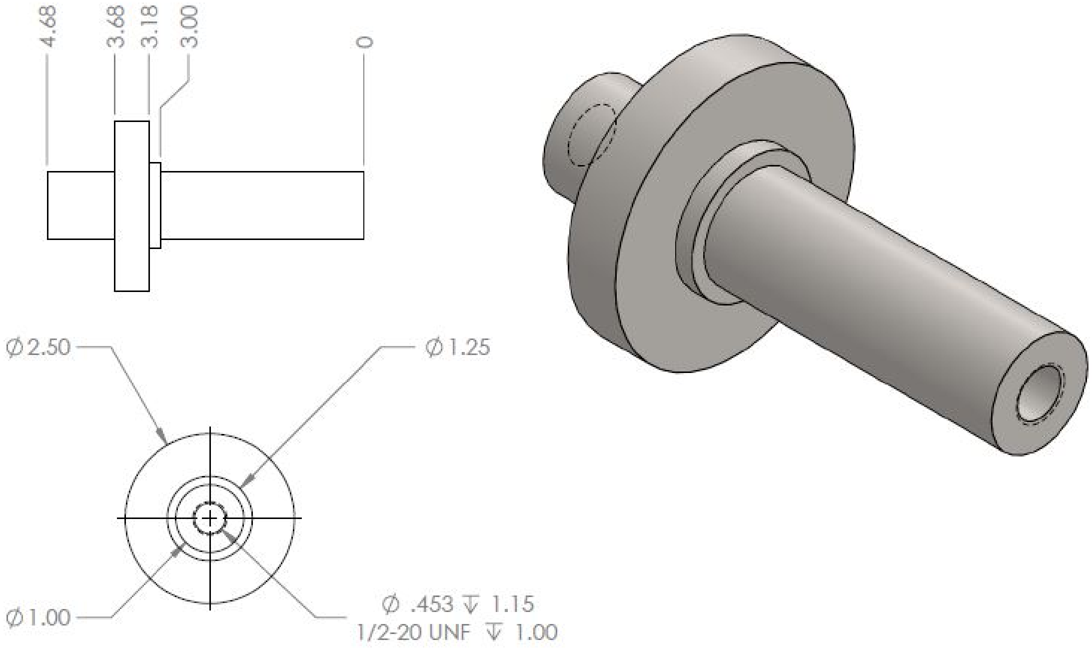


Figure 8: Center Axle

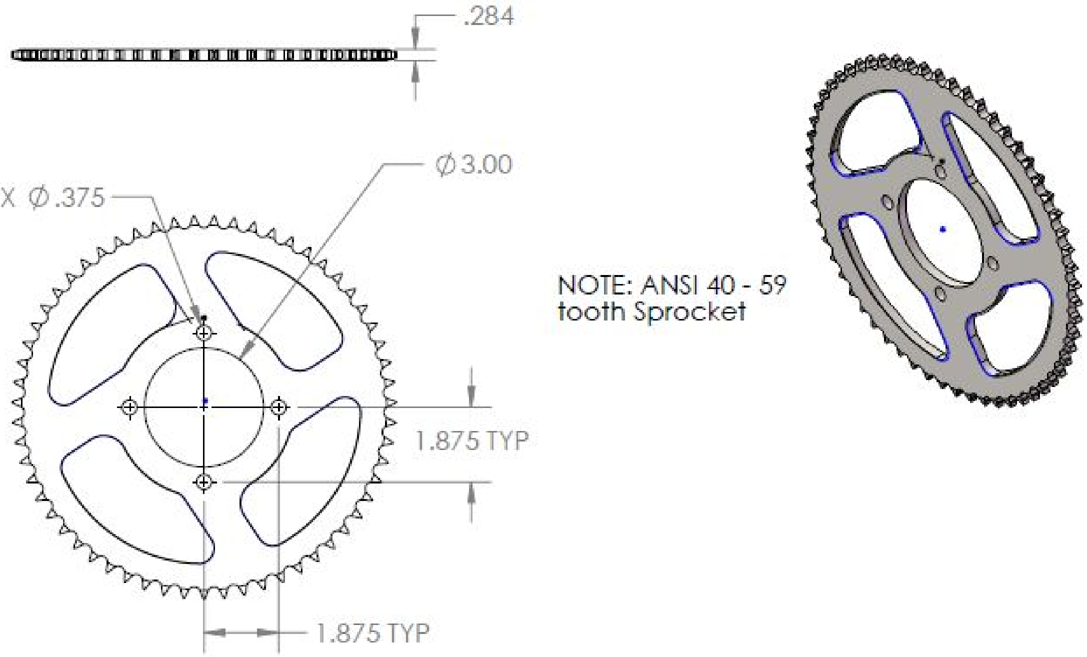


Figure 9: Sprocket

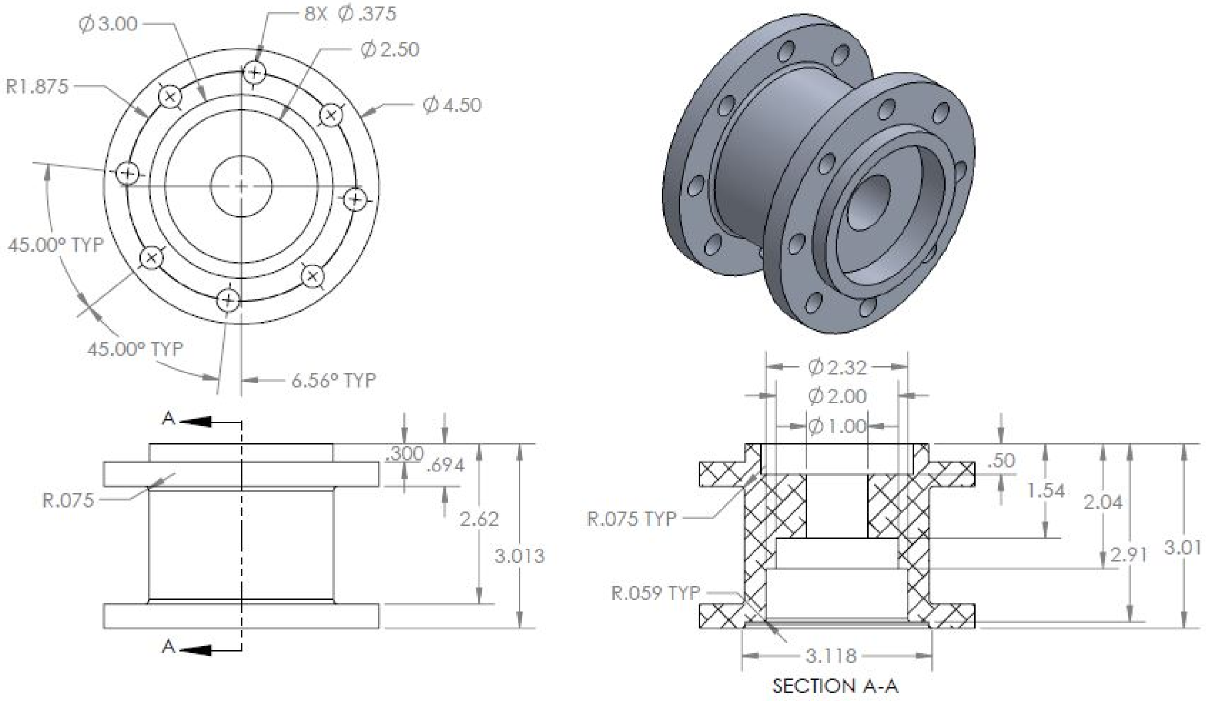


Figure 10: Spindle 1

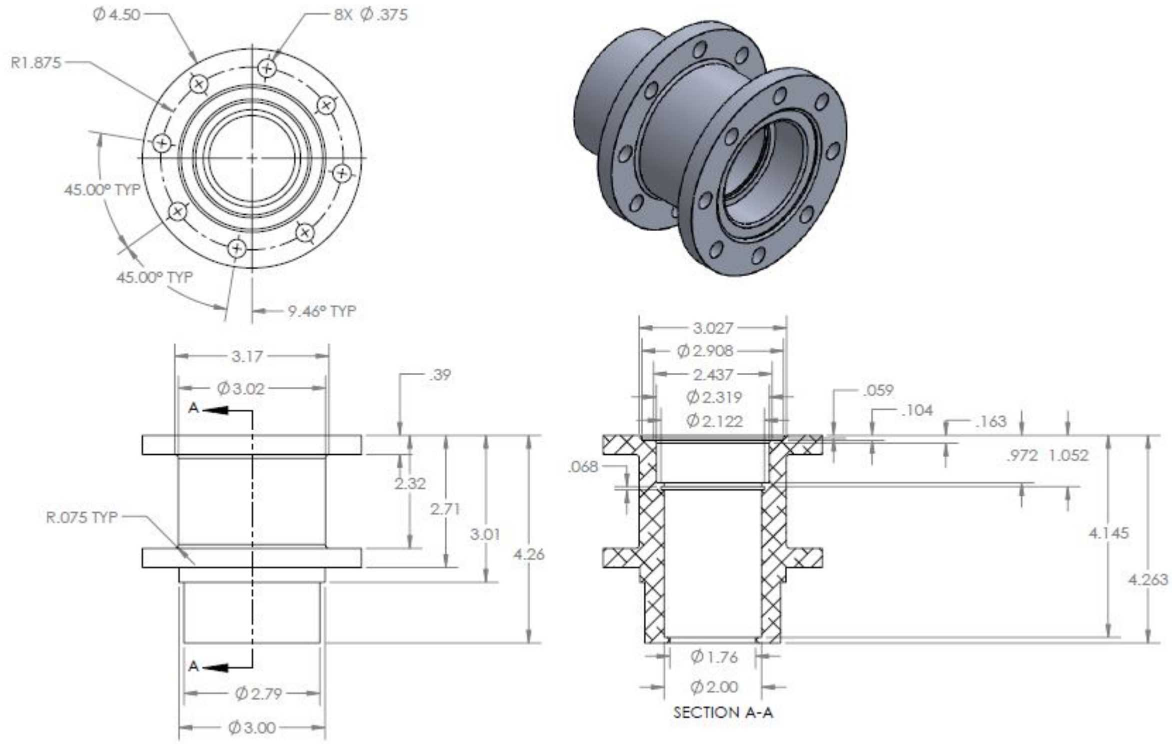


Figure 11: Center Axle

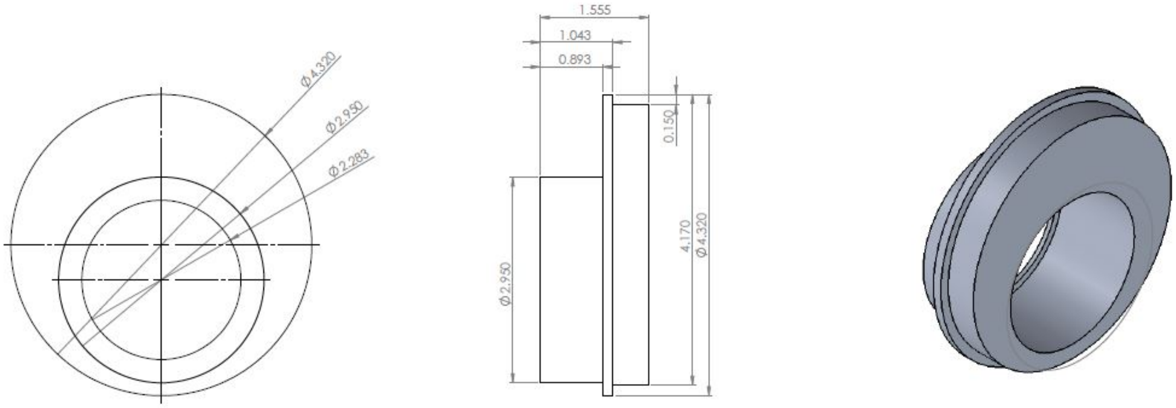


Figure 12: Eccentrics

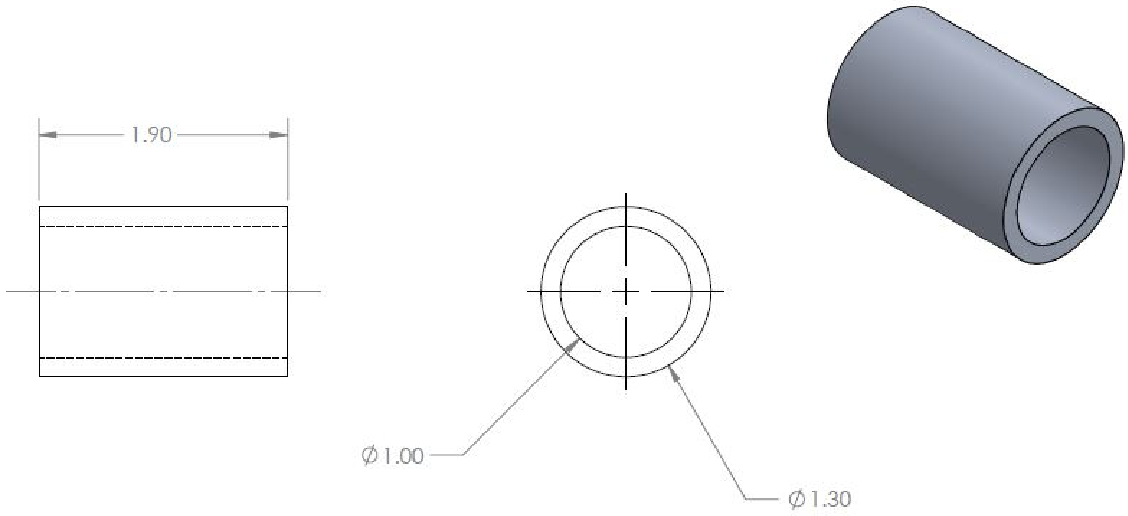


Figure 13: Bearing Spacer

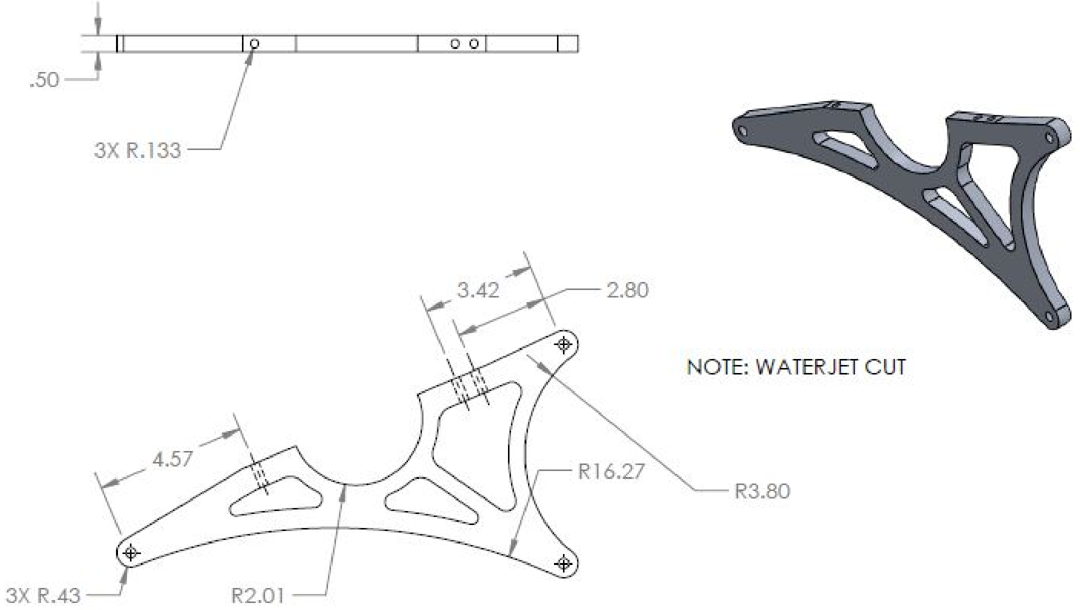


Figure 14: Axle Support Bottom

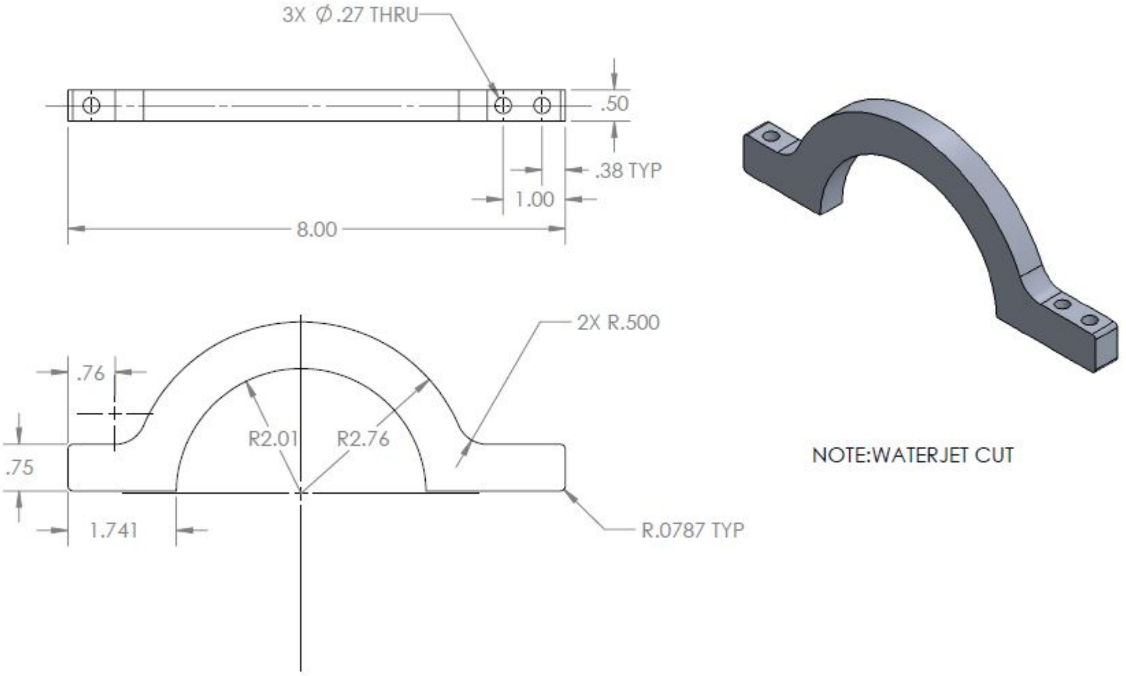


Figure 15: Axle Support Cap

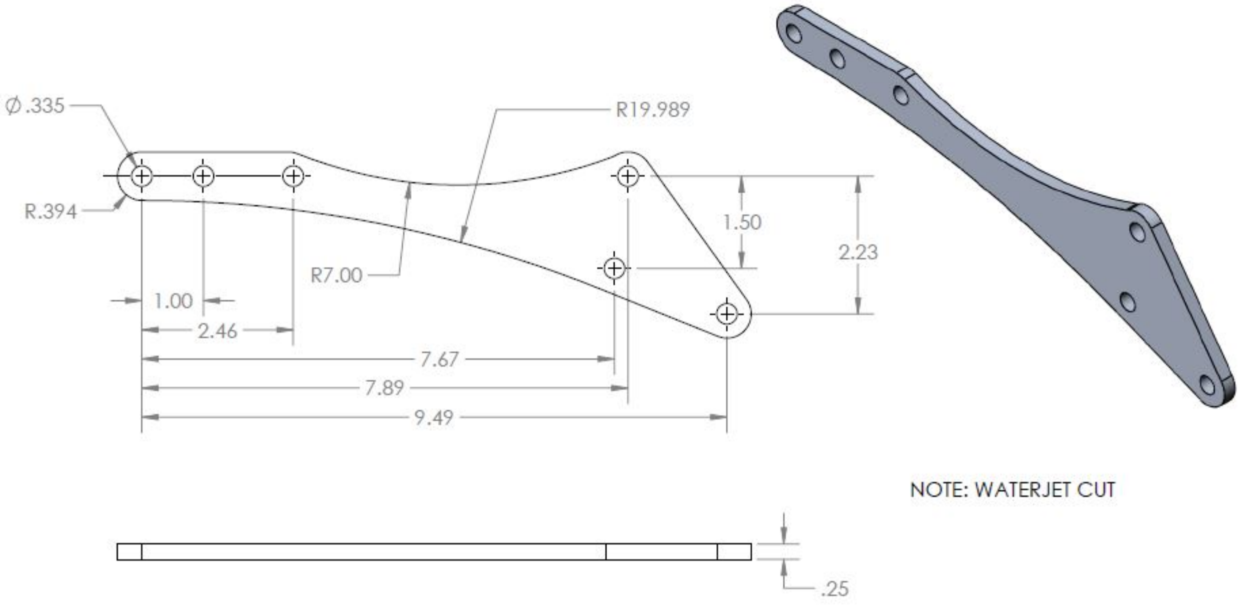


Figure 16: Motor Mounting Bracker

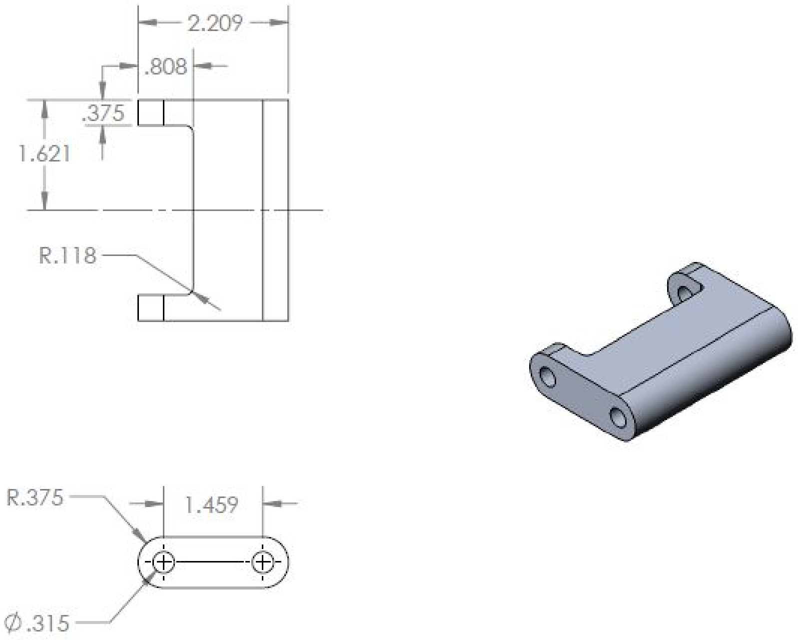


Figure 17: Motor Spacer 3

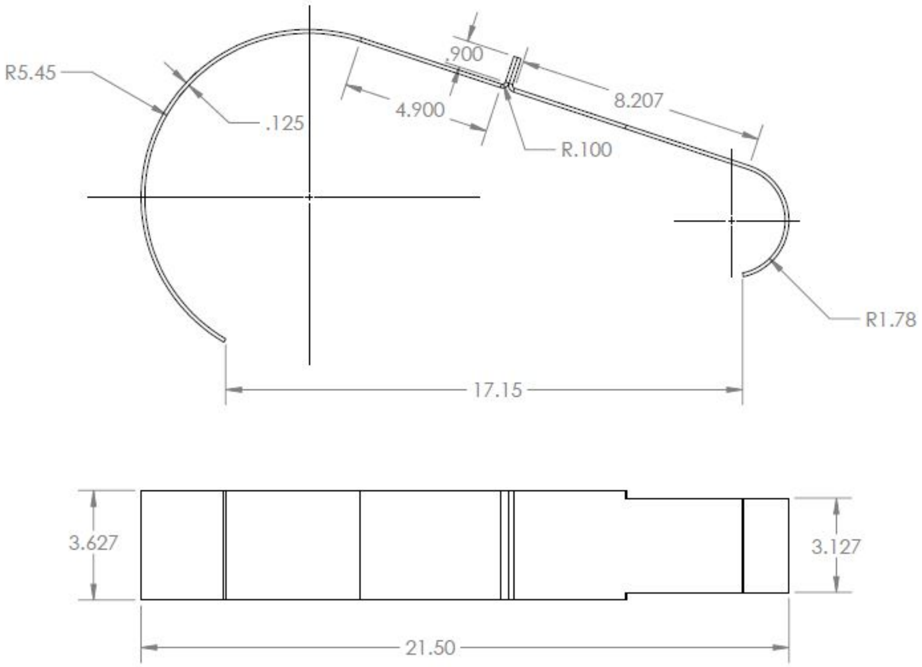


Figure 18: Chain Guard

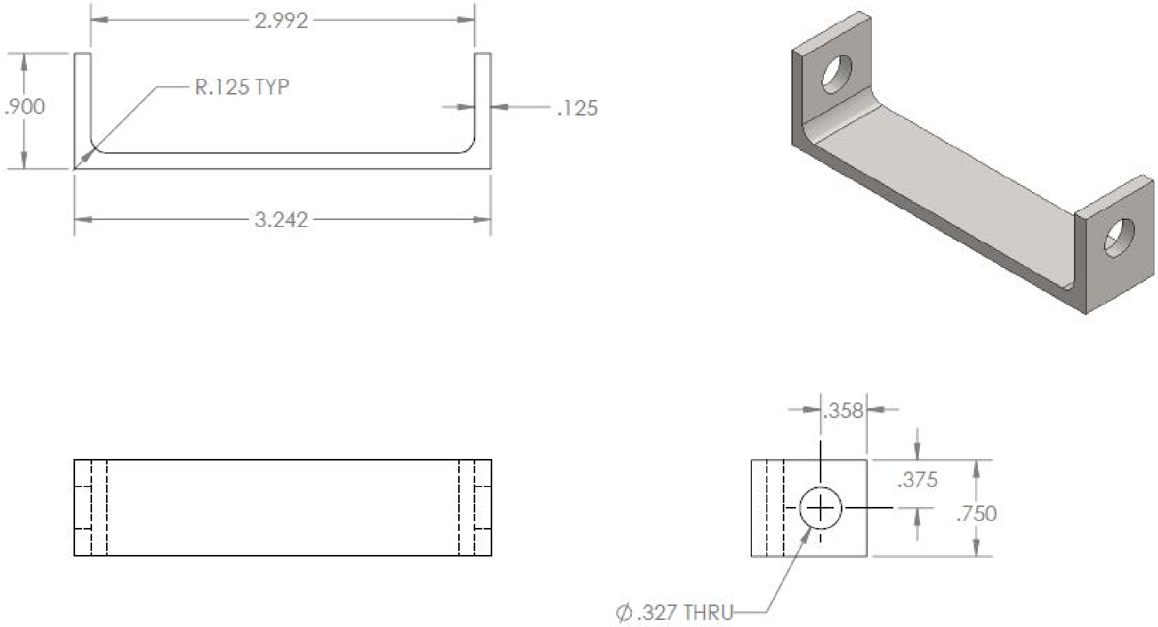


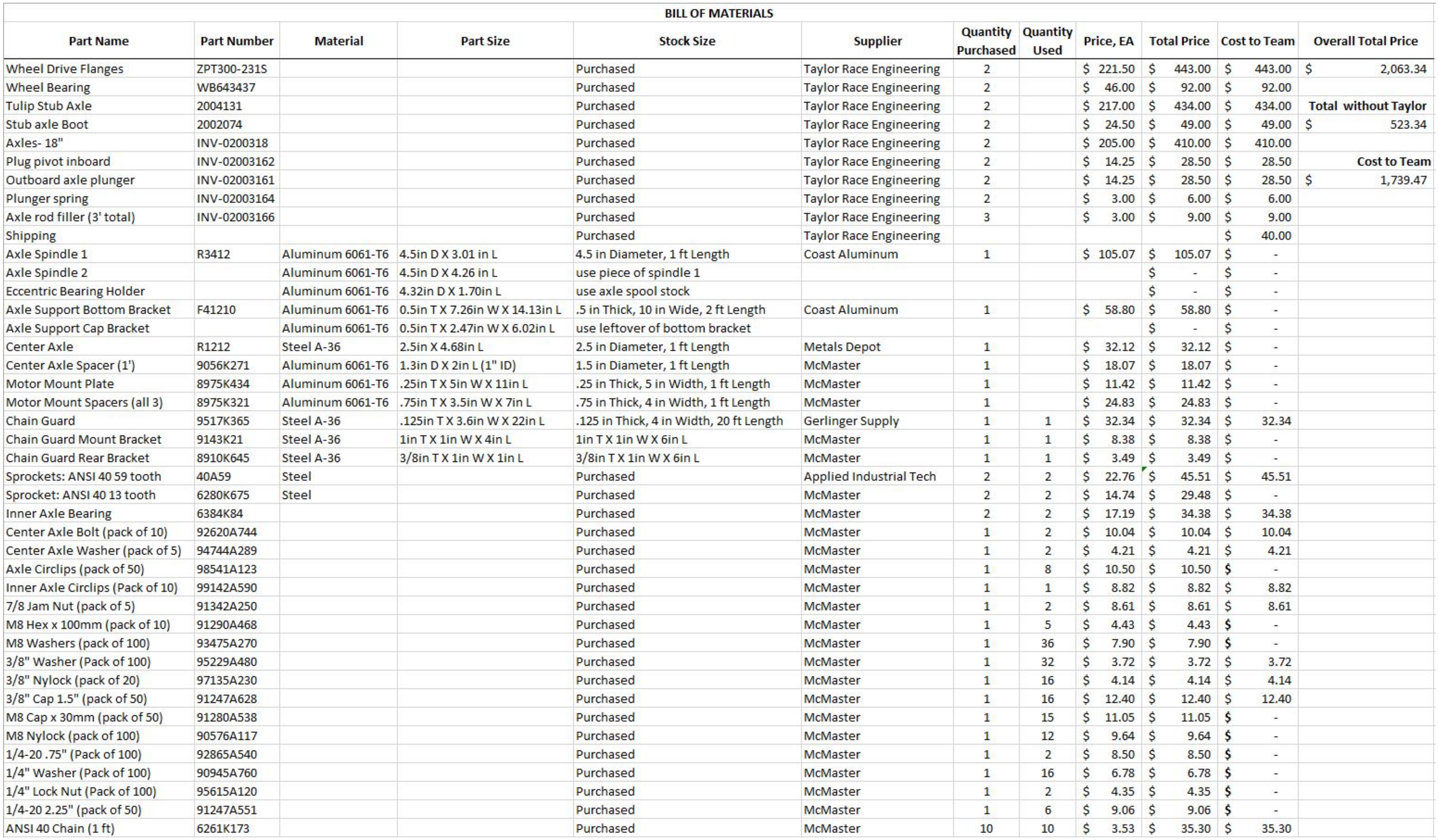
Figure 19: Chain Guard Bracket

3 Bill of Materials

The financial goals were to keep overall costs as low as possible, preferably below \$500, through sponsorship and donations. \$2,100 was budgeted for new axles from Taylor Race Engineering and \$500 for the remainder of the project. Included in the bill of materials are retail prices of all materials that were necessary for the project. Costs for machine time in the Engineering Fabrication Laboratory and CNC machining were excluded from this report. Manufacturing time, labor, and consumables will need to be taken into account for volume production.

A copy of the bill of materials is included on the following page. The first value in the Overall Total Price column is the amount needed to build an additional drivetrain assembly. The value below, Total Without Taylor, is the price for all materials excluding Taylor Race Engineering parts. The third value, Cost to the Team, is the amount spent to build the powertrain for this year's vehicle. This value reflects over \$300 in donated parts and materials.

The team went a little over budget with this system. Costs may be reduced by purchasing smaller quantities of some components, such as bolts, as the minimum stock quantities were more than necessary to build a single drivetrain. For mass production, these changes would keep the project under budget.



BILL OF MATERIALS

Part Name	Part Number	Material	Part Size	Stock Size	Supplier	Quantity Purchased	Quantity Used	Price, EA	Total Price	Cost to Team	Overall Total Price
Wheel Drive Flanges	ZPT300-231S			Purchased	Taylor Race Engineering	2		$ 221.50	$ 443.00	$ 443.00	$ 2,063.34
Wheel Bearing	WB643437			Purchased	Taylor Race Engineering	2		$ 46.00	$ 92.00	$ 92.00	
Tulip Stub Axle	2004131			Purchased	Taylor Race Engineering	2		$ 217.00	$ 434.00	$ 434.00	**Total without Taylor**
Stub axle Boot	2002074			Purchased	Taylor Race Engineering	2		$ 24.50	$ 49.00	$ 49.00	$ 523.34
Axles- 18"	INV-0200318			Purchased	Taylor Race Engineering	2		$ 205.00	$ 410.00	$ 410.00	
Plug pivot inboard	INV-02003162			Purchased	Taylor Race Engineering	2		$ 14.25	$ 28.50	$ 28.50	**Cost to Team**
Outboard axle plunger	INV-02003161			Purchased	Taylor Race Engineering	2		$ 14.25	$ 28.50	$ 28.50	$ 1,739.47
Plunger spring	INV-02003164			Purchased	Taylor Race Engineering	2		$ 3.00	$ 6.00	$ 6.00	
Axle rod filler (3' total)	INV-02003166			Purchased	Taylor Race Engineering	3		$ 3.00	$ 9.00	$ 9.00	
Shipping				Purchased	Taylor Race Engineering					$ 40.00	
Axle Spindle 1	R3412	Aluminum 6061-T6	4.5in D X 3.01 in L	4.5 in Diameter, 1 ft Length	Coast Aluminum	1		$ 105.07	$ 105.07	$ -	
Axle Spindle 2		Aluminum 6061-T6	4.5in D X 4.26 in L	use piece of spindle 1					$ -	$ -	
Eccentric Bearing Holder		Aluminum 6061-T6	4.32in D X 1.70in L	use axle spool stock					$ -	$ -	
Axle Support Bottom Bracket	F41210	Aluminum 6061-T6	0.5in T X 7.26in W X 14.13in L	.5 in Thick, 10 in Wide, 2 ft Length	Coast Aluminum	1		$ 58.80	$ 58.80	$ -	
Axle Support Cap Bracket		Aluminum 6061-T6	0.5in T X 2.47in W X 6.02in L	use leftover of bottom bracket					$ -	$ -	
Center Axle	R1212	Steel A-36	2.5in X 4.68in L	2.5 in Diameter, 1 ft Length	Metals Depot	1		$ 32.12	$ 32.12	$ -	
Center Axle Spacer (1')	9056K271	Aluminum 6061-T6	1.3in D X 2in L (1" ID)	1.5 in Diameter, 1 ft Length	McMaster	1		$ 18.07	$ 18.07	$ -	
Motor Mount Plate	8975K434	Aluminum 6061-T6	.25in T X 5in W X 11in L	.25 in Thick, 5 in Width, 1 ft Length	McMaster	1		$ 11.42	$ 11.42	$ -	
Motor Mount Spacers (all 3)	8975K321	Aluminum 6061-T6	.75in T X 3.5in W X 7in L	.75 in Thick, 4 in Width, 1 ft Length	McMaster	1		$ 24.83	$ 24.83	$ -	
Chain Guard	9517K365	Steel A-36	.125in T X 3.6in W X 22in L	.125 in Thick, 4 in Width, 20 ft Length	Gerlinger Supply	1	1	$ 32.34	$ 32.34	$ 32.34	
Chain Guard Mount Bracket	9143K21	Steel A-36	1in T X 1in W X 4in L	1in T X 1in W X 6in L	McMaster	1	1	$ 8.38	$ 8.38	$ -	
Chain Guard Rear Bracket	8910K645	Steel A-36	3/8in T X 1in W X 1in L	3/8in T X 1in W X 6in L	McMaster	1	1	$ 3.49	$ 3.49	$ -	
Sprockets: ANSI 40 59 tooth	40A59	Steel		Purchased	Applied Industrial Tech	2	2	$ 22.76	$ 45.51	$ 45.51	
Sprocket: ANSI 40 13 tooth	6280K675	Steel		Purchased	McMaster	2	2	$ 14.74	$ 29.48	$ -	
Inner Axle Bearing	6384K84			Purchased	McMaster	2	2	$ 17.19	$ 34.38	$ 34.38	
Center Axle Bolt (pack of 10)	92620A744			Purchased	McMaster	1	2	$ 10.04	$ 10.04	$ 10.04	
Center Axle Washer (pack of 5)	94744A289			Purchased	McMaster	1	2	$ 4.21	$ 4.21	$ 4.21	
Axle Circlips (pack of 50)	98541A123			Purchased	McMaster	1	8	$ 10.50	$ 10.50	$ -	
Inner Axle Circlips (Pack of 10)	99142A590			Purchased	McMaster	1	1	$ 8.82	$ 8.82	$ 8.82	
7/8 Jam Nut (pack of 5)	91342A250			Purchased	McMaster	1	2	$ 8.61	$ 8.61	$ 8.61	
M8 Hex x 100mm (pack of 10)	91290A468			Purchased	McMaster	1	5	$ 4.43	$ 4.43	$ -	
M8 Washers (pack of 100)	93475A270			Purchased	McMaster	1	36	$ 7.90	$ 7.90	$ -	
3/8" Washer (Pack of 100)	95229A480			Purchased	McMaster	1	32	$ 3.72	$ 3.72	$ 3.72	
3/8" Nylock (pack of 20)	97135A230			Purchased	McMaster	1	16	$ 4.14	$ 4.14	$ 4.14	
3/8" Cap 1.5" (pack of 50)	91247A628			Purchased	McMaster	1	16	$ 12.40	$ 12.40	$ 12.40	
M8 Cap x 30mm (pack of 50)	91280A538			Purchased	McMaster	1	15	$ 11.05	$ 11.05	$ -	
M8 Nylock (pack of 100)	90576A117			Purchased	McMaster	1	12	$ 9.64	$ 9.64	$ -	
1/4-20 .75" (Pack of 100)	92865A540			Purchased	McMaster	1	2	$ 8.50	$ 8.50	$ -	
1/4" Washer (Pack of 100)	90945A760			Purchased	McMaster	1	16	$ 6.78	$ 6.78	$ -	
1/4" Lock Nut (Pack of 100)	95615A120			Purchased	McMaster	1	2	$ 4.35	$ 4.35	$ -	
1/4-20 2.25" (pack of 50)	91247A551			Purchased	McMaster	1	6	$ 9.06	$ 9.06	$ -	
ANSI 40 Chain (1 ft)	6261K173			Purchased	McMaster	10	10	$ 3.53	$ 35.30	$ 35.30	

Figure 20: Bill of Materials

4 Calculation Notebook

4.1 Motor Brackets

Material: 6061-T6 Aluminum

4.1.1 Scenario 1: Steady State Operation

Forces: Weight of Motor (80 lbs)
Torque: Moment on each motor sprocket (70 ft-lb)
Fixed Points: The three mounting points of the motor brackets. The bolts in the brackets.
Assumptions: Chassis brackets are rigid

4.1.2 Scenario 2: Lateral Forces During Turning

Forces: 1.5g Side Loading (120 lbs)
Fixed Points: The three mounting points of the motor brackets. The bolts in the brackets.
Assumptions: Chassis brackets are rigid.

4.1.3 Scenario 3: 10g Bump

Forces: 10g vertical load (800 lbs) Fixed Points: The three mounting points of the motor brackets. The bolts in the brackets Assumptions: Chassis brackets are rigid.

4.1.4 Worst Case Scenario: Scenario 3 - 10g Bump

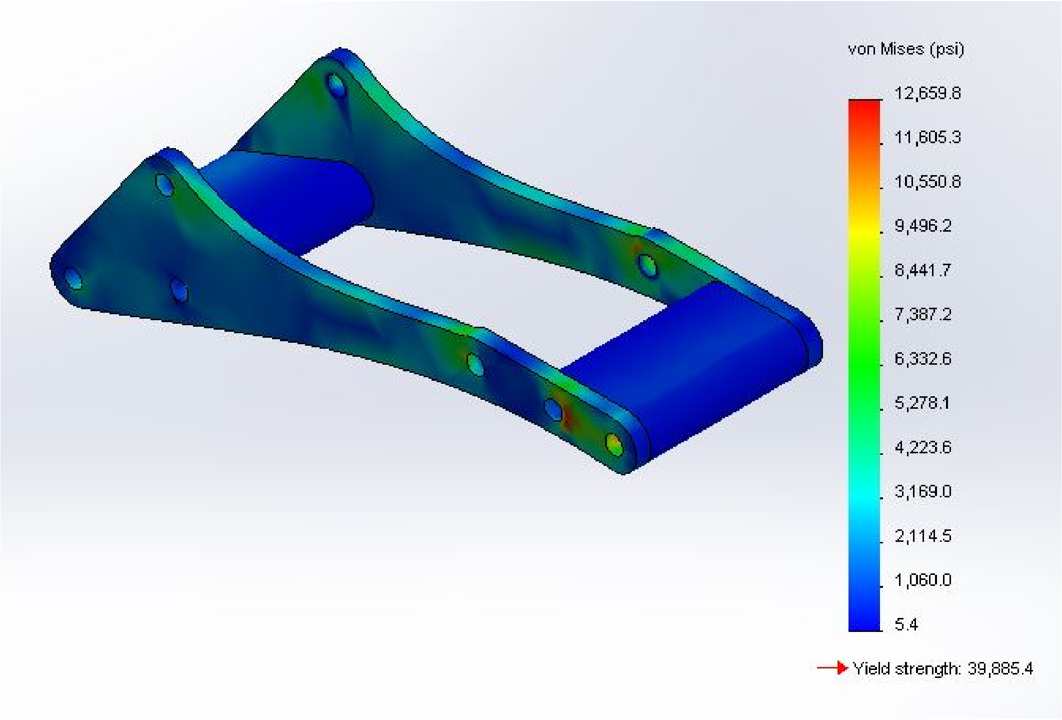


Figure 21: FEA Results: Scenario 3 - 10g Bump

4.2 Center Axle

Forces: 763 lbf spread over over the contact area with bearings. 763 lbf spread over over the area on opposite end of bearings that sits on spindle.
Fixed Points: The outside flat ends of the smaller cylinder.
Assumptions: Both motors outputting torque in opposite directions. Bearings have seized and all of the torque is converted into normal forces on the part
Material: Plain Carbon Steel

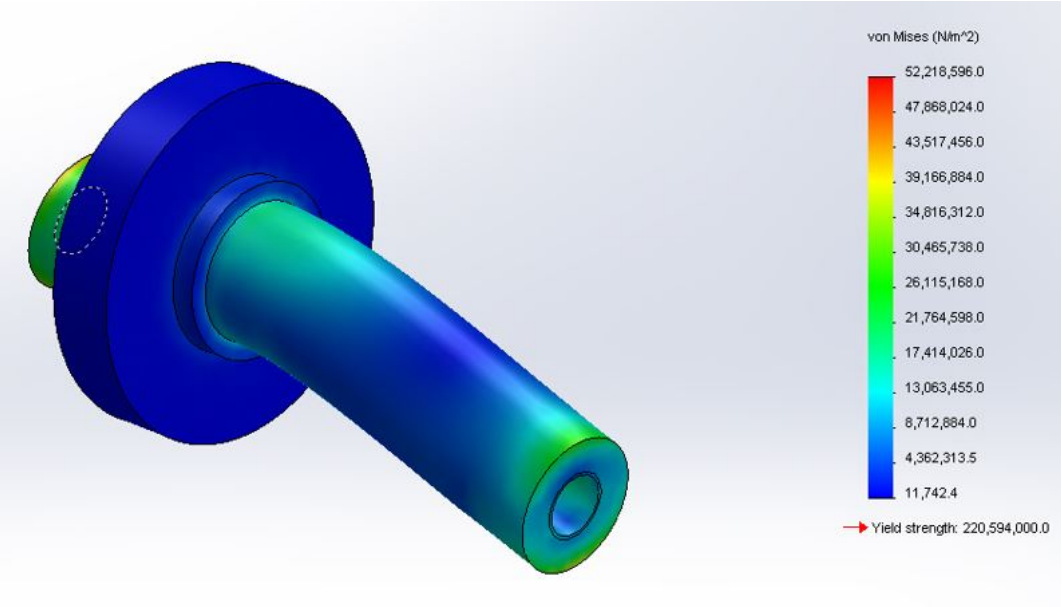


Figure 22: FEA Results: Center Axle

4.3 Spindles

Material: 6061-T6 Aluminum

4.3.1 Spindle 1

Forces: 763 lbf spread over the four bolt connections
Fixed Points: The bolt holes at the sprocket connection on the opposite side of where the torque is applied
Assumptions: Full torque from motor applied to spindles. Opposite connections lock up. Whole component under torsion.

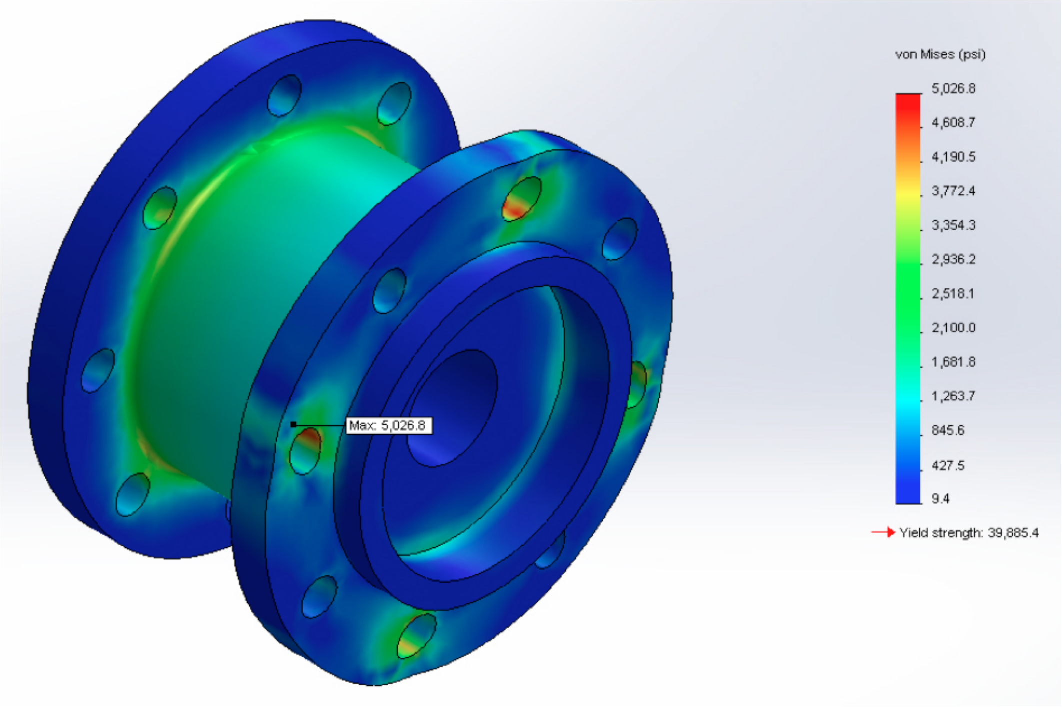


Figure 23: FEA Results: Spindle 1

4.3.2 Spindle 2

Spindle 2 is larger than Spindle 1 in all respects and experiences the same forces, therefore it is reasonable to assume Spindle 2 is sufficiently strong for this application.

4.4 Axle Supports

Material: 6061-T6 Aluminum
Forces: Lateral forces during full throttle (750 lbs) and 10g vertical bump (200 lbs)
Fixed Points: The three legs of the bracket were fixed to simulate a bolt-through-tab connection. The cap was secured to the bottom bracket with three SAE grade 5 $\frac{1}{4}$-20 bolts.
Assumptions: Brackets is rigid.
Minimum Factor of Safety: 3.4

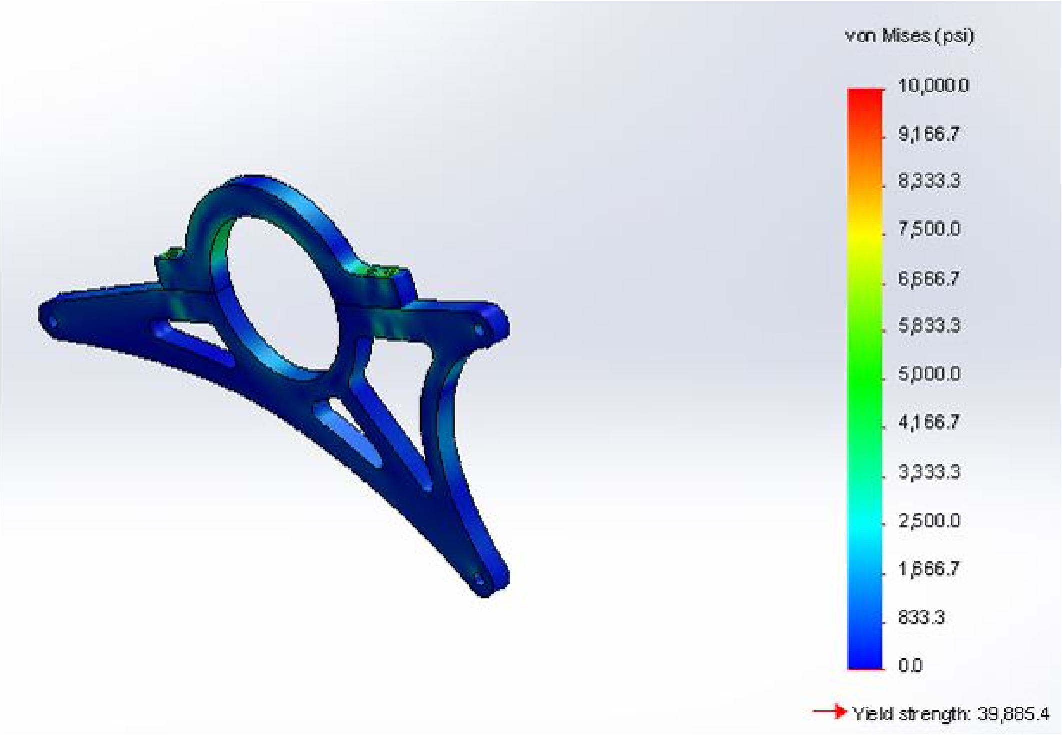


Figure 24: FEA Results: Axle Supports

4.5 Sprockets

Material: 6061-T6 Aluminum
Forces: Full throttle force along the chain (720 lbs) applied evenly to half of the teeth on the sprocket.
Fixed Points: Four bolted connections with Grade 5 $\frac{3}{8}$-16 in bolts.
Minimum Factor of Safety: 4.18

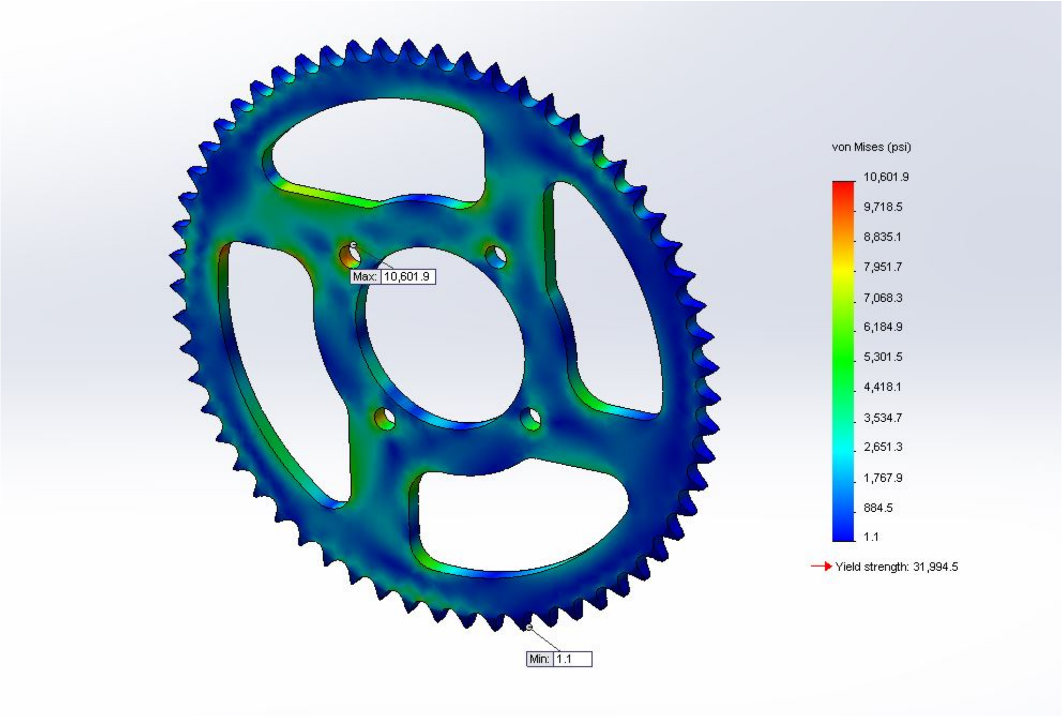


Figure 25: FEA Results: Axle Supports

4.6 Fatigue

4.6.1 Sprocket

Forces: Full throttle force along chain (720 lbs) applied evenly to half of the teeth on the sprocket.
Mission: Cyclical loading from zero to full load over 1 million cycles
Fixed Points: Four bolted connections with Grade 5 $\frac{3}{8}$-16 in bolts.

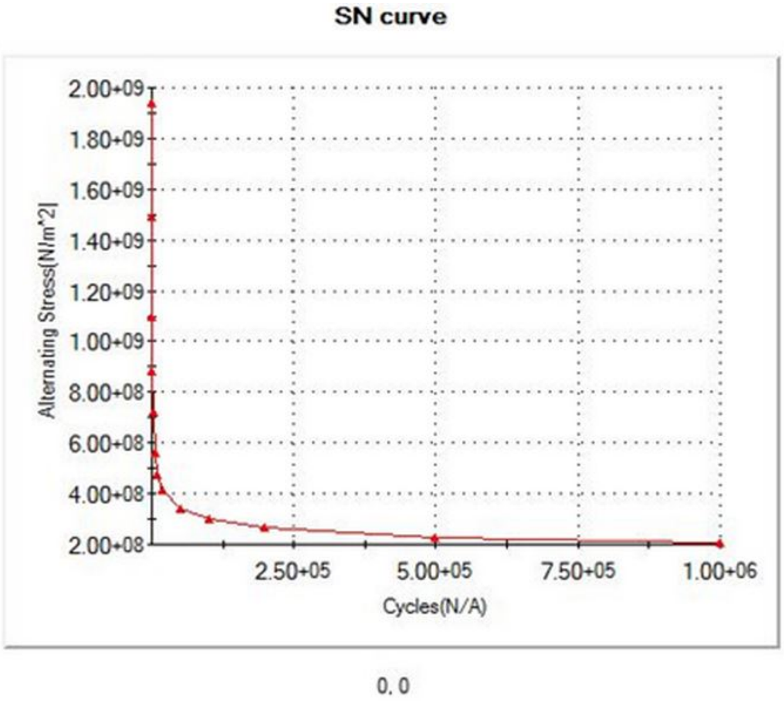


Figure 26: Fatigue Results: Sprocket SN Curve

Goodman's mean stress correction was used to estimate the lifetime of the sprockets. The results showed that it will last for more than one million cycles. This approximates to over twelve hours of continuous operation at maximum rpm, a very unrealistic loading condition.

4.6.2 Chains

Size ANSI 40 chains were chosen for this application. They are smaller and lighter than size 50 ANSI chains, however, they are not as commonly found. Their smaller width, higher possible gear ratio, and lighter weight made them more ideal in this application. The smaller width allows the system to be thinner, simplifying motor mounting. Due to chassis height limitations, the major sprocket diameter is limited to about a 10 inch diameter which allows for a maximum 60 tooth size. Choosing a gear ratio of 4.5 meant that the small sprocket on the motor would have to be 13 toothed and 2.33 inches in diameter. The following calculations for chain load were based off of the maximum torque output from the motors and the minimum sprocket size.

$$70ft \cdot lb = 2.33in\frac{12in}{1ft} \cdot Xlb \tag{1}$$

where

$$X = 721lb\ on\ chain \tag{2}$$

The working load of normal ANSI 40 chain is listed as 437 lb on McMaster, the source of the chain. According to Shigleys Mechanical Engineering Design, the minimum tensile strength of ANSI 40 chain is 3,130 lb. Operating conditions the chain for this car will not approach the minimum tensile strength, so the chain is unlikely to break due to high stresses. It will at times exceed the rated working load but will not exceed this value on average as they will only be used at the calculated torque in short spikes, not a continuous load. This means that the chain could have a relatively short lifetime while in use on the car, and if an issue does arise such as stretching too quickly, a heavyweight chain can be purchased.

To determine the estimated lifetime of the chains, fatigue calculations of both the plates and rollers were calculated. These calculations find the horsepower which the chain will be rated for based on 15,000 hours running at full load.

Horsepower load for plates

$$H_1 = 0.004N^{1.08} \cdot n^{0.9} \cdot p^{3-0.7}hp = 20.55hp \tag{3}$$

where
N = 13 teeth on smallest sprocket
n = 6000 rpm peak
p = $\frac{1}{2}$ inch link length for ANSI chain

Horsepower load for chain rollers:

$$H_2 = \frac{1000 \cdot Kr \cdot N_1^{1.5} \cdot p^{0.8}}{n^{1.5}} = 0.98hp \tag{4}$$

where
Kr = 17 for ANSI 40 chain
N = 13 teeth on smalles sprocket n = 6000 rpm peak
p = $\frac{1}{2}$ inch link length for ANSI chain

In this application, the rollers have a much smaller power allowance. Comparing our peak output power, 53.64 hp, our lifetime would be reduced by a factor of .95/53.64, giving a lifetime of 274 hours. In this application, peak power will only be reached for small spikes, so the lifetime will be much longer, but even 274 hours is enough for this years testing and competition. ANSI 40 chains are ideal because they're cheap, lightweight, and are strong enough to last for the prescribed lifetime.

When designing a chain drive, an important factor to keep in mind is chain wear. A desired effect known as hunting tooth, where each link in the chain contacts each tooth on all sprockets involved, allows the chain linkage to wear even across the entire system. In order to create this desired effect, the sprocket teeth count must not have any common factors. For this reason, the final drive will be using 13 and 59 tooth sprockets. While 13 is not a factor of 60, if a change in gear ratios is made at a later date, the 59 tooth sprocket will be able to be mated with a 14 tooth small sprocket, as opposed to a 60 tooth sprocket that would not allow this change.

To determine the desired gear ratio, a MATLAB simulation was written to model the acceleration performance of the car using a forward euler time-stepping method. The script calculated the forward traction force and subtracted rough estimates of aerodynamic drag and rolling resistance at increasing speeds of the vehicle. Vehicle speed and motor rpm were also calculated and graphed to visualize performance results. Given the drive train configuration was a single speed, the only variable input was the final drive ratio through varying sprocket sizes. Through a guess and check method, a final drive gear ratio of 4.54 was determined to produce the desired performance results initially stated in the objective specifications of the project. The figure below shows the results.

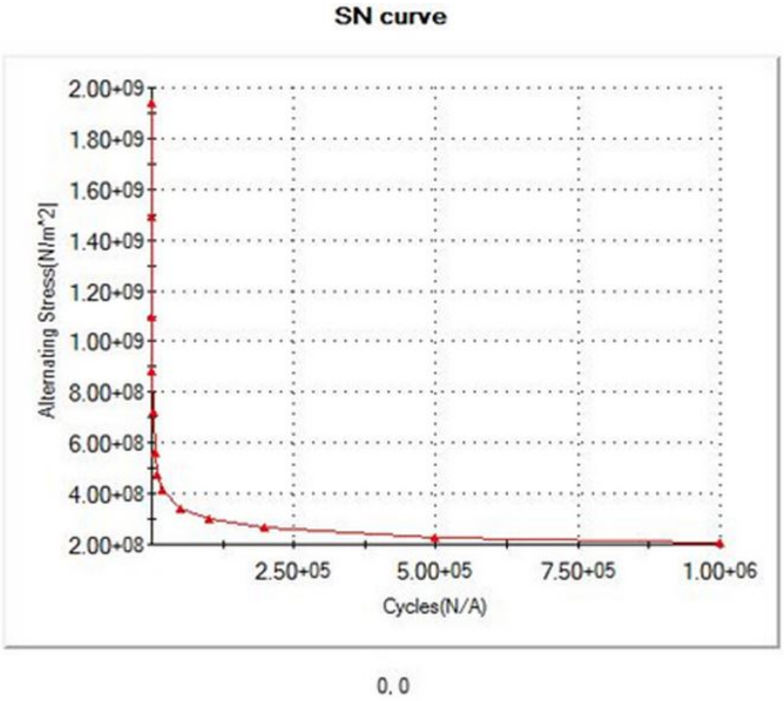


Figure 27: Fatigue Results: Sprocket SN Curve

The MATLAB script code used and output can also be found in Appendix A. This code also approximates the time run in the acceleration event, a 75 meter straight-line acceleration from a standing start. Approximate time to complete the event, expected speed to across the finish line, and the acceleration in gs expected for the event are determined.

This simulation is highly idealized as it does not account for wheel slip, especially while accelerating from a stop. The torque vectoring system is planned to include wheel slip controls which will throttle back the torque when excessive wheel slip is detected. This should help the car accelerate at the highest possible rate, which will be determined by tire and track conditions almost exclusively. The goal achieved by setting such a high ratio is to move the limiting factor to the wheels, not to be limited by the vehicle gearing.

5 Summary Report

5.1 Design Goals

Design specifications were chosen at the beginning of the project and are outlined as follows:

- Design for strength and reliability through fatigue and strength analysis
- Conform to all 2014 Formula SAE rules
- Allow for free movement between two halves of the rear axle for independent wheel drive
- 250 ft-lb of torque or more at each wheel
- RPM exceeds 4000 at motor side
- Maximum speed greater than 70 mph
- Acceleration from 0 to 60 in about 3 seconds

- System must safely endure 30 minutes of continuous race operation

Machining of components was accomplished using the on campus Engineering Fabrication Laboratory. Some complex parts were completed using on campus CNC machines, and also externally using waterjet cutting. Purchasing of components from suppliers was to be avoided unless manufacturing methods proved too difficult and costly to achieve the desired design. These parts were ordered from Taylor Race Engineering. Because of the manufacturing complexities of the stub axles and flanges, it is not feasible to fabricate these parts in the facilities at UC Davis. While they could be custom-designed and sent out to be fabricated at a third party machine shop, the added complexity and cost make it advantageous to work with available products on the market. The end product, including both the rear axle and motor mounting, will have been fabricated and useable for FE1 by beginning of Spring 2014.

5.2 System Analysis

5.2.1 Strengths

1. Rigid and refined axle assembly
   (a) simple shapes for ease of manufacturing
   (b) compact
   (c) low maintenance
   (d) easy to disassemble
   (e) reusable in future car designs
2. sleek design of mounting brackets
   (a) maximize aesthetics and minimize material
   (b) 2D shapes for easy manufacturing
3. eccentric chain tensioning
   (a) allows for up to 1 inch of axle movement to accommodate any chain length
4. Easy axle removal from supports
   (a) easily remove axle from vehicle for maintenance with clamping cap design
5. motor mounting orientation
   (a) allows for swapping between two sizes of motors with ease due to face mounting only (motors are different widths)

5.2.2 Weaknesses

1. axle support orientation is non ideal for operating conditions
   (a) main forces are against relatively weak points of the design
   (b) should be oriented as if hanging off the rear of the car to reduce size and increase strength
2. Oversized student design parts that use more material than necessary

5.2.3 Incomplete Work

1. FEA was only done on major student designed components
2. Purchased parts were assumed to withstand forces from the system as they are steel and have been independently tested by the manufacturer
3. Optimization of components to meet a particular factor of safety was not fully done to reduce material usage
4. Designing all components without using purchased parts; inability to manufacture splines necessitated the purchase of some materials

5.2.4 Possible Redesign

1. It would be beneficial to add an additional chassis member and reorient the mounting points of the axle supports as if the axle was hanging off the rear of the chassis. The supports in this orientation would form an A shape off the rear of the chassis that would be more logical than the current design, considering the direction of the main forces are toward the front of the vehicle. It would also be possible to make the length of chain shorter, bringing the axle closer to the motors to reduce chain slop. However, this would necessitate a redesign of the suspension, which was not possible for this years vehicle.
2. If the ANSI 40 chain wears too quickly during the testing phase or competition, it may be replaced with ANSI 50 chain to improve drivetrain durability by simply swapping out sprockets.
3. Account for manufacturing time and costs in redesign: larger fillets where necessary to reduce tool requirements, parts that only utilize 3 axis machining operations, and indicated precision sections that correctly match mating parts.

6 Part Description

6.1 Motors

Two Z-Force 75-7 passively air-cooled, radial flux permanent magnet, brushless motors from Zero Motorcycles were selected from a variety of motors for the powertrain configuration. These motors were chosen because of their maximum power output of 40 kW each, compact pancake style, and because they were donated to to the team. The motors are connected to the rear axle by way of ANSI 40 sprockets and chain to transmit power to the rear axle at a reduction ratio of 4.52. Each motor powers an individual rear wheel through the axle to allow for the torque vectoring system to dynamically allocate power.

6.2 Axle Assembly

The rear axle assembly was designed for each motor to operate independently from each other to accommodate a torque vectoring system. Two sprockets transmit the power from the motors to each half of the axle assembly. A steel center axle interfaces with each side of the assembly through two radial ball bearings, allowing each half to rotate independently of each other while keeping the two halves axially constrained using a snap ring and axial positioned bolts. The aluminum spindle parts serve a dual purpose. One is to connect to the center axle and two is to transmit the torque from the axle sprockets out too the wheel drive flanges. The wheel drive flanges receive the torque from the spindles and transmit it to the stub shafts through a splined connection. From the stub shafts, the torque is transmitted to the half shafts through a CV joint out to the rear wheels.

The wheel drive flanges and stub shafts were purchased from Taylor Race Engineering, whereas the rest was manufactured by the team. Due to complex shapes, the eccentric bearings holders and spindles were

CNC manufactured on campus while the center axle and bearing spacer were manufactured by hand in the Engineering Fabrication Laboratory (EFL) student shop.

6.3 Axle Supports

Supporting mounts for the axle assembly were designed to allow adjustment of the eccentric bearing holders and ensure the axle would not move during hard cornering and full throttle acceleration. There are a total of 2 supports, each consisting of a bottom support bracket and top cap. The bottom support bracket was designed to bridge between three structurally sound beams in the rear of the chassis, while also providing easy removal of the axle assembly from the vehicle. The axles themselves feature an eccentric holder that allows for chain tensioning. This required the cap piece to be designed with a small gap between it and the bottom bracket to clamp down the eccentric holders once the desired chain tension was dialed in. Additionally, the eccentric is notched with a centerline and the axle mounts are etched with degree ticks to ensure the each half of the axle is equally tensioned.

Both of these parts were tested using FEA for static and fatigue loading scenarios. The main forces of concern were the chain tension force from the motors and the possibility of a 10g vertical bump. The results displayed a minimum safety factor of 3.4 which was twice as good as expected. Both parts will be made of aluminum that will were waterjet cut because of their size and requirement for a custom jig that is time consuming using traditional milling processes.

If the assembly was to be redesigned, it would be beneficial to add an additional chassis member and reorient the mounting points as if the axle was hanging off the rear of the chassis. The supports in this case would form an A shape off the rear of the chassis that would be more logical than the current design, considering the direction of the main forces that the axle assembly is subjected to.

6.4 Spindles

The spindles are central components that connect to the center axle and transmit the torque from the axle sprockets out to the wheel drive flanges. Each spindle has a unique design for connecting one half of the axle to the other. Spindle 2 is more complex because it houses the radial ball bearings held in place by an internal retaining ring. The ball bearings provide the only contact between the two halves of the axle to allow for the necessary independent rotation. Spindle 1, on the other hand, is rigidly attached to the center axle by means of a bolted connection.

On the outside of each spindle, 59 tooth sprockets attach directly to the inside flanges via a circular array of four $\frac{3}{8}$"-16 bolts. On the outside flange of each spindle, the wheel drive flange mates precisely up to and into the spindle via another circular array of four $\frac{3}{8}$"-16 bolts.

6.5 Center Axle

In order to keep the two halves of the axle axially constrained and prevent bending, a solid rod, the center axle, was inserted between them. A flange was added to one side to increase the resistance to the bending moment as it interfaces with that half of the axle. Either end of the axle is tapped for $\frac{1}{2}$" 20 bolts which will be used to hold the axle in place along with washers on both halves. Along the longer half, the right side in the image above, two bearings will interface with the second spindle to give free rotation as well as constrain both spindles with the ends of the center axle. This prevents the spindles from colliding and binding in the center.

Steel was chosen as the material for this part because of the potential for high bending forces acting on it as high torque is transferred through the chains. A small amount of deflection was desired to prevent binding. The part was hand lathed in the Engineering Fabrication Laboratory.

6.6 Center Axle Spacer and Bearings

The bearings were sized to fit onto the center axle and into the spindle. They will not experience a high rotational speed as the two halves of the axle will spin at similar speeds. There will be a fairly high load but negligible thrust loading. As the load is distributed between the two bearings, they are sized adequately to comply with the peak loading.

6.7 Sprockets: 13 & 59 teeth ANSI 40

The chains and sprockets are purchased steel parts used to transfer the power from the motors to the axle. After ANSI 40 chain was chosen, which has a ? inch link length, was decided upon, teeth counts could be picked. The teeth counts were decided based on the desired reduction ratio from a simple MATLAB calculation. This resulted in a final drive ratio of 4.54:1, which reflects both top speed and acceleration figures near our target.

In order to achieve this high ratio, a small 13 tooth sprocket was used. ANSI 40 chain will not work effectively at teeth counts smaller than 12. Rather than going with the minimum, a 13 tooth sprocket was more ideal because of a phenomenon called hunting tooth. This means that the chain will drift as it rotates, and will result in the most even wear possible. For the same reason, a 59 tooth sprocket was chosen to pair with the 13 tooth. Hunting tooth is given when the two different sprockets do not share any factors. Two odd toothed sprockets are used so that if, in future years, the ratio is desired to be changed, more choices would be available. For instance, it would be possible to change the 13 tooth sprocket out for a 14 tooth one.

The 59 tooth sprocket helped set the position of the rear axle in the frame as the teeth are not allowed to stick below the bottom of the frame per competition rules. To reduce the rotational inertia, speed holes were added to the 59 tooth sprocket. These were machined in the Engineering Fabrication Laboratory.

6.8 Eccentrics

The eccentric bearing holders were designed to provide a method of chain tensioning that was simple and easy to operate. The axis of each circle is offset by 0.5, allowing for 1 of travel front-to-back of the axle assembly position relative to the motors for a full 180 degrees of rotation. The eccentrics contain the wheel bearings which are press fit into the holder with an external lip on the outside edge to contain the bearing laterally. The same wheel bearing is also press fit onto the wheel drive flange part to form the basis of the stub shaft end assembly. The external circular edge is seated inside the axle support bottom bracket and clamped down into place with the axle support cap piece via three ?-20 bolts. The eccentric is also notched with a centerline and the axle mounts are etched with degree ticks to ensure the each half of the axle is equally tensioned.

The eccentrics were CNC machined from donated 5x5 aluminum bar stock, cut and faced down in the EFL, and then precision milled in a Mori Seiki NMV5000 CNC machine. They are designed to have an interference fit and were machined with an interior finishing pass filled with chatter to increase friction on the inside of the part. This way, when the bearing is pressed into place, it makes for better interference

6.9 Taylor Race Engineering Parts

6.9.1 Tulip stub axles

The tulip stub axles are a purchased part that combines the stub shaft with a tripod bearing housing that is part of the CV joint. This part is made of steel and slightly modified in length to fit within the axle assembly. The splines on the stub shaft interface with the wheel hub splines to transmit torque.

6.9.2 Wheel drive flanges

The wheel drive flanges are a purchased part that is made of steel and originally designed to mount wheels to a stub axle in an outboard upright. For this design, however, they have instead been used in line with the axle to connect the spindles to the stub axles. The splines on the inside of the hub interface with the stub shaft splines to transmit torque.

6.9.3 Half Shafts

The half shafts are a purchased part made of steel and are used to transmit torque from the axle stub shaft to the outboard stub shaft. The tripod bearings that fit within the tulip/bearings housings spline onto the ends of the half shafts and are held in place with two external retaining rings on either side. The half shafts are hollow, which allows insertion of a plastic rod to be fitted with a spring on one end to act as a centering device for the shaft during operation to prevent knocking.

6.9.4 Tripod Bearings

The tripod bearings are a repurposed part from the previous years car. The tripod bearing is part of the CV joint that allows for multi-directional movement of the half shafts during operation while transmitting full torque. The bearing splines onto the half shaft and is held in place with two external retaining rings on either side. The bearing also fits inside the tulip/housing on the ends of the stub shafts.

6.10 Motor Mounting Assembly

The motor mounts consist of four spacer pieces and two motor mounting brackets. The mounting brackets are made of ? plate aluminum and bridge between the two bottom bars in the motor section of the chassis using four 1/16 tabs. Two of the four spacers are placed on the ends of the mounting brackets in between the brackets. These are bolted in combination with the mounting tabs using long M8-1.25 bolts and an additional long M8-1.25 bolt joining just the mounting brackets together. The other two spacers are placed in between the top mounting holes of the motors. The forward most spacer is made of aluminum and bolts to a pair of tabs on the nearby chassis cross member with long M8-1.25 bolts. The fourth spacer is made of steel and is welded to the motor half of the chain guard. The motors are bolted to the motor mounts with the same M8-1.25 bolts in two spots. The top two motor mounting bolts will run through each of the top two spacers with M8-1.25 bolts.

6.11 Chain Guard

A chain guard or shatter shield is a requirement by the competition rules. It is intended to contain drivetrain parts which might separate from the car and also useful in preventing large chain deflections due to improper tensioning. The chain guard must be made of ? steel at least three times the width of the chain it is covers and follow the chain path including the wrap around the sprockets. It must terminate parallel with the lowest point of each respective sprocket.

Our design ran two chains parallel, therefore it was decided that a single chain guard was to cover both drive chains while leaving at least one chain width of material on either side to comply with the rules. The part was split in half to ease installation and removal, using two ? -20 bolts and nylock nuts to bolt the halves together. It is secured in two locations: bolted to the motors with a bracket welded to the top of the front half, and bolted to the chassis with a welded tab in the back.

7 Assembly Procedures

1. Axle Assembly
    (a) Center Axle Assembly
        i. First, the center axle will be bolted to Spindle 1 with a $\frac{1}{2}$-20 bolts and washer. Second, the 59 tooth sprockets will be bolted to the inside flanges of the both Spindle 1 and 2 with ? bolts, washers, and nuts. Third, the center axle will be inserted into Spindle 2. Fourth, the internal bearings and bearing spacer will be slipped onto the center axle until they fit snug against the internal retaining lip of Spindle 2. Fifth, the internal snap ring will be put in place to prevent the bearings from sliding within Spindle 2. Sixth, a $\frac{1}{2}$-20 bolt and washer will be inserted into the bearing side of the center axle to axially constrain the two halves.
    (b) Stub shaft end assembly
        i. First, the wheel bearing will be press fit into the eccentric holder. Second, the wheel drive flange will be press fit into the wheel bearing. Third, the tulip stub shaft will be inserted into the wheel drive flange from the eccentric holder side. Fourth, the nylock jam nut will be threaded and tightened onto the threaded end of the tulip stub shaft. A total of two of these assemblies will be made.
    (c) Full Axle Assembly
        i. Each of the two stub shaft end assemblies will be bolted onto the ends of Spindles 1 and 2 of the center axle assembly using four $\frac{3}{8}$-16 bolts, washers, and nylock nuts each.
    (d) Complete Axle Assembly
        i. First the 2 bottom bracket supports will be bolted into the chassis mounting tabs using M8-1.25 bolts, washers, and nylock nuts. Second, the full axle assembly will be placed into the supports with the eccentric bearing holders fitting into the cutout in the bottom support brackets. Third, the cap will be loosely bolted onto the bottom support brackets with ?-20 bolts, washers, and nuts. Fourth, the half shafts will be connected to the tulip stub shafts and sealed with a rubber boot on both sides. Fifth, the full axle assembly will be rotated for optimal chain tension and the ?-20 cap bolts securely fastened to prevent the axle from rotating eccentrically while maintaining the desired chain tension.
2. Motor Mount Assembly
    (a) The motor assembly will be assembled outside the vehicle to maximize the accessibility of certain components. First, the 13 tooth drive sprockets will be keyed and bolted on to the output shafts of each motor. Second, each motor mounting bracket will be bolted to the bottom two mounting holes on each motor with M8-1.25 bolts. These bolts will also be safety wired to each other to positively lock them into place. Third, the two spacer pieces between the bottom brackets will be bolted into place with long M8-1.25 bolts, washers, and nylock nuts. Only the internal holes will be bolted as the others need to include the tab when mounting. Fourth, the front top aluminum spacer and the rear top steel spacer welded to the front half of the chain guard will be bolted to the motors using the same M8-1.25 bolts used in the bottom mounting holes. Each pair of bolts on each bracket will be safety wired to each other to achieve positive locking. Lastly, the motor mount assembly will secured to the mounting tabs in the car with three long M8-1.25 bolts, nuts, and nylock nuts at each corner of the mounting bracket and the top front aluminum spacer.

8 Material Choice and Manufacturing

1. Axle support bottom & cap bracket: 6061-T6 Aluminum
   (a) easy manufacturability and light weight
   (b) waterjet cut to reduce manufacturing complexity and time
   (c) eccentric holding circle was finished machined by milling after being waterjet cut. This ensured a tight fit that would increase the friction holding the eccentric in place when clamped into place.
2. Spindle 1 & 2: 6061-T6 Aluminum
   (a) attainable manufacturing and lighter weight
   (b) wrap milled on a Mori Seiki NMV5000 CNC machine
   (c) machined from donated 5x5 aluminum bar stock from Coast Aluminum
   (d) Parts were machined in 3 different orientations which required two 3 axis paths and one 5 axis path.
      i. The top and bottom sections were machined in a low-setting steel vice to ensure solid part fixturing. Both 3 axis paths were machined in this vice; the first paths were the precision dimensions, followed by the less crucial sections.
      ii. To machine the center, the part was refixtured for a third time in a new vice. This vice had a smaller jaw, but sat much further off the trundle, allowing enough space for the tool to machine the part at a 90 degree angle.
   (e) Square stock was preferred because of more accurate origin indication and higher machining precision when manufacturing circular parts. Square stock is also easier to realign when removed from a vice to be inverted for machining of the other side. The circular side is fixtured in angled brackets inside the square vice. When the part is flipped, the remaining square stock is required for centering because accurately resetting the part to the same angle would otherwise be impossible and the bolt holes would not line up.
3. 59 tooth sprocket: steel
   (a) resistant to warping under impulse loading
   (b) high repeated loading creates high fatigue stress
   (c) purchased component; no other materials available
4. 13 tooth sprocket: steel
   (a) resistant to warping under impulse loading and high repeated loading which create high fatigue stress
   (b) purchased component; no other materials available
5. Center axle: A36 steel
   (a) to resist any bending from the high chain tension forces
   (b) lathed in the EFL by hand
6. Eccentric bearing holder: 6061-T6 Aluminum
   (a) easy manufacturability and lighter weight
   (b) milled on a Mori Seiki NMV5000 CNC machine
   (c) machined from donated 5x5 aluminum bar stock from Coast Aluminum
   (d) interior finishing pass filled with chatter to increase friction on the press-fit bearing
7. Motor mount spacers: 6061-T6 Aluminum

    (a) easy manufacturability and lighter weight
    (b) milled by hand aided by CNC programming in the EFL

8. Motor mount side plate: 6061-T6 Aluminum
    (a) easy manufacturability and lighter weight
    (b) waterjet cut to reduce manufacturing complexity and time
9. Tulip stub axle: steel
    (a) compact and high strength to maximize reliability
    (b) purchased component; no other materials were available
10. Wheel drive flange: steel
    (a) purchased component; no other materials were available
11. Half shaft: steel
    (a) sized for FSAE vehicle application
    (b) purchased component; no other materials were available
12. Tripod bearing: steel
    (a) sized for FSAE vehicle application
    (b) purchased component; no other materials available
13. Bearing spacer: 6061-T6 Aluminum
    (a) easy manufacturability and lighter weight
    (b) machined on a lathe by hand in the EFL
14. Chain guard and accompanying motor mount spacer: A36 steel
    (a) required to be made of steel as stated in the competition rules
    (b) spacer made of steel to enable it to be welded to the chain guard
    (c) cut, rolled, and welded in the EFL
15. Mounting tabs: 4130 steel
    (a) common tab thickness of 1/16 used throughout chassis for easy welding
    (b) plasma cut from a large sheet, ground down, and redrilled in the EFL

9 List of manufacturing processes and Associated Parts

- **CNC:** Spindle 1, Spindle 2, Eccentric Bearing Holder (x2)
- **EFL Mill/Lathe:** Motor Mount Spacers (x4), Center Axle, Bearing Spacer, Chain Guard
- **Plasma Cut:** Steel Mounting Tabs (x18)
- **Waterjet Cut:** Axle Support Bottom Bracket (x2), Axle Support Cap Bracket (x2), Motor Mount Side Plate (x2)
- **Purchased:** Tulip Stub Axle (Taylor Race Engineering), Wheel Drive Flange (Taylor Race Engineering), Half Shafts (x2)(Taylor Race Engineering)
- **Reused:** Tripod Bearings