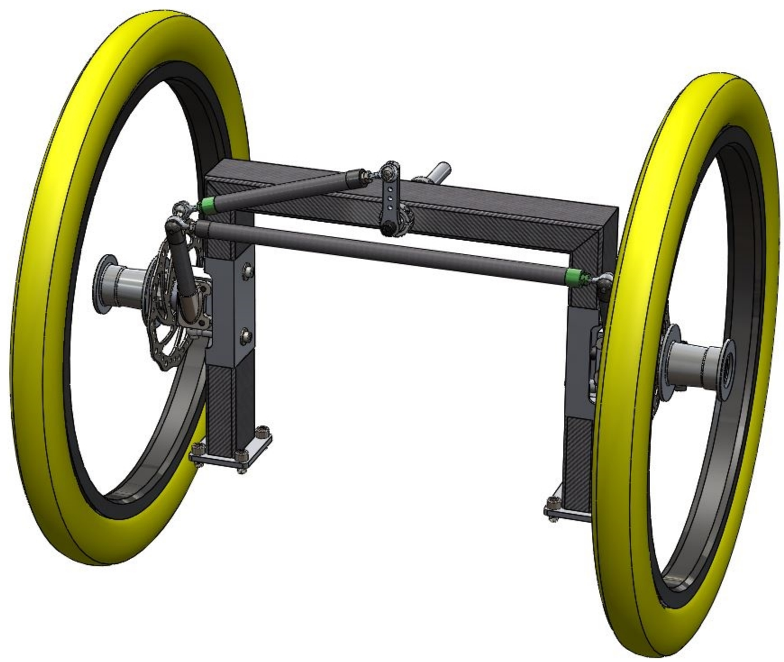
Cal Poly Supermileage Steering System

Final Design Report

June, 2017



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Executive Summary

The following report outlines the full design process that the senior project team went through to develop a steering system for the 2018 Cal Poly Supermileage vehicle from the development to the manufacturing and testing of the senior project steering system. The team was successful in reducing the weight of the steering system from 12.64 to 5.85 pounds while remaining within the cost budget provided for the Cal Poly Supermileage team. The new steering system initially failed drop testing which resulted in the uprights pulling out of the bottom carbon supports. This failure was repaired with a small redesign to the steering system and retested. Testing shows that the steering system will be strong and stiff enough for proper implementation into the 2018 Supermileage vehicle. Learnings from this report will provide the club with valuable information and a prototype steering system to use as a platform to improve and implement in their 2018 competition vehicle.

1.0 Introduction

Cal Poly Supermileage Vehicle team (SMV) is an engineering club that designs and builds a prototype vehicle with the purpose of maximizing fuel efficiency. They compete in the annual Shell Eco-marathon Americas (SEM), a competition sponsored by the Royal Dutch Shell Company, where schools across North and South America come together to find the most fuel-efficient vehicle. At the time this report was written, the club was designing a new chassis for the 2018 competition, which is where this senior project team came in. The steering system is one of the major components of the vehicle, and the club wanted a senior project team to design a reliable, lightweight, and ergonomic steering system to install in their new car.

Figure 1. Cal Poly's 2-16 Supermileage vehicle during a competition run in the 2016 Shell Eco-marathon held in Detroit, Michigan.

The main stakeholder and customer of this senior project was the Cal Poly Supermileage team, as the final product will be installed in their vehicle. According to the team, the 2016 steering system was too heavy and unreliable. During the 2016 competition, some parts failed, which they would like to avoid with the new design. Another stakeholder of the project was the driver of the vehicle. The 2016 steering system had problems interfering with track visibility due to its size, and due to colliding with the driver's body while turning. Although the SMV team and the driver shared some requirements for what they wanted in the steering system, there were some desires that did not align. For example, the club wanted to make the steering system as compact as possible, but the driver wanted more room for ergonomics. The senior project team needed to treat these conflicting requirements carefully throughout the process. Shell was also considered to be another stakeholder to this project as they put forth various rules and regulations that Supermileage vehicles must abide by in order to compete.

The team that undertook this project consisted of three mechanical engineering students. The members included Sean Michel, SMV member and previous president, Lucas Rybarczyk, the 2016 SMV president and 2015 steering lead, and Giovanni "Gio" Murillo, a new member of SMV and a "fresh pair of eyes" to assess previous SMV design decisions.

2.0 Background Information

Before proceeding to the detailed design phase of the project, the team conducted background research for the Supermileage steering system design in various areas. They first turned to basic steering geometry research. In addition, the team looked at the design of the past Supermileage car's design to gain information about what worked and what did not work. Gio also interviewed Laura Kawashiri, SMV's driver at the time for feedback on past designs and to ask for suggestions on what she would want to see in the new design. The team also did research into the most fuel-efficient car ever designed, the PAC-Car II. In addition, more conventional vehicles, namely Cal Poly Formula SAE and Baja, were looked at the gain insight on their steering systems.. Finally, the team referenced the 2017 Shell Eco-marathon Americas Chapter I rules specific for steering. Although the senior project aims to design a steering system for the 2018 competition, they will design to the 2017 rules because the 2018 rules have not been released yet and drastic rule changes are generally released at least two years prior. Detailed discussions on the results of this research are below.

2.1 Steering Geometry

Because the team is designing a steering system, steering geometry was one of the first things researched as it can make or break a vehicle's handling and stability. A prototype division Supermileage vehicle generally has three wheels – two steered wheels in the front and a single powered rear wheel. Although a Supermileage vehicle is a very unique type of vehicle, it is still affected by general trends from changing the steering geometry. One of the most valuable resources for Supermileage specific steering geometry data is a book written by the ETH Zurich Supermileage team that set the world record of 12,660 miles per gallon (mpg) in 2005. In the design of the world record holding vehicle, PAC-Car II, the designers performed a multitude of tests to gather data on how steering geometries such as camber and toe-in affects the drag on the vehicle. These tests use the same tires and loading conditions as the Cal Poly vehicle, so it is very applicable. Following is a discussion of various geometric aspects that the team found critical to the steering system's design.

2.1.1 Ackerman Steering

One of the biggest factors in a determining the geometry of a steering system is how much the wheels turn into the curve to avoid scrubbing the tires laterally while cornering. Theoretically, the optimal geometry is derived from calculating Ackerman steering angles. The basis for Ackerman geometry lies in the fact that the inside and outside wheels are on different radii while cornering. It uses linkages to change the amount the inner and outer wheel turns to compensate for the difference in the radius each wheel turns at. Ackerman geometry allows each wheel to follow a path that is tangent to the curve, theoretically allowing it to roll efficiently around corners. As illustrated in Figure 2, the inner wheel is turned more sharply than the outer wheel and each of the steered wheels are normal to a line drawn from the center of the turn to the wheel.

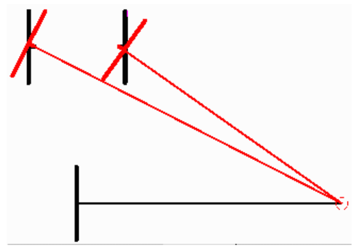


Figure 2. Ackerman steering example diagram (Peter Eland -Tricycle steering geometry – introduction).

One of the most useful resources for calculating Ackerman geometry is from a website created by a trike designer by the name of Peter Eland. He has worked in trike design since 2000 and has developed various Excel spreadsheets for calculating Ackerman steering angles for different trike steering designs. This resource was very useful when the team designed the steering uprights, knuckles and Ackerman arms. Ackerman steering geometry, however, assumes that the vehicle is slowly turning a corner, and does not take into account dynamic vehicle effects. That being said, the Supermileage vehicle takes corners at a relatively low speed, making Ackerman geometry relevant.

2.1.2 Caster Angle

Caster angle is another geometric factor in the steering system. This angle plays a great role in handling and steering feedback to the driver. Caster angle is the angle between the wheel turning axis and true vertical. A positive caster inclines away from the direction of vehicle forward motion and a negative caster leans toward the direction of vehicle motion. Figure 3 shows how caster is measured. According to a 2008 senior project, where students designed a steering system for a past Supermileage vehicle, the caster angle is key to giving the vehicle's steering self-centering and stability while traveling in a straight line.

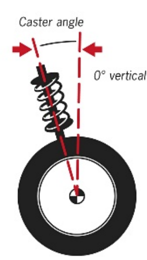


Figure 3. The caster angle is defined as the angle between true vertical and the steering axis when viewed from the side of the wheel. Is has great effect on handling and steering force required to turn the wheel.

Caster angles vary greatly depending on the vehicle in consideration. Modern passenger vehicles vary between 0°–5°. The trike designer, Peter Eland, cites trikes as having a caster between 10°–14°. Go-karts can have upwards of 20°–30° of caster. Not much research has been done on caster angles with regards to Supermileage vehicles. The 2016 Supermileage steering system ran with a caster of 12° and this was discovered to be too high based on driver feedback, as it was difficult to turn the vehicle.

2.1.3 Camber Angle

Camber is a geometric factor that directly affects vehicle handling and stability. Camber is defined as how the wheels are inclined when viewed facing the front of the vehicle. A positive camber tilts the top of the tires outward and a negative camber tilts the top of the tires inward. Figure 4 shows what the different camber configurations look like.

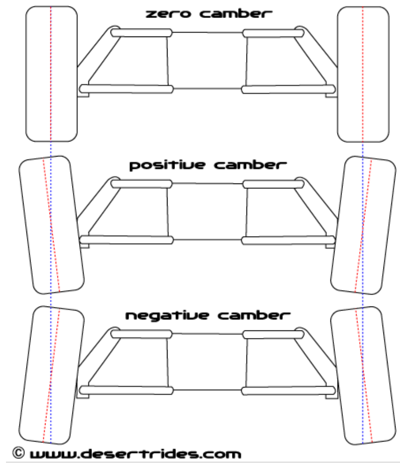


Figure 4. Camber angle is the angle of the tilt in the wheels when viewed along its longitudinal axis, and can affect vehicle stability and cornering characteristics. (Town Fair Tire)

A negative camber is generally preferred as it improves the lateral stability of the car, however there is a tradeoff with rolling resistance. The previous 2016 Cal Poly SMV steering system was designed for −3° of camber, however poor material choice, manufacturing and assembly of the steering system caused the camber to become nearly 0°.

The designers of the PAC-Car II cite camber as being one of the more important geometries that need to be taken into account when designing a Supermileage vehicle. The designers of the PAC-Car II performed testing to quantify the effects of camber on rolling resistance, which produced the plot seen in Figure 5.

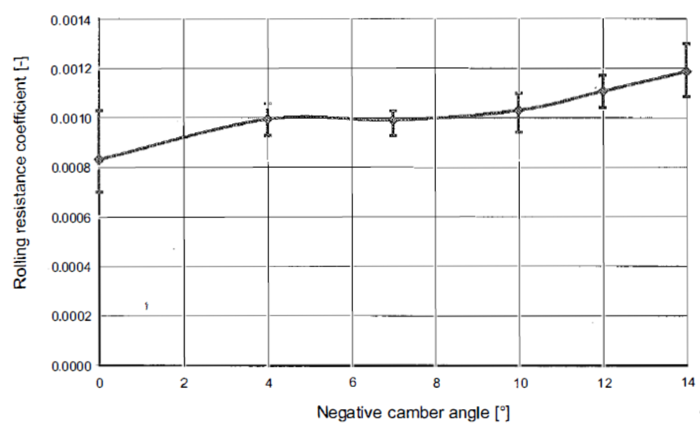


Figure 5. Negative Camber angle and its effect on rolling resistance. Rolling resistance is seen to be minimal when the camber angle is 0˚. (The World's Most Fuel Efficient Vehicle)

Unsurprisingly, neutral camber is best for rolling resistance using Michelin Supermileage competition tires. However, at 0˚ of camber, the wheels were slightly unstable due to oscillations in lateral force. With slight camber, the lateral forces towards the centerline of the vehicle provide more stability and what they called 'lateral guidance'. This likely helps with reducing rolling resistance. With this data in mind, the PAC-Car II team chose a camber angle of -8º in order to minimize frontal area affecting aerodynamic drag while providing stability (*The World's Most Fuel Efficient Vehicle*).

2.1.4 Toe Angle

The toe angle is the angle between the tire and vertical plane when measured from a top down view of the vehicle. When a vehicle's wheels are tilted inward toward the direction of forward motion they are said to be toed-in and in the opposite case, they are said to be toed-out. Figure 6 provides a diagram of two toe configurations on a normal passenger car. Not pictured is a setup with perfectly parallel wheels which is said to be neutral toe. Toe angle can affect the handling of the vehicle and stability, however even slight increases in toe angle will significantly increase tire drag.

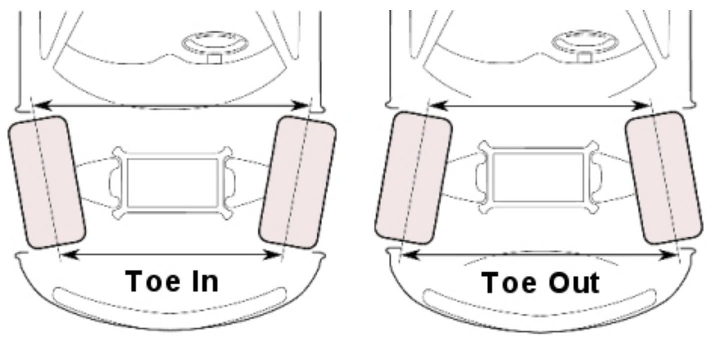


Figure 6. Toe Angle can have great impact on the handling and rolling resistance of the wheels. (Town Fair Tire)

The PAC-Car II research group found that slight toe-in can affect the 'lateral guidance' much like camber. However, toe-in can significantly affect drag if overdone, thus it is important to control this angle. Figure 7 below illustrates the effects of toe-in angle on tire drag.

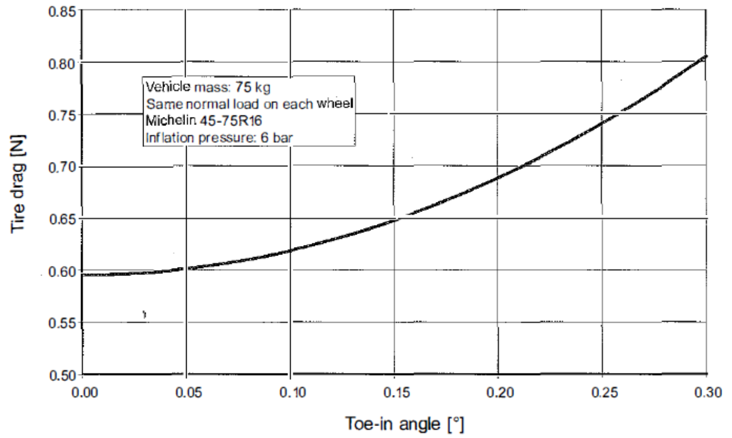


Figure 7. The effect of toe-in angle is plotted against tire drag. (The World's Most Fuel Efficient Vehicle)

Using this data, the senior project team used a toe-in angle of 0˚ since camber will also provide the lateral tracking needed for vehicle stability. Since tire drag is significantly affected by the toe-in angle, the toe angle was designed to be adjustable after assembly to counter act any toe-in caused by tolerances in components or loading.

2.1.5 Steering Axis Angle (King Pin Inclination) and Scrub Radius

The steering axis angle (or king pin inclination) of a steering system is a geometric angle that is created by the angle that the steering uprights actuate around in order to turn the vehicle. Figure 8 shows how the steering axis angle is measured relative to the center of tire contact.

The distance "D" on the figure is called the "scrub radius". The team's research indicates that as close as possible to 0 inches of scrub radius is ideal for lower speed cars as this helps with vehicle handling. A near 0 inch scrub radius is also said to have the lowest tire drag, however a study could not be found to verify this claim with regards to Supermileage vehicles. Scrub radius is more important for vehicles that have a suspension system due to suspension effects and as such is less important for Supermileage vehicles which generally do not have suspension. Ideally, the steering axis angle should intersect the center of where the tire contacts the road in order to reduce steering scrub and reduce energy lost when turning.

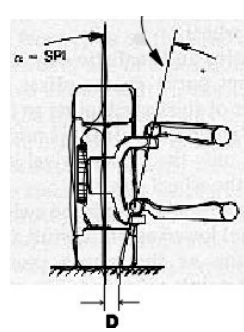


Figure 8. Steering axis angle measurement is the angle of the steering axis when viewed down the longitudinal axis, much like camber. It also helps in steering feedback to the driver and minimizing tire wear around corners.

2.1.6 Track Width and Wheelbase

The last two major geometric considerations in the steering system are the track width and the wheelbase. The track width is defined as the distance between the centerpoints of the two front wheels in the vehicle. The wheelbase is defined as the distance between the centerpoints of the front and rear wheels of the vehicle. Figure 9 summarizes how these measurements are made.

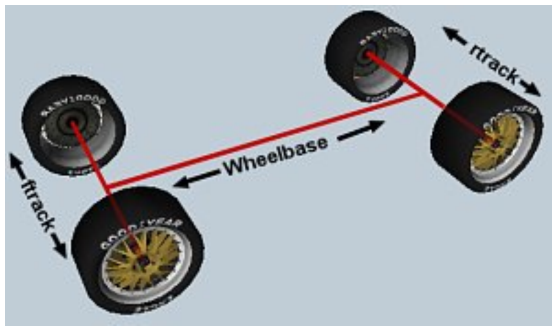


Figure 9. Track width is the distance between two adjacent tires and wheelbase the distance between the front and back wheels. The Supermileage vehicle only has one rear wheel, so the track width only refers to the distance between the front wheels.

2.2 Cal Poly 2016 Supermileage Car

The 2016 SMV car's steering system, a simple 4 bar steering system, was designed in SOLIDWORKS as pictured in Figure 10. It was fabricated using a variety of carbon fiber layups and manual/CNC machining of aluminum parts. The main problem with this steering system was that it suffered a structural failure in the main carbon fiber structure while at competition.

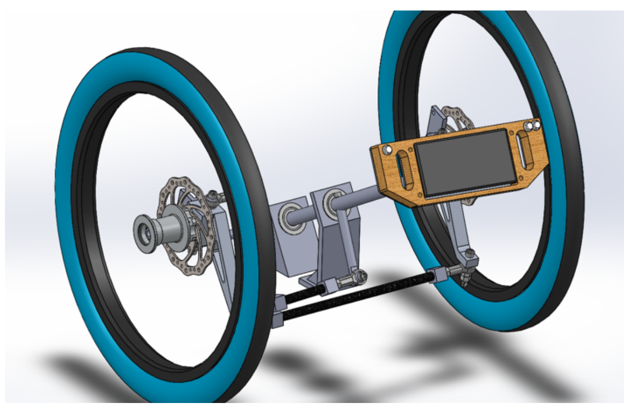


Figure 10. A SOLIDWORKS model of the steering system installed into the 2016 Supermileage vehicle.

As seen in Figure 11, the carbon fiber holding the vertical steering supports delaminated from the removable steering baseplate. Even though the car was tested thoroughly at the Allan Hancock Emergency Vehicle Operations Course in Lompoc, California, the team failed to account for the rougher road conditions of Detroit, Michigan.

Figure 11. Photo of the steering plate taken during competition after the car was brought in for repairs. A structural failure can be seen in the carbon fiber steering system.

Another issue with the 2016 steering system is that many of the components were overdesigned to the point where the steering system became a significant part of the weight of the car. Most components were not designed with calculations to back up the designs so many of the parts ended up heavier than necessary. Table 1 breaks down of the weight of the steering system.

Table 1. Weights of the 2016 Supermileage steering system.

Steering Component	Weight [lbs]
Total Steering System Weight (with wheels)	15.67
Subframe, steering column assembly, knuckle mount	9.74
Steering wheel, bolts, sheet metal brackets	1.93
Knuckles, axle ends and brake calipers	0.97
Wheels with tire, rim, hub, sealant and brake rotor	3.03

The total weight of the steering system was approximately 15.70 lbs As the SEM competition cars are designed for high fuel efficiency, weight is a major concern for the club. Without the wheels, the steering system weighed 12.64 lbs This is the number that the team will aim to reduce as the same wheels will be used for the 2018 vehicle.

The previous driver of the Supermileage vehicle said she faced several issues when using the previous steering system. The driver had to exert a significant amount of force to turn the vehicle in tight turns. Additionally, the steering wheel itself was too low and big. It collided with the driver in tight turns, forcing her to lean into the turn in order to use those extra degrees of turning. Since the steering wheel is too big, the driver also has less visibility available to them. This issue, however, also depends on the top half of the car that holds the windshield which can also be mitigated in the chassis design. Driver issues are discussed further in a later section.

Tests with this car were performed to gather data and compare it to what was actually designed of the steering system. These tests were also performed to confirm some of the issues with the previous system, following are some of the findings.

- Turning radius for a right-hand turn is 23.4 feet (7.1 meters) and the turning radius for a left-hand turn is 21.7 feet (6.6 meters). Ideally, these values would both be the same, however they are both under the required 26.2 feet (8 meter) turning radius.
- The steering system removed from car and unloaded required 0.66 lbs of force to turn it in either direction.
- The steering system in the car with Sean also in the car took 12 lbs of force to turn the steering in either direction while the car was stationary. This is similar in weight to the normal, lighter driver sitting in the car as the engine was removed from the car during this test.
- The steering system in car with Sean in the car took 7 lbs of force to turn the steering in either direction while the car was moving at speeds averaging between 2 mph to 10 mph.
- The steering wheel turns a maximum of approximately 10.5° in either direction to actuate the wheels and has nearly 1:1 steering.
- The steering wheel has approximately 3° of slop in either direction. Most of this slop comes from the go-kart quick release used in the column; however, there is also small play in the steering linkages.

Some of these issues relating to the driver also stemmed from issues with the steering geometry. The caster of the previous car was 12°, which is likely too much for the vehicle's application. As mentioned previously, the camber was designed for approximately $-3°$, however when the car was manufactured the inaccuracy in the carbon supports reduced the camber to nearly 0°. The king pin inclination angle was designed to point directly to the contact patch of the tire and the road.

2.3 Driver Interview

As part of understanding the issues confronting the current vehicle, Gio interviewed the current SMV driver. Since the vehicle is so cramped and small, only one member of the team has been able to drive the vehicle. Laura Kawashiri, currently a mechanical engineering graduate student, has driven the past three SMV designs. In her opinion, the most recent vehicle has been the most successful as far as ease-of-use and overall design of the steering system. This is because the actuation felt solid and sturdy while also making her feel safe from harm by the system. The worst, most difficult to use steering system in her opinion was the 2014 vehicle, which had two rudder-like levers used for steering, rather than a traditional steering wheel. When comparing the two vehicles, the button placement on the steering wheel of the current vehicle was more intuitive and the steering system had less resistance, making it easier to turn.

Focusing on the 2016 vehicle, Laura had several suggestions and commented on improvements that could be made for the new steering system design. First, the wooden steering wheel currently in place had a softer feeling compared to a previous design made of carbon fiber that had sharp edges. However, she thought the buttons could be placed more intuitively on the steering wheel, so that she can instinctively use them rather than having to look down at the steering wheel. Furthermore, the steering wheel got in the way of her view of the track, significantly reducing visibility shown in Figure 12.

Figure 12. A wooden steering wheel with a phone to display information was used in the 2016 Supermileage vehicle. The steering wheel is almost touching the driver even in a neutral position.

A big concern Laura had with the 2016 steering system is that when she had to make tight turns on the track, the steering wheel hit her stomach and she had to lean into the turn to rotate the wheel completely. On the topic of driver comfort, the brake and gas pedals were directly at the front end of the vehicle. She had to place her feet on the sides of the chassis to not rest her feet on them and accidentally apply braking pressure. She described this position as an uncomfortable, pigeon-toed position. She suggested placing the pedals to the sides so one can rest their feet in the middle. The tie-rod of the steering system ran directly underneath her legs, so she had to bend her knees while keeping her feet to the side of the chassis. The tie rod can be seen as the aluminum rods that run parallel to the ground in Figure 13 . She also suggested placing a cover over the tie rod so she can rest her legs and not worry about increasing the friction in the steering system or damaging components.

Figure 13. Tie rods from Cal Poly's 2016 vehicle. The tie rods were placed below the knees of the driver to allow for movement.

The previous vehicle had steering support columns that extended from the floor of the chassis to the ceiling. She prefers the smaller support columns that are currently installed as they obstruct her view less and are more comfortable on her knees. However, the support columns were not designed well and failed by delaminating from the baseplate during a competition run. Reliability by designing and building the supports correctly the first time is something Laura emphasized.

Steering resistance is another important driver concern. Laura thought that the 2016 car had the best steering feedback up to that point. It was not as easy to drive as a commercial vehicle with power steering, but she did not have to exert a significant amount of force until about 10° at the steering wheel. At that angle, she had to apply about 10 lbs of force.

In summary, the main features Laura wanted in the new steering system were increased visibility, increased reliability, better feet placement, ways to avoid hitting the tie rods and ways to avoid hitting the steering wheel in tight turns. The team aimed to make the steering system as reliable, intuitive and ergonomic as possible so that the new driver for the 2018 vehicle does not come across the issues Laura faced and aimed to diminish driver fatigue during competition.

2.4 PAC-Car II

The PAC-Car II, pictured in Figure 14, was a Swiss Supermileage car project developed at ETH Zurich (Swiss Federal Institute of Technology) and is recognized as the most fuel-efficient car in the world. In 2005, the PAC-Car II, achieved a gasoline equivalent of 12,660 mpg (5385 km/l) at the Shell Eco-marathon Europe competition in Ladoux, France using hydrogen fuel cell, setting a world record (*The World's Most Fuel Efficient Vehicle*).

Figure 14. PAC-Car II being tested on a track by the ETH Zurich Supermileage team.

The features of the car overall are very impressive with a drag coefficient of 0.075 and an overall chassis weight of 64 lbs Unfortunately, the PAC-Car II used a rear wheel steering system which is now banned by the competition rules due to several accidents rear wheel steer caused in subsequent years. The creators of the vehicle wrote a detailed design document where they discussed design decisions and research that went into the production of the PAC-Car II called "The World's Most Fuel Efficient Vehicle: Design and Development of PAC-Car II" which served as a useful reference for the senior project team.

2.5 Cal Poly Formula SAE and Baja SAE Steering Systems

Two other Cal Poly-designed steering systems were investigated; Cal Poly Formula SAE team's and Baja SAE team's. Both of these teams use a wheel as the main driver input into the steering actuation, as required by their competition rules. In order to actuate the front wheels of the car, both teams use a rack and pinion style gearbox with connecting rods running from the rack to the steering uprights as seen in Figure 15.

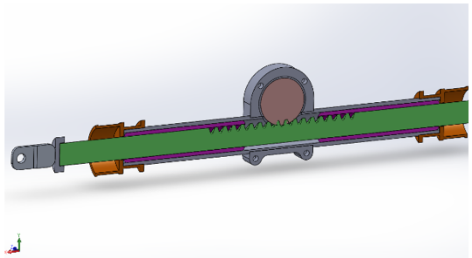
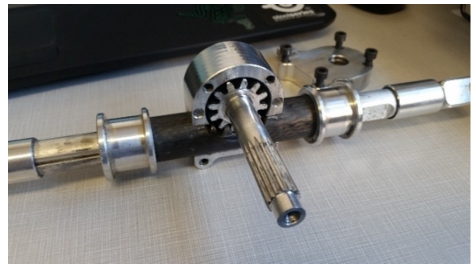
 

Figure 15. SOLIDWORKS CAD file for current Baja rack and pinion (left) and Formula SAE's senior project rack and pinion steering assembly.

Both of these rack and pinion setups were designed and manufactured as senior projects for their respective clubs several years ago and have been repaired and improved upon throughout the years. The critical design factor of a rack and pinion system, if one was to be considered for a Supermileage project, is the pitch diameters of the two gears. This is a factor in determining the steering ratio of the system; the ratio of degrees turned at the steering wheel to degrees turned at the front wheels. The Baja rack and pinion has a steering ratio of 4.18 and the Formula SAE rack and pinion has a steering ratio of 3.14. These steering ratios when compounded through the whole steering system would create an even greater steering ratio due to twisting in the steering column and Ackerman geometry. This large steering ratio could create issues in the Cal Poly Supermileage vehicle, as the driver does not have much room to turn the steering wheel before it jabs into them. As a reference, the previous 2016 Cal Poly Supermileage car had a steering ratio of roughly 1:1. In order to get a similar steering ratio from a rack and pinion, gears with a pitch diameter of only 0.25 inch would have to be used.

Another potential issue with a rack and pinion style system is the overall slop of the system. The current Formula SAE Steering Lead said slop was an issue in the design of their current system. The combined play in their steering wheel quick release spline, steering column, spline into the rack and pinion, rack and pinion interaction and connecting rods created a slop of about 7°. As the 2016 Supermileage car could only turn approximately 10.5° left or right, this would impact the max turning angle of the steering wheel.

2.6 Shell Eco-marathon Rules

Every year, the Shell Eco-marathon organizers publish a rulebook that details various rules that the vehicle has to abide by. Several of these constraints pertain to the steering system and other subsystems that interface with the steering. Without meeting these requirements, the vehicle will not be allowed to compete in the competition, making the design useless.

The team combed through the 2017 Eco-marathon rules to find any rules that pertain to the steering system. Following is a list of all rules that must be followed:

- Vehicle track-width must be at least 19.7 inches (50 centimeters) measured where the tires meet the ground
- The vehicle must be steered by the front wheels only
- The turning radius must be a maximum of 26.2 feet (8 meters) at the outer wheel
- Steering system must be designed to prevent the wheels from hitting the vehicle body or any other components of the vehicle
- Each wheel must have its own brake

- Both front brakes must be activated by one lever
- Brakes must be able to be activated without the driver's hands leaving the steering system
- Brakes must have a mechanism to prevent the driver from adjusting them during competition runs

The "vehicle track width" requirement affects the decisions for the overall size of the steering system and the envelope of the entire vehicle. As mentioned before, Shell limits the vehicles to front wheel steer only due to safety reasons. This limits design possibilities, such as a lower profile rear wheel steering system. With the maximum turning radius set by the rules, the team needed to design the steering geometry to turn efficiently across the entire range. Designing the wheels to turn so they do not hit the vehicle body was also part of the senior project team's direct scope, though it is directly dependent on chassis design decisions. The rules stating that each wheel must have a brake required us to design a brake mount for each wheel.

3.0 Objectives

The main purpose of this project was to develop a new steering system for SMV. Taking into consideration the rules put forth by Shell Eco-marathon, Laura's experiences with past Supermileage Vehicles and competitors' vehicles, the team was able to create a list of customer requirements:

Table 2. Customer requirements that are pulled from competition rules, the team, and the driver. Shell (1), Vehicle Driver (2) and Cal Poly Supermileage Team (3).

Requirement #	Customer	Requirement
1	1,2,3	Structurally sound
2	3	Lightweight
3	2	Easy to operate
4	1,3	Complies with competition rules
5	2	Driver space
6	2	Doesn't obstruct vision
7	2	Easy access to brakes
8	2	Intuitive buttons
9	1,2,3	Mechanically reliable
10	3	Minimal profile
11	3	Cost within team budget
12	3	Easy to service
13	3	Efficient steering geometry
14	3	Adjustable toe
15	3	Adjustable caster
16	3	Adjustable camber

Using the customer requirements, the team developed a Quality Function Deployment (QFD) tool to translate them into engineering specifications. The team created a "House of Quality" chart to relate the requirements put forth by the customers to a list of specifications. The House of Quality can be found at the end of the report in Attachment A.

To create this QFD chart, the team created a column of their customers' requirements and compared them to various engineering specifications for the project. If the customer requirement was highly correlated with the specification, it was given a value of 9. If not, the correlation was given a value of 3 (medium) or 1 (low).

The values assigned to each correlation were summed for each individual specification. These values were assigned for relative importance from 1 to 5, with 5 being the most important, to each specification. This was multiplied by the correlation sum and compared to the value of every other specification as a percentage of the total. The list of engineering specifications developed from the QFD is presented in Table 3 and each specification is discussed afterwards. The table was updated for the changes that the team encountered while preparing for CDR.

Table 3. Engineering Specifications based on Customer Requests. (A) Analyze, (T) Test, (I) Inspect

Parameter Description	Requirements or Target	Tolerance	Risk	Compliance
Geometry angle change	Camber 0.5˚ / 0˚ Toe-in	±0.05°	M	A, T
Pass drop test w/250 lbs	6 inches minimum	–2in	M	T
Weight w/o wheels or brakes	< 6 lbs	+1 lb	M	A, T, I
Driver steering force	< 7 lbs while driving	+1 lb	L	T
No excessive play	0.5° left or right	±0.25°	M	T
Track width	52.5 cm	±2.5 cm	H	A, I
Minimum turning radius	≤ 8 m at outside wheel	0	H	A, T
Prevent wheels from hitting chassis or other components	No contact	0	H	A, T
Driver clearance from steering actuation	> 0.5 inches	–0.1 inch	H	A, I
Window area coverage	< 25%	±5%	M	I
Steering system cycling capabilities	>300 cycles		M	A
Size	Fits inside 2018 vehicle	-	M	A, I
Total parts cost	< $500 (parts and labor)	$100	M	I
Disassembly time for two people	10 min.	±2 min.	L	T

If the vehicle cannot be entered into the competition because the specification was not met or the function of the steering system would be severely compromised, it was labeled high risk. If not meeting the goal would not compromise the function, but may adversely affect performance, the specification was given a medium risk. If not meeting the specification would not affect the function of the steering system or had an alternate solution, it was labeled low risk.

The most important specifications developed were related to the Shell Eco-marathon rules. The rules related to the steering are as follows: the minimum turning radius of the steering system must be at a minimum of 8 meters, the track width must be at least 50 centimeters and the tires must not touch any part of the chassis. These specifications totaled 26.7% of the design importance. These are the most important specifications because if the design did not meet them, it would not be able to compete, and as such were labeled high risk.

Building a reliable, light weight steering system was next in order of importance. By placing a limit on how much the system deflected under load, the team planned to ensure that the geometry remained stable. Similarly, by withstanding an impact from a fall of about 6 inches, the team designed the steering system to prevent changes in steering geometry if the car rolled off a curb under full load. These two specifications limit bending of the materials in the steering system. Another reliability specification was to design the steering system to last more than 300 cycles. A cycle meaning the steering wheel is rotated fully clockwise and counterclockwise. These specifications totaled 17.3% of the design importance. These specifications were labeled medium risk since the steering system would still function and be competition ready if the specifications are slightly off target.

Opposing the stiffness of the steering system are the limits on weight and size. The team aimed to manufacture a steering system that weighed 38% less than the current system; 6 lbs without the weight of the wheels and brakes. A middle ground had to be found between lightweight, small size and high stiffness by considering the use of composite materials in the design. These totaled 13.6% of the design importance. These were also labeled as medium risk, since these specifications are not critical to the function of the system, but not meeting them may adversely affect the performance.

Moving on to specifications for driver efficiency, several specifications were made to address the issues with the current vehicle. First, it was important that the steering wheel would not interfere with the driver. The steering wheel must have at least a half inch clearance from the torso and legs of the driver so that they can use the full steering capabilities without twisting or hitting their bodies. Next, the driver must be able to see the track sufficiently to navigate the course effectively. As such, the steering wheel must not cover more than 25% of the windshield. These specifications totaled 15.6% of the design importance.

Driver ergonomics are also an important factor in the design of any steering system. However, a Supermileage vehicle is not one designed for driver comfort. Maximum fuel efficiency is more important than driver ergonomics and as such, these specifications scored lower. The steering wheel must not provide more than 7 lbs of resistance during the maximum turning radius. This was specified to ensure the driver is not constantly fighting the car to stay in a turn and to reduce driver fatigue. For better steering feedback, the play within the steering system should be less than 0.5°. These two specifications totaled 8.3% of the design importance.

Designer interaction with the system and overall steering budget were also two incredibly relevant specifications the team considered. The steering system must be able to be disassembled by two people within 10 minutes in case emergency repairs or replacements are necessary. During test days or race days, every minute helps to capture as much data or ensure a position in the next round of racing. Creating an easy to assemble and disassemble system ensures the best use of time. In addition, the club aimed to spend a maximum of $500 in parts and outsourced labor, but this number is slightly flexible if sponsorships or other sources of income are found for the club. These specifications totaled 7.6% of the design importance, with cost accounting for 6.2% of that.

In short, the overall scope of the project was to design, fabricate and test the front-end steering system for the 2018 Supermileage vehicle. This included the attachment of the front wheels to the car, the actuation of these wheels, the steering mechanism through which the driver will actuate these wheels and a way to mount brakes to these wheels. The team also considered ways to prevent contact between the driver and the wheels and the wheels and the chassis. The brake actuation mechanism will be left to the Supermileage team to design.

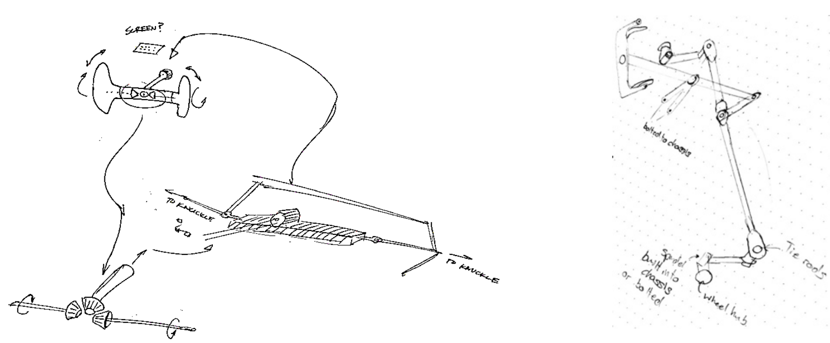
4.0 Design Development

This section details the ideation and idea selection processes that were used to find the most suitable design to use for the Supermileage steering system. Throughout ideation sessions, the project was split into two overarching categories: driver interface and steering actuation. This allowed for more concentrated efforts into each portion of the design. Following the ideation sessions, a day was spent prototyping of some of the ideas using K'NEX. These models helped to visualize driver interface concepts. To narrow down the number of concepts, Pugh matrices were developed to rate the solutions and decide the top solutions for each category.

4.1 Ideation Sessions

Ideation consisted of three sessions. The first session involved the senior project team members writing ideas on post-it notes and posting them into a morphological chart with the two categories mentioned above. These sketches were quick and meant to generate as many ideas as possible from any number of inspirations. Some of the initial driver interface ideas generated included joystick, rudder, drive-by-wire steering, and several U-shaped steering inputs. Concepts for actuation involved bevel gears, tie rods running underneath the carriage, tie rods mounted on an upside-down U-shaped frame, and a traditional rack and pinion.

The second ideation session consisted of a concentrated "brain sketching - scamper" session where five minutes were spent on 6 categories of known steering actuation systems. The 6 categories were solid linkage, rack and pinion, wrist steer, rudder, push/pull, and the final category was any creative mechanism that one can think of. Senior project team members took the five minutes to sketch their Supermileage-friendly version of each of the categories. These sketches combined many of the ideas that were thought of during the previous ideation session into a more comprehensive drawing. Some of these sketches are shown on Figure 16 and Figure 17.

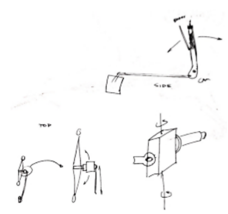


(a)
Twist-Steering and Rack and Pinion

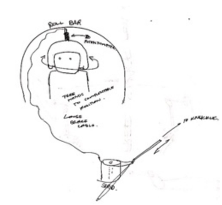
(b)
Solid-Axle Actuation

Figure 16. Sketches of twist-steering and solid axle actuation made during ideation sessions.

The first notable sketch, Figure 16(a), modeled a steering wheel with internal bevel gears. The idea was that the steering wheel would be able to twist to provide the actuation needed to turn the steering column. The steering column would then actuate a rack and pinion, which would push the tie-rods, thus turning the wheels. This idea would allow a steering ratio to be implemented into the steering system that would allow the driver to better control the vehicle without having to turn the whole wheel. Figure 16(b) demonstrates a solid-linkage actuation system similar to a go-kart steering system. This is a similar type of steering system used in the 2016 Cal Poly Supermileage vehicle. Additionally, the sketch shows a U-shaped steering wheel with brake levers attached to the steering column.



(a)
Push-Pull Steering Mechanism



(b)
Smart Steering

Figure 17. More sketches made during idea generation.

Next, Figure 17(a) shows a concept for a push-pull steering mechanism. The idea was that a lever with a cam would be used to actuate the motion of the wheels by rotating the spindle with a solid link. This was much like the steering system of the PAC-Car II, but adapted for front wheel steering, instead of their rear wheel steer. Finally, Figure 17(b) is a concept where the driver has a potentiometer attached to their helmet, which sends electrical signals to a servo, controlling the motion of the linkage attached to the wheels. This concept would allow the driver to keep their hands free, allowing the driver to reach for buttons and brake levers where it is more comfortable.

The third brainstorming session was another morphological chart session in which ideas on post-it notes were posted onto a board with categories. However, this time, the whole Cal Poly Supermileage team took part in the session. With approximately ten members, many more ideas came of this session. Some new ideas for driver interface included chains/wires/ropes/pulley system, foot pedal steering, variable ratio mechanism, lean-steering, and remote controlled steering. New actuation ideas included hydraulic actuation, electric actuation and belt pulley systems.

The team also considered hydraulic actuation and electric actuation as possibilities for steering actuation methods. Hydraulic actuation would consist of using a system of hydraulic fluid powered pistons attached to the driver input and to the steering arms in order to actuate the wheels. Electric actuation would use a system of servo motors controlled by the driver to actuate the wheels. As per competition rules, if this system were used then some control system would also have to be included to self-center the wheels in case the driver input mechanism fails. A pulley steering system would use a series of pulleys wired into the driver input and also wired into the Ackerman steering arms. In order to actuate the wheels, the driver would pull one side of the steering wheel closer to them in order to put force on a steering arm and turn the wheels.

4.2 Prototyping

As a steering system has a large human interface portion, prototyping was essential to idea selection. Since the members of the team are too tall to fit in the actual vehicle, a mockup of the vehicle's track width and height was created using two wood 2x4s to evaluate the ergonomics of each of the team's driver interface concepts. Figure 18 shows team member Lucas holding a prototype U-shaped steering wheel, testing how much room there is available to physically turn the wheel. Some of the more feasible ideas generated during ideation were turned into physical prototypes using K'NEX and foam core.

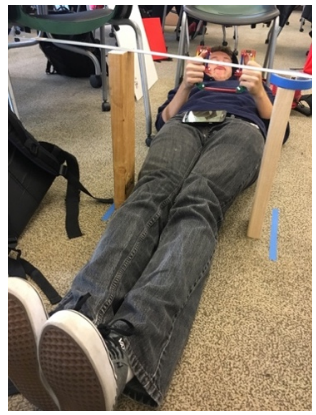
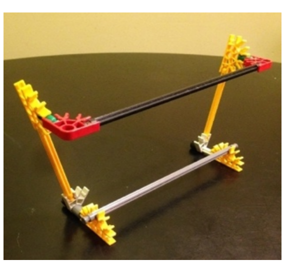
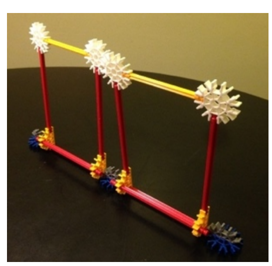


Figure 18. Lucas evaluates the ergonomics of a steering concept during a prototyping session.

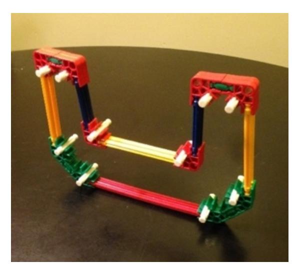
Some of the concepts evaluated during the prototyping session included a U-shaped steering wheel, joystick steering, foot pedals, and steering with a twistable steering 'wheel'. During the prototyping session, a new idea of directly steering with the tie rod, a linkage that connects the two front wheels for stability, was thought of. During prototyping, many ergonomic factors that influence the design surfaced. First, the spatial constraints of a Supermileage vehicle were much tighter than expected. The driving position would not allow for many movements that a typical passenger vehicle would allow. For example, there was little room to move the arms above the elbow. Systems such as a push pull system that require large movements of the entire arm fell out of favor. Second, the steering mechanism could easily block the driver's view because of the reclined position. As a result, seeing over the steering system easily became a priority for the team.



(a)
Four Bar Linkage – Steering Bar



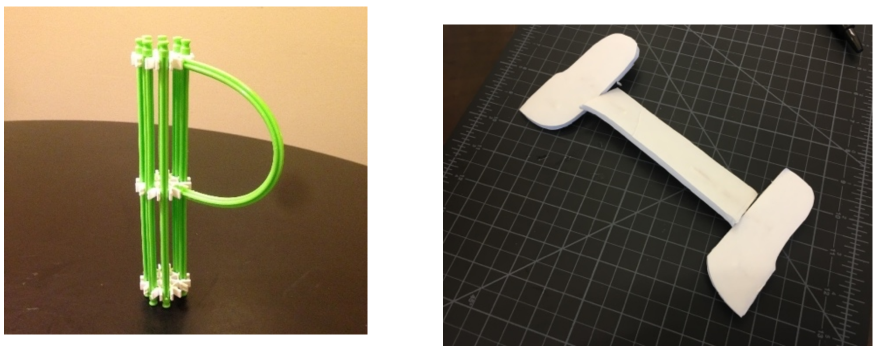
(b)
Foot Pedal Steering



(c)
U-Shaped Steering Wheel

Figure 19. Some of the prototypes evaluated during the prototyping session is evaluated.

The "Four Bar Direct Linkage" seen in Figure 19(a) was modeled to see if an ergonomic steering wheel based on twisting motions of the wrists could be created. The driver would hold onto the vertical lighter colored K'NEX pieces and actuate the top black bar by moving their wrists left and right. This black piece would be connected directly to each Ackerman arm to turn each wheel left and right. The team found this idea worth further investigation due to its simplicity and weight savings. The idea also did not critically obstruct driver view; however, many questions remain about its ergonomics and steering input force. Foot pedal steering shown in Figure 19(b) was another idea the team prototyped. Initially, this idea was thought to be able to free the hands to better actuate brakes and buttons, however, after experimentation with the ergonomics of this design, the team found it very difficult to modulate the pedals accurately enough to precisely steer a vehicle and found the motion unintuitive. The foot pedal system also blocked visibility much more than other concepts as the knees have to be raised to steer. The U-shaped steering wheel prototype in Figure 19(c) was modeled to test the visibility available to the driver with this design. It was intuitive and small enough to warrant further analysis.



(a)
Joystick Concept

(b)
Twistable Steering Wheel

Figure 20. Two more prototypes evaluated during prototyping session.

A joystick prototype was created as another type of driver interface, shown in Figure 20(a). This helped demonstrate the range of motion available if a joystick was placed between the legs of the driver or to either sides of the driver. Additionally, the joystick produced the idea of having a button placed in the palm of the driver for the dead-man's switch that automatically shuts off the engine, required per the competition rules. The twistable steering wheel in Figure 20(b) was an idea generated in the second ideation session. The concept was modeled using foam board and toothpicks to simulate the twisting motion. The prototype was made to test how comfortable it would be to twist the hands to steer rather than the traditional turning of a wheel. It was found that the twisting motion was feasible within the space constraints and it did not block the visibility of the track. However, many questions remain on its intuitiveness and steering feedback, which would require further testing.

4.3 Concept Evaluation and Selection

Following idea generation and prototyping, the team chose five concepts for driver input and four concepts for steering actuation to further analyze. These ideas were assessed using weighted decision matrices to determine the overall best design from the two categories. A decision matrix consists of a comparison of proposed concepts to a datum, in this case the 2016 steering system, using common criteria. Each concept was scored by deciding whether it fulfills the criteria better than, less than or the same as the datum. Each of the criteria was weighted based on importance and the weighted sum was used to choose the best design.

Ideas that made it to design evaluation from ideation were as follows: using a direct input steering bar, steering controlled by foot pedals, a U-shaped steering wheel, joysticks placed at the sides of the driver that translates side to side twisting to steering motion, and a twisting steering wheel that uses fore-aft twisting. The steering actuation ideas that reached the design evaluation phase were as follows: a hydraulic piston actuation system, a rack and pinion, a chain or belt turning mechanism and an electric servo motor controlled system. All of these ideas for both categories made it through ideation because they seemed like the most feasible ideas that would satisfy all customer requirements while not being too outlandish, expensive, against competition rules or un-manufacturable within the timeframe of the project.

4.3.1 Second Driver Interview

Following idea generation and prototyping, the past driver, Laura, was interviewed for a second time to receive her feedback on the ergonomics and feasibility of some of the ideas. First of all, she stated that she would much rather see a traditional steering wheel over other interfaces like the twist steering wheel. Her reasoning behind this reflects the importance of making an intuitive steering interface that uses muscle memory from operating a regular car. She argued that a traditional steering wheel, like the one currently installed in the 2016 vehicle, also allows the driver better leverage when negotiating a corner. She described that under tight cornering, she naturally leaned into the turn and pulled down on the steering wheel. From her experience, the ideal placement of the steering wheel allows the driver's elbows to be at about a 90° angle, with their thumbs in a neutral position compared to her wrists. Her input on driver interface was taken into consideration when creating the decision matrices used to narrow down the ideas. A category of "intuitive steering" was added to the driver interface decision matrix and weighed a 5 out of 5.

During the second interview, Laura noticed that the concept was missing a heads-up-display (HUD). She would like the HUD to show speed, average speed, elapsed time and lap time similar to how the Race Capture data system was integrated into the 2016 vehicle. Similarly, Laura also suggested a scheme for the button placement. She stressed making the throttle a button, preferably on the right side of the steering wheel. The dead-man's switch would go on the left-hand side of the wheel. Finally, the ignition and horn can go on the right-hand side or in the middle of the steering wheel.

4.3.2 Decision Matrices

More factors considered in the decision matrices were the manufacturability and reliability of the proposed steering concepts. Manufacturability was important in choosing the driver interface because the Supermileage team would prefer to be able to create it in-house and be able to make necessary repairs with ease. Ideally, it would only be made once and repairs would be rare, leading it to be weighed a 3 out of 5. Reliability, on the other hand, was weighed a 4 out of 5. Similarly, weight was weighed a 4 out of 5, so finding a common ground between reliability and weight was critical. Ergonomics was important to the driver, and is closely related to intuitive steering, scoring 4 out of 5 and 5 out 5, respectively. Cost to purchase or manufacture parts was very important to the design, causing it to be weighed 5 out of 5. Other factors important to the driver are visibility, minimal introduction of play and steering force needed by the driver to turn, each weighing 3 out of 5. Good button placement would be beneficial to the driver, but not essential to function so it is weighed a 2 out of 5. Finally, assuming repairs need to be made during testing, the steering system must be somewhat easy to disassemble and reassemble, weighing it a 1 out of 5.

Table 4. Decision matrix used to evaluate ideas for the driver interface. From this analysis, the team found that a U-shaped steering wheel is the best design choice for the Supermileage car.

Decision Matrix - Driver Interface

Concept Selection Legend Better + / Same S / Worse -	***Importance Rating***	2016 Steering Wheel	A. Steering Bar	B. Foot Pedal Steering	C. U Shaped Steering Wheel	D. "Twist" Steering	E. Joystick
		Solution Alternatives					
Visibility	**3**		S	-	+	+	+
Minimal play introduced	**3**		+	-	S	-	S
Ease of manufacturing	**3**		+	-	S	+	S
Button placement	**2**		-	-	S	S	+
Weight	**3**		+	+	+	-	S
Ergonomics	**4**		-	-	S	+	+
Intuitive steering	**5**		-	-	S	-	-
Cost	**5**		+	-	S	-	S
Sum of Positives			4	1	2	3	3
Sum of Negatives			3	7	0	4	1
Sum of Sames			1	0	6	1	4
Weighted Sum of Positives			14	3	6	10	9
Weighted Sum of Negatives			11	25	0	16	5
TOTALS			**3**	**-22**	**6**	**-6**	**4**

Table 4 is the decision matrix used to evaluate different concepts for the driver interface with the steering system. The best concept was the U-shaped steering wheel, scoring 6 points above the 2016 steering wheel. The U-shaped wheel scored better mainly due to its improved visibility and lower weight. Many of the other criteria, such as ergonomics remained the same, although that may not be a bad thing considering Laura liked having a steering wheel. Joystick and a steering bar came as close runner ups. The joystick steering would have better visibility as there would be fewer linkages in front of the driver, but scored poorly in ergonomics and intuitiveness. The steering bar seemed to have scored better due to its overall simplicity. Due to its complexity and un-intuitiveness, twist steering scored worse than the datum. The foot pedal steering was the worst and scored poorly across the board. From these findings, the U-shaped steering wheel was chosen as the main concept because it scored the highest out of the concepts.

Table 5. The decision matric used evaluate ideas for the steering actuation. Keeping the solid linkage system proved to be the best option for the steering system.

Decision Matrix - Steering Actuation						
Concept Selection Legend Better + / Same S / Worse -	**Solution Alternatives**					
	Importance Rating	Solid linkages	A. Hydraulic	B. Rack and Pinion	C. Chain/Belt	D. Electrical
Weight	**4**		-	S	+	-
Driver steering force	**3**		+	+	S	+
Minimal play introduced	**4**		+	-	-	+
Driver clearance/Visibility	**3**		+	S	+	+
Total parts cost	**5**		-	-	S	-
Disassembly time	**1**		-	+	S	-
Ease of Manufacturing	**3**		-	-	-	-
Reliability	**4**		-	S	-	-
		Sum of Positives	3	2	2	3
		Sum of Negatives	5	3	3	5
		Sum of Sames	0	3	3	0
		Weighted Sum of Positives	10	4	7	10
		Weighted Sum of Negatives	17	12	11	17
		TOTALS	**-7**	**-8**	**-4**	**-7**

Table 5 was used to evaluate the best concept for the steering actuation. All proposed systems scored negative compared to the solid linkage system used in the 2016 vehicle. While hydraulic and electrical systems would be able to provide a low input force from the driver, the fact that they required extra heavy equipment such as pistons and batteries caused these ideas to fall out of favor. The reliability of these systems was also questionable since a leak in hydraulic lines or a depleted battery can render the steering system useless. Manufacturing these systems is also more complicated which caused these systems to lose more points. A rack and pinion was shown to introduce play into the system as seen when the team looked at Formula SAE and Baja's steering systems. This characteristic plus the complexity of manufacturing the system and its cost caused this system to fall out of favor. A chain or belt system scored the highest among the concepts, but it still scored 4 points less than the 2016 system. This idea was rejected mainly due to the possibility of losing the chain or belt while driving making it unreliable. As such, the team has decided to stay with a solid linkage steering system, however, the placement of the linkages was reevaluated to be more ergonomic for the driver.

4.3.3 Preliminary Design

To summarize, the design concept that scored the highest from decision selection is a U-shaped steering wheel attached to a solid linkage mechanism to actuate the wheels. The team created a preliminary CAD model of this steering system to better visualize this concept. This preliminary concept is shown in Figure 21. To better accommodate driver ergonomics, the tie-rod is placed above the driver's thighs instead of below them. During the later detailed design, the team evaluated the exact tie-rod locations as to not interfere with driver egress and visibility.

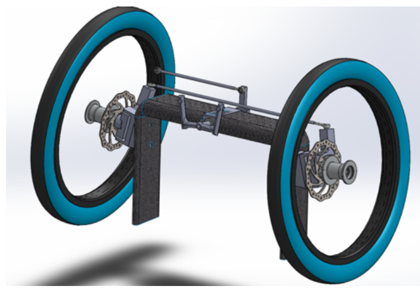


Figure 21. A preliminary CAD model of the selected idea that incorporates the U-shaped steering wheel and solid linkages.

Looking back to the design specifications, this design would be able to accommodate the customer requirements adequately. The linkages and steering wheels can easily be designed to make them lightweight and reliable. From our driver's feedback and decision matrices it was found that the U-shaped steering wheel was the most intuitive and ergonomic while minimizing interference with visibility. There would be plenty of locations for buttons to be placed on the steering wheel. With a solid linkage mechanism, toe angle can be adjusted while being mechanically reliable. Although it may not be the best for overall size, the easy of manufacturing and servicing compared to other systems also makes the solid linkage system a good choice.

5.0 Final Prototype Design

The team worked from the Preliminary Design review on November 15th, 2016 up to the Critical Design review on February 7th, 2017 on refining their design while also performing necessary analysis. The final design will be discussed in detail in this section.

5.1 Final Design Solid Model

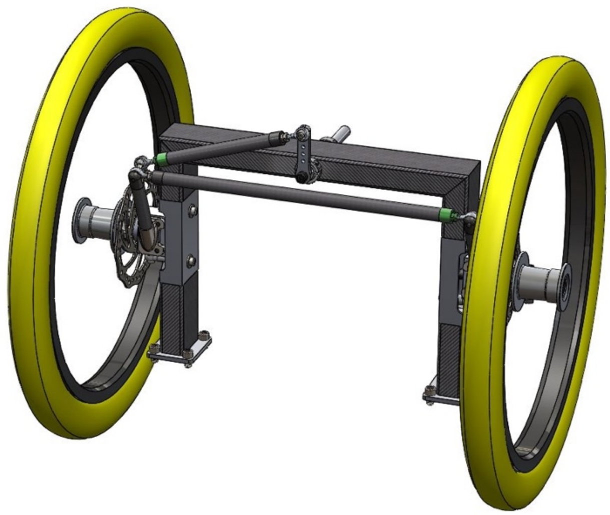


Figure 22. A rendering of the final design for the 2018 Supermileage steering system.

Working from the design that the team presented in PDR, the team refined the design into its final form before manufacturing. This final design can be seen in Figure 22. In order to simplify the overall steering assembly design, the system was broken into four separate subsystems. These separate subsystems are the subframe assembly, the axle assembly, the steering column assembly and the tie rod assembly. The subsystems interact in the following manner: the driver applies a rotational moment using the steering wheel through the steering column that applies a force along the attached tie rod. These tie rods apply a force onto the Ackerman arms of the axle assembly which causes the wheels to turn. These three subsystems are all mounted onto the subframe that bolts into the chassis of the Supermileage vehicle.

Following is a discussion of the steering geometry that the team decided on. After that, each subsystem is described in detail along with the analysis that validated the designs of the subsystems.

5.2 Steering Geometry Decisions

As the team began the detailed design of each individual part, the team also finalized the steering geometry that they would use. These geometry decisions drove the design of several parts so it was paramount that these geometric parameters be determined first so that the parts could be designed around them.

5.2.1 Ackerman Geometry

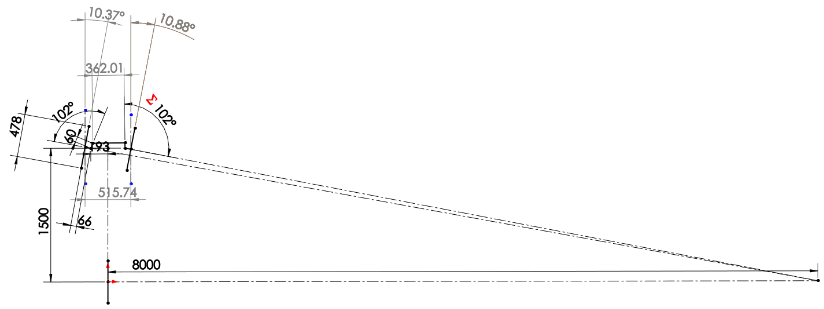


Figure 23. Ackerman SOLIDWORKS model

Ackerman steering was one of the first calculations that the team performed to confirm the design of the Ackerman arms that will be discussed in detail later. Ackerman steering calculations were performed using a SOLIDWORKS steering model, as seen in Figure 23, and the Ackerman 4-bar trike design spreadsheet developed by Peter Eland. Both tools used simple Ackerman models to calculate the approximate arm length and angle to meet the teams required 8 meter turning radius specification of the competition. Using the Ackerman Excel spreadsheet first, the team found that the ideal Ackerman arm dimensions were 60 millimeters out from the kingpin and angled approximately 12° inward. See Attachment B for a screenshot of the Ackerman Excel tool from Peter Eland. The spreadsheet results were then checked using the SOLIDWORKS model to confirm accuracy over a wide range of turning radii to ensure that the car could meet the various turning radii encountered at competition.

5.2.2 Camber

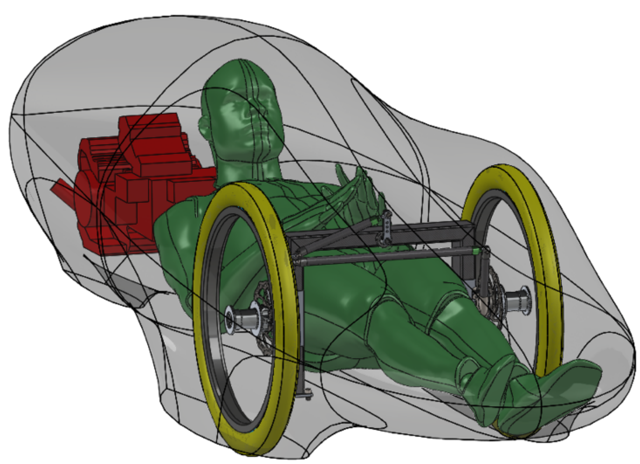


Figure 24. The steering system installed into a concept model of the 2018 Supermileage vehicle.

Camber studies were performed using the new 2018 chassis model in SOLIDWORKS, seen in Figure 24. The team worked to maximize the turning angle of the wheels while also reducing the frontal area of the chassis to minimize aerodynamic drag. Negative camber was also reduced as much as possible while also trying to keep aerodynamic drag down. It was settled on a negative camber of -0.5° mostly due to packaging issues within the 2018 chassis design. Preliminary CFD analysis from the SMV team also showed that the aerodynamic drag was slightly lower with a shallower camber angle for the chassis' shape. Although tire rolling resistance is theoretically lowest at 0º of camber, as seen in Figure 5 in the preliminary discussion of camber, oscillations in lateral force will cause real world rolling resistance to become erratic. This slight camber will therefore help with keeping the car stable while cornering.

5.2.3 Toe

The senior project team is going to use 0.0° of toe as both positive and negative toe drastically increase tire drag as seen in Figure 6 in the preliminary discussion of toe. Designing a fixture to align the toe in a competition setting is high recommended.

5.2.4 Steering Axis Inclination and Scrub Radius

It was decided to align the steering axis inclination directly with the contact patch of the wheel and the road that would produce a scrub radius of 0 inches. This was decided as a near zero scrub radius helps with vehicle handling at low speeds. As a Supermileage vehicle generally does not go above 20 mph, this is the ideal design. In addition, a near 0 inch scrub radius is said to have the lowest tire drag, however the team could not find a study to confirm this claim. Overall, however, SAI is not that critical of an aspect in Supermileage vehicle design as the vehicle has no suspension system and does not run over uneven terrain that can cause erratic steering behavior, which would warrant further analysis into the effects of scrub radius.

5.2.5 Caster

Figure 25. The Supermileage car has an unexpected off-roading event during testing that damaged the steering system and prevented caster testing.

The team decided to use a caster angle of 6° taken from an average of past steering systems that were too low or too high. The team had planned testing various caster angles, however complications arose. During testing at the Santa Maria Airport autocross track in early January, the 2016 Supermileage vehicle had an unexpected off-roading event caused by parts in the steering column mount failing. The crash caused further damage to the steering and braking system in the vehicle. The senior project team attempted to repair the steering system; however, misalignments due to the repair made test data for different caster angles unusable. Around this time, a steering system for the 2017 competition was being implemented into the vehicle. Preparing the vehicle for competition did not allow the team to schedule testing specifically for caster testing.

5.3 Subframe Assembly

Figure 26. A rendering of the subframe assembly. It is characterized by the carbon tubes, uprights, rod ends, lugs, and base flange.

Seen in Figure 26, the subframe assembly is the main structural component that steering components attach to and which attaches to the car chassis itself. It is responsible for maintaining steering geometry under load and providing rigidity to the whole steering system. The subframe consists of an upside down “U” shape structure made from carbon fiber tubes manufactured with carbon fiber tubing with uprights machined from aluminum. The subframe was designed so that the driver’s lower body fit in the opening below the U shape and to be able to mount the steering wheel up high. This allows the steering linkages and column to be out of the way of the driver during egress and operation unlike past designs. The axle assembly would mount into the aluminum uprights via the rod ends that are located by precision machined holes and shoulder screws. The upper corners of the subframe would be aligned and connected by high strength epoxy and internal lugs machined out of aluminum as seen in Figure 27.

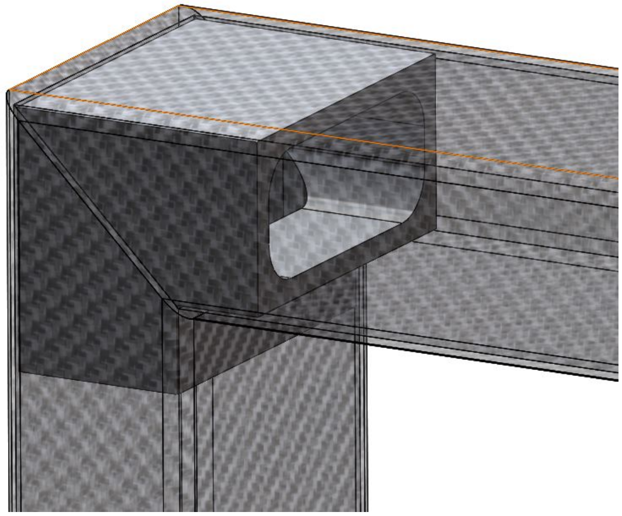


Figure 27. Internal lugs machined out of aluminum will align and bond the carbon tubes with high strength epoxy.

The internal dimensions of the frame are set to be approximately 13 inches wide and 10.5 inches tall. These dimensions are based off of the driver's body and designed to give approximately 0.5 to 1 inch of clearance on each side while wearing a racing suit so as to not interfere with egress and operation, meeting the team's specification. While this is a tight fit, it is part of the nature of prototype vehicles, trying to push the extremes of performance. The 2018 chassis, which was being designed concurrently by the SMV team at the time of writing, was designed to accommodate the size of this steering system.

5.3.1 Carbon tubing

Much of the sub frame is manufactured from 2"x1" rectangular carbon fiber tubing purchased from RockWest Composites. The team chose to buy pre-made tubing over manufacturing them themselves due to the superior mechanical properties and dimensional accuracy that RockWest is able to offer. From a packaging standpoint, the width of the tubes used in the sub frame must not exceed 1 inch so that it can clear the driver while maintaining a tight track width. Both rectangular and round tubes were considered for the subframe. Using the composite layup schedule that details fiber orientation provided by RockWest on their website, the effective bending stiffness (EI) -the effective modulus of elasticity of the composite part multiplied by the area moment of inertia of the cross section- was calculated using a composite calculator script for similar available tubes. Table 6 shows effective stiffnesses of different tubes taken into consideration.

Table 6. Effective bending modulus of different carbon fiber tubes available from RockWest Composites with width of 1 inch.

Tube	Description	Wall Thickness [in]	Effective Stiffness [lb-in^2]
25507	2"x1" Rectangular tube	0.065	1.30E+06
46314-HM	1" OD Round Tube with high modulus carbon	0.044	6.13E+05
45419-HM	0.5" OD Round Tube with high modulus carbon	0.125	1.19E+05

The 25507 rectangular tube had the highest EI of 1.3E6 lb-in^2 so it was chosen. Even though the smaller round tube had a much thicker wall thickness than the larger tube or the rectangular tube, the cross section was too small to provide enough stiffness. The rectangular shape also allows for a larger surface area for epoxy that will be used to connect the tubing to each other in the upper corners, uprights, and mounting flange. It also allows for easier manufacturing of the lugs as the team does not need to machine circular profiles. Although superficial, it will also have a cleaner aesthetic, being connected to rectangular uprights.

Stresses in the carbon tubes were analyzed using the same composite calculator script, the design factor to failure was over 50. To analyze the stiffness of the frame, the subframe was modeled as a cantilever beam. Note that the cross bar was neglected in the stiffness analysis to be conservative as the free end will introduce more deflection. The beam was modeled in three segments: a carbon fiber rectangular tube mentioned above, then an aluminum channel, and another carbon rectangular tube. The aluminum was modeled as a channel 2 inches wide and 1 inch tall with a wall thickness of 0.1 inch. It is notably missing any stiffening feature added for simplicity and to be conservative. Each segment of the beam was modeled as its own cantilever beam, however the rotation at the tip of the last segment, using small angle approximation was added to the lateral deflection of the next segment. Loading on the subframe was calculated using an Excel tool utilizing tire data and vehicle parameters to calculate lateral forces, normal forces, and longitudinal forces from the wheel while cornering at the tightest and fastest corner experienced by the car. From these loads, the reactions seen at the end of the rod ends, and therefore the subframe were calculated. Deflections from all three segments were combined and are plotted in Figure 28.

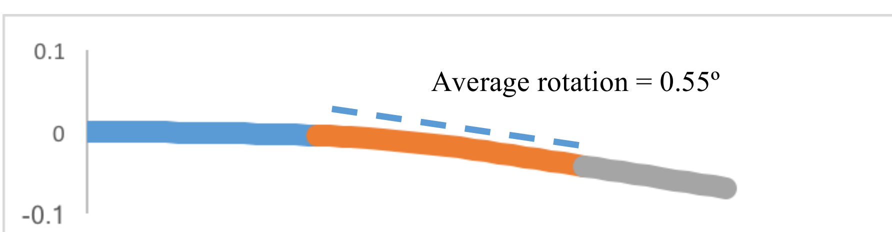


Figure 28. Deflection of the composite subframe. The average rotation of the upright is 0.55º.

From this analysis, the most important result was the average rotation at the aluminum portion as it will dictate the change in camber while the vehicle in in operation. Using the tool, the rotation was found to add 0.55º to negative camber. Although this is slightly above our specification of loading not changing the deflection more than 0.5º, the conservative assumptions justify being slightly over specification.

5.3.2 Corner Lugs

The lugs are an aluminum L-shaped part that was designed to be used to fit the carbon fiber tubes together at the top corners. These machined parts both align and strengthen the joint. The mounting flange mounts to the bottom of the subframe and has a bolt pattern to attach to the chassis. Both parts connect to the inside of the rectangular tube with Hysol E-60HP high strength epoxy which has a shearing strength on aluminum of approximately 2500 psi. To analyze the amount of overlap required to properly bond to the carbon, the shear stress in the epoxy was calculated by turning the maximum bending moment into a line load at the epoxy, and dividing by the area of epoxy. Assuming a max shear strength 2500 psi, the calculated length into the tube required will be 0.11 inches. However, since the shear strength of epoxy is usually found in idealized laboratory condition with perfect test pieces, this minimum length was quadrupled.

5.3.3 Uprights

The uprights are used to mount the rod ends that secure the axle assembly. These uprights are designed to be machined out of 6061-T6 aluminum due its superior machinability and adequate mechanical properties. The two holes precisely locates shoulder bolts as even slight misalignment in the rod ends can change the caster angle. The bottom rod end will have a standoff machined directly into the upright to control steering axis inclination as well. The upright will have flanges on the top and bottom that will be epoxied to the inside of the carbon tubing much like the lugs and mounting flange and a 0.85 inch overlap will be utilized.

The cross section of the main portion is shaped much like a 2x1 inch channel with a uniform thickness of 0.1 inch as done in the stiffness calculations. Stress analysis was also performed assuming this uniform cross section ignoring the two end caps and stiffening features. Using the loads calculated in the turning model, it was found that the worst-case stress element is located in the position shown in Figure 29.

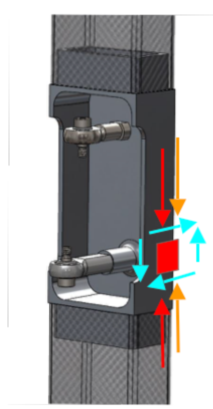


Figure 29.The worst-case element on the upright is the corner near the lower rod end where compressive stress from bending on both axis and transverse shear add up.

This stress element experiences compressive stress from bending along both axis, along with shear loads from transverse shear for thin walls, torsion, and induced torsion from bending an open cross section beam. In the analysis, stresses from torsion and induced torsion will be neglected as the moments that cause them will be relatively small compared to the bending moments and transverse shear. Using Von Mises failure criteria, this worst-case stress element has a design factor of 4.59.

Analysis on the shoulder screws and holes were done assuming that all of the normal load from the ground to the vehicle is experienced by the top hole only. The top hole was designed to have a diameter of 0.25 inches. This was chosen because it is the only available shoulder screw that can fit in the #10-32 rod ends. The screw will be in direct shear as it will be screwed all the way into the rod end, and has a design factor for failure of 15.3. Failure from the screw thread pulling out due to lateral has a lower, but still large design factor of 4.88. Yielding on the inside of the upper hole from the screw modeled as a pressure across projected area of the hole was found to have a design factor of 4.45. From these calculations, the team is confident that the upright will not fail during operation. Although one may argue that the upright is overdesigned, stiffness discussed above was a higher limiting factor. Looking forward, with more analysis tools like FEA, future Supermileage teams may be able to design a more optimized geometry for stiffness while further minimizing weight.

5.3.4 Rod Ends

The rod ends support the axle assembly and are used to create the steering axis about which the axle rotates. The top rod end was designed to take all of the normal loading from the vehicle, so a thrust rated rod end was chosen for this part. Using McMaster-Carr's specification sheet, the design factor for the thrust on their smallest thrust rod end was 3.79. Using the same rod end and assuming material properties as similar to ones found in steel alloy fasteners, the maximum bending stress from the resultant of the forces in the lateral plane had a design factor of 2.94. The resulting forces should rotate the rod end by 0.3° adding to the camber, however, this is assuming that the rod end does not have a bolt in it.

5.4 Axle Assembly

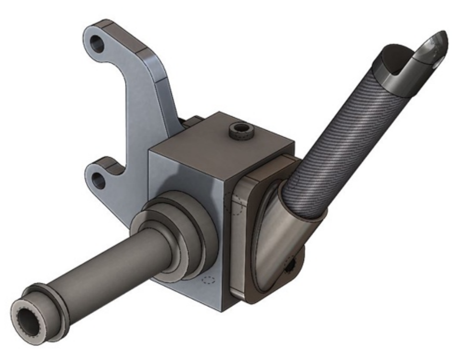


Figure 30. The axle assembly

The axle assembly consists of four separate pieces; the knuckle, Ackerman boss, brake boss and spindle. It was decided to separate the axle assembly into these separate parts instead of combing them to simplify the manufacturing of the overall assembly along with reducing the stock material used to actually manufacture the part. The axle assembly is secured by bolts running through the rod ends mounted to the subframe. These rod ends allow the entire axle assembly to rotate about its steering axis and turn the wheels of the car when a force is applied along the tie rod to the Ackerman arms. The following sections will discuss the individual components of the axle assembly.

5.4.1 Knuckle

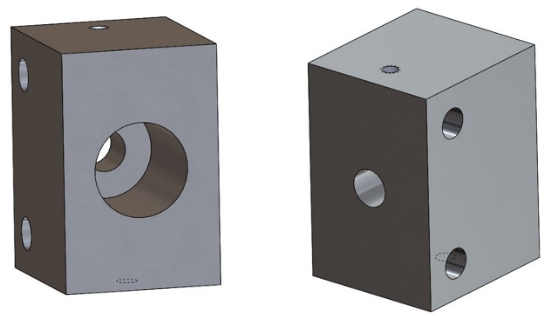


Figure 31. A rendering of the knuckle block that the axle assembly is bolted into.

The main piece that everything bolts onto is the knuckle, seen in Figure 31. The knuckle is a block of machined 6061 aluminum with various tapped and through holes for the purpose of mounting all of the other components. 6061 aluminum was chosen due to its lighter weight than steel and the fact that the knuckle itself doesn't undergo any significant direct loads.

The axle spindle itself mounts in a 0.75 inch bore in the knuckle and is secured into place with a 5/16-24 bolt that threads into the axle spindle. The through holes on the sides of the knuckle are for mounting the brake bosses and Ackerman bosses.

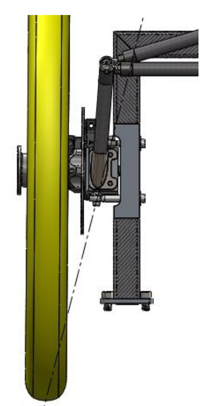


Figure 32. The steering axis is designed to pass through the center of the contact patch of the tire for a 0 inch scrub radius.

The tapped holes for the bolts that go through the upright rod end are placed so that the geometric constraints for camber and SAI are met as mentioned above. As seen in Figure 32, the steering axis lines up with the contact patch of the wheel and the road. Also, the resulting camber is seen to be –0.5°.

Some previous Supermileage steering systems, including the 2016 steering system, chose to make the knuckle and Ackerman arm one part for the sake of simplicity. However, this did require two custom Ackerman arm parts for a left and a right side, cost about $200 in aluminum and took a significant amount of time to CNC machine. The senior project team chose to separate the knuckle and Ackerman arm because this allows for a simpler part to machine (and therefore make replacements) and the knuckle is symmetric for the left and right axle assemblies.

5.4.2 Ackerman Bosses

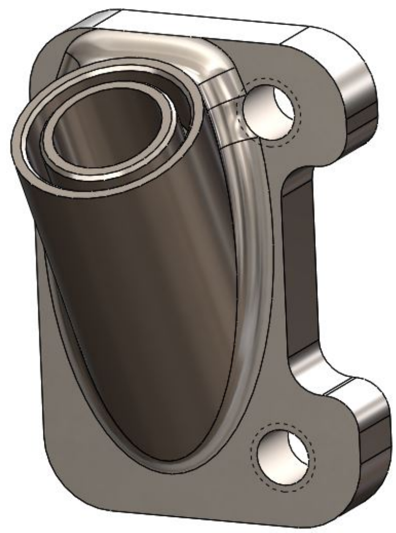


Figure 33. The Ackerman boss will be metal 3D printed to manufacture the abnormal geometry used to properly align the Ackerman arm.

As seen in Figure 33, the Ackerman bosses are two unique parts; one for the left side and one for the right. These parts have carbon rods mounted in the slot of the part and to form the entire Ackerman arm assembly. The slot is angled to meet the 12° Ackerman requirement between the longitudinal axis and the Ackerman arm, and also so the carbon rod lengths meet the 60 mm Ackerman arm length. The mounting holes on the bosses are tapped so that through bolts can be ran through the knuckle and threaded into the Ackerman boss. In this way, the Ackerman bosses serve as a nut to bolt the brake bosses and Ackerman bosses to the knuckle. To meet the unique geometric requirements of this part, SLM metal 3D printing was chosen to manufacture the part using the Cal Poly IME department's SLM machine.

5.4.3 Brake Bosses

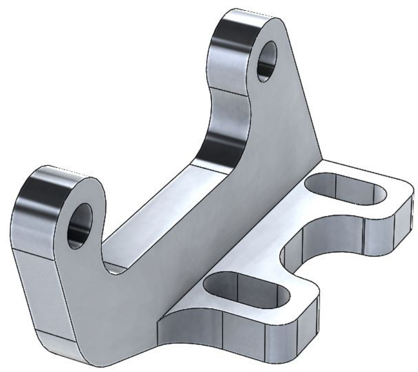


Figure 34. The brake boss is used to mount the brake. Since the brakes will remain the same, this brake boss will be recycled form the past Supermileage vehicle.

As seen in Figure 34, the brake bosses are two attachments to the knuckle that the brake adapters are mounted on. The piece is a CNC machined part made from 6061 aluminum L-channel. These parts simply reuse the previous year's car as the dimensions for the brakes and brake adapters are exactly the same and they withstood the braking forces encountered last year. Also, the distance from the knuckle surface and the required mounting location for the brake calipers are similar to last year and within tolerances for the part to be reused.

It was chosen to create separate bosses instead of incorporating brake mounts into the knuckle to reduce the overall size of the knuckle. If the team wished to try and skip the brake bosses and brake adapters, they would have to increase the height of the knuckle by about 1 inch in order to bolt the caliper directly on.

The part could be trimmed down or use thinner walled L-channel stock than the current 1/4 inch to reduce weight. However, manufacturing new bosses from 3/16-inch-wall L-channel would save only approximately 0.02 lbs per boss. As such, the senior project team is going to save the time and money spent doing this and try to find weight savings elsewhere, such as the tie rods.

5.4.4 Spindle

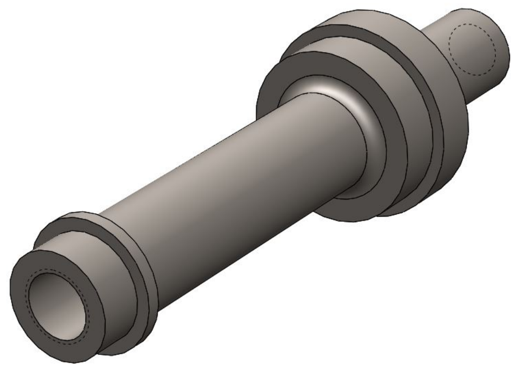


Figure 35. The spindle is used to mount the wheel onto the knuckle. This project will utilize 4340 steel instead of aluminum to maintain bearing surfaces and reduce play.

As seen in Figure 35, the axle spindle is what the wheel hub mounts onto. The wheels, hubs and brake rotors are all parts that have been used for the Supermileage vehicle for the past couple years so the axle simply needs to provide a way to mount the wheels onto the knuckle assembly. A custom axle was designed with critical dimensions for the bearing surfaces of the Cannondale Lefty Hubs, which uses 6902 and 6805 bearings. The axle spindle also has two tapped holes for bolts, the metric endcap screw for the hub and the imperial bolt for securing the axle spindle to the knuckle. The axle mounts into the knuckle through a locating clearance fit of 0.000 to 0.004 inches and is backed up by a bolt on the other side of the knuckle.

Bearing surfaces dictated the design and material selection for this part. The Supermileage team had previously ran into issue with the bearing surfaces of the part being marred when using 6061 aluminum so that the wheels began wobbling on the bearing surfaces. The team stepped up to using 7075 aluminum for the 2016 Supermileage vehicle's axles, however they still ran into similar issues. It was recommended by Materials Engineering graduate student, David Otsu, that the senior project team use 4340 chromoly steel for the axles this iteration. The senior project team has decided to move forward with his suggestion and machine the axles from 4340 chromoly steel. See Attachment C for David Otzu's detailed report on the axle material selection and heat treat schedule. As steel is approximately three times heavier than aluminum, the part was thinned down in the middle to save weight.

5.5 Steering Column Assembly

The steering column assembly consists of five parts; two flanged sleeve bearings, two shaft collars, a steerer, a steering column, and a bolt to attach the steerer to the steering column. Figure 36 below shows this assembly on its own.

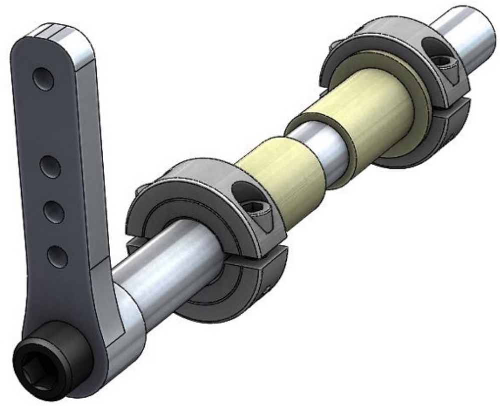


Figure 36. The steering column assembly where the steering wheel will be mounted.

The sleeve bearings is epoxied to the carbon fiber subframe, the steering column will go through the bearings and be located axially by the shaft collars. Finally, the steerer attaches to the steering column with a 5/16”-24 X 1” bolt. This bolt was convenient for the design since the inside diameter of the steering column is ready to be tapped for a bolt very close to this size. Since the scope of the project changed to not include the steering wheel, the team is leaving the free end of the steering column as an unmodified tube which will be able to be customize to attach to the 2017 steering wheel in the future.

5.5.1 Steering column

The steering column is the component that transfers the rotation of the steering wheel to the rotation of the steerer. Since weight is an important specification, this column will be made out of aluminum, but 2024-T3 aluminum, instead of 6061. This material was chosen due to its higher yield and shear strength which allowed the column to have a smaller cross section and as such reduced weight. A lighter material would have been carbon fiber, but this material does not hold the tolerances or surface finish needed to rotate freely through the flanged sleeve bearings. In order to ensure the steerer and steering column rotate together, there will be flat features machined on the steering column and steerer. These features can be seen in Figure 37.

Figure 37. A close up of the mating surfaces of the steering column to the steerer.

Two load cases were used to analyze the steering column and choose appropriate critical dimensions. The first was a worst case, hard braking and tight turning case. This case saw 50 lbs of force being transferred through the tie rod to the steering column and was analyzed for shear from twisting. A FS of 8.1 was calculated with a 1/2 inch diameter tube, more than enough to handle this load case. Another load case assumed the driver lifting up or pushing down on the steering wheel with a force of 35 lbs of force at a distance of 4 inches from the supported edge of the column. This load case was tested for bending and saw a FS of 3.2, ensuring the column will not yield with this load case.

5.5.2 Steerer

The steerer is a part made out of 6061-T6 aluminum that will translate the rotational movement of the steering column to the short tie rod. As previously mentioned, the flat features on the steerer ensure it will rotate with the steering column. While designing this component, the team noticed that depending on where the tie-rod is attached, the steering ratio can be altered. The four holes on the steerer seen in Figure 38 will allow the driver the freedom to choose steering ratios of 1:1, 1.5:1, 2:1, and 3:1.

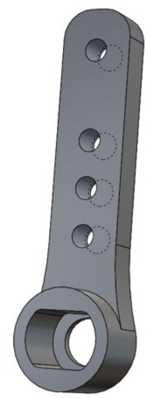


Figure 38. The steerer rod that can adjust the steering ratio based on use preference.

Bending and transverse shear caused by the tie rod were also taken into account found to have a FS of 4.17. The worst-case load saw the steerer rotate only 0.2° at the tip.

5.5.3 Flanged Sleeve Bearings

The team realized that the 2016 vehicle's bearings used in the steering column assembly were vastly over designed and as a result too heavy. The number one option chosen by the senior project team were MDS-filled nylon flanged sleeve bearings. The surface of this material ensures smooth rotation of the steering column, reducing friction between the surfaces. These bearings are rated at 200 lbs of thrust and radial force and do not require consistent lubrication.

Other materials considered were bronze, oil-embedded flanged sleeve bearings. While these were rated to handle much higher loads, they were heavier and were deemed unnecessary by the team due to the added weight.

5.6 Tie Rod Assembly

Figure 39. The tie rod assembly that connects the two wheels. The short tie rod connects the steer to one of the wheels to initiate turning.

There are several similar tie rod assemblies within the steering system; Figure 39 shows the assembly for the longest tie rod that connects the two Ackerman arms together. The shorter tie rod that connects the steering arm and the two Ackerman arms all use the similar tie rod design. The Tie Rods are made up of 3 main components: carbon fiber tubes from DragonPlate, bungs, and 10-32 male rod ends.

The tie rods need right handed threaded rod ends on one side and left hand threaded rod ends on the other to allow the rod to be twisted in one direction and either decrease or increase the length of the overall tie rod. If two right hand threaded bungs were used, the tie rod would simply unthread from one rod end while threading into another making adjusting the length impossible.

Carbon tubes were used in place of a solid metal piece spanning the tie rod distance for weight savings and increased strength. A design factor of over 50 was calculated for buckling of the tie rods.

5.7 Weight Analysis

One of the most important specifications of this senior project is to manufacture a steering system that weighs less than six lbs Careful consideration of material choice and part design was made to provide the team with the lightest possible steering system. At the time of CDR, the system was estimated to weigh 3.55 lbs, much less than the specification. This was calculated using SOLIDWORKS' mass properties feature to find the volume of different parts and then multiplied by their respective material densities to find the mass of each part. A brief summary of the estimated weights of each subassembly can be seen in Table 7. The weights of each subsystem. For a closer look at the mass of each individual component, refer to the bill of materials in Attachment D. Following is a brief overview of the weights of the main assembly components.

Table 7. The weights of each subsystem. Cur projected total weight is much lower than the target weight of 6 lbs

Category	Description/Notes	Weight [lbs]
Sub-frame Assembly	Includes uprights and carbon fiber frame	1.558
Steering Column Assembly	Includes sleeve bearings	0.157
Knuckle Assemblies	Includes L&R bosses	1.667
Tie Rods Assemblies	Includes both short and long tie rods	0.170
	Totals:	3.551

The subframe assembly is composed mostly of rectangular carbon fiber tubing from Rock West Composites. The cross bar is estimated to weigh 0.031 lbs The carbon fiber tube connecting the bottom base plates to the uprights will weigh 0.008 lbs each and the tube connecting the uprights to the cross bar will weigh 0.006 lbs each. These are light components, but come at a steep price, later seen in the cost analysis. The heaviest components of the subframe are the CNC machined aluminum pieces; the uprights, base brackets, and corner lugs. These aluminum pieces weigh a combined total of 1.120 lbs The combined weight of the screws and rod ends is 0.380 lbs

The steering column assembly weighs in at a total of 0.157 lbs The heaviest part of this subsystem is the half-inch aluminum steering column, followed by the steerer. Additionally, the shaft collars, sleeve bearings, and 5/16 inch screw weigh 0.037 lbs

The knuckle assemblies are the heaviest part of the steering system so far. The 4340 steel spindles are the heaviest part of the subsystem and were iterated upon to make them as light as possible; 0.334 lbs each. The 6061 aluminum knuckles each weigh 0.263 lbs The Ackerman boss is a critical component that the team estimates will weigh 0.125 lbs

The final subsystem considered consists of the tie-rod assemblies. The short and long tie rod assemblies combined will weigh only 0.170 lbs The weight savings comes from choosing round carbon fiber tubing for the tie rods. Two components will be machined in-house; the left hand-threaded aluminum bungs used to thread rod ends to the carbon fiber tubing. These will weigh an estimated 0.024 lbs, while the right hand-threaded DragonPlate-bought bungs will weigh 0.035 lbs This presents the team with an opportunity to save weight and money at the expense of time by machining the right hand threaded bungs in house.

5.8 Safety Considerations

Manufacturing of the steering system itself is safe. The most dangerous part is the chemicals required in the carbon layups, but proper safety precautions will be taken when performing these layups, including wearing personal protective equipment. See Attachment E, the Design Hazard Checklist.

If a critical component of the steering system were to fail, the driver would likely lose complete control of the steering of the car. However, as the car doesn't travel faster than 20 mph, a crash will only damage the outside chassis and not the driver.

There are also several pinch points that the driver could encounter within the steering system. A requirement from Shell is to have wheel guards to protect the driver from the spinning wheels. However, these cannot be manufactured until the chassis itself is manufactured for the 2018 car so this falls upon the future Supermileage team to design and implement.

5.9 Maintenance

The subframe was designed with high factors of safety so that it would not break or delaminate like the previous year's steering system. If the carbon tubes were to break, carbon fiber layups could be done to patch them or re-attach them together. The aluminum uprights being the most complicated and likely time consuming part will ideally not break thanks to the team's analysis. However, the senior project team will make all the G-code needed to CNC replacement uprights readily available should the need arise.

Consideration was put into the design of the Ackerman axle assembly so that if threads were to strip or a piece yields, the part could be re-manufactured and replaced. The knuckle, Ackerman boss, break boss and axle spindle could all be made with backup replacement parts for competition.

The steering column assembly can have replacement parts for the steerer and column that could be swapped out if the parts yield.

The tie rods are all simple parts that could also have replacement parts at the ready if a tie rod breaks. It might be difficult to replace the Ackerman arms bonded into their bosses if they were to yield however. Replacement Ackerman bosses would be the ideal solution for this.

5.10 Cost Analysis

The budget set aside by Supermileage for this senior project was $500. At the time of critical design review, the estimated cost of materials was $543.45. However, this does not take into consideration raw materials already owned by Supermileage, mostly in the form of aluminum stock. In order to facilitate manufacturing, pre-fabricated rectangular and round carbon fiber stock was purchased at an estimated $250 from Rock West Composites and DragonPlate, which is more than half of the team's budget and the largest ticket items. Below is an abbreviated cost table, organized by assemblies.

Table 8. The costs of each component of the steering system. The total cost of the project is projected to be approximately $540.

Category	Description/Notes	Cost [USD]
Sub-frame Assembly	Includes uprights and carbon fiber frame	$288.48
Steering Column Assembly	Includes sleeve bearings	$37.86
Knuckle Assemblies	Includes L&R bosses	$125.12
Tie Rods Assemblies	Includes both short and long tie rods	$91.99
	Totals:	$543.45

A more detailed list of the parts being used and their respective stock can be found at the end of this report as Attachment D, Bill of Materials. At the time of CDR, the team met the $500 specification as there is a tolerance of $100 on this specification.

6.0 Product Realization

The following section outlines the manufacturing process to build the prototype. It documents the successes and failures during manufacturing and construction. Learnings from this section can be used to guide future design of parts for Supermileage and other manufacturing projects. All of the CNC machined components were manufactured in Cal Poly IME department's HAAS Advanced Manufacturing Lab. Any other manufacturing and assembly took place in the Hangar or the Mustang '60 machine shop. Figure 40 shows the completed prototype the senior project team built.

Figure 40. Completed 2018 Supermileage steering system prototype.

6.1 Main Changes Encountered During Manufacturing Phase

This section outlines the main changes, the team had to implement when issues were encountered during the manufacturing stage of the project. Smaller, part-by-part changes will be discussed in their respective part manufacturing sections.

The mounting flanges were removed from the final design. The future Supermileage team said that they had little interest in making the steering removable and would prefer the steering be completely bonded into the car. This would allow the steering itself to be more rigid and provide an overall safer and more reliable design. This also allowed the team to not have to CNC manufacture two more components.

6.2 Subframe Manufacturing

The main components for the Subframe that needed to be manufactured include both the Left and Right Uprights, the Corner Lugs and cutting and mitering the Carbon Rectangular Tubes.

6.2.1 Left and Right Uprights

The uprights were CNC machined on a Haas VF2 mill. The operations were chosen in such a way to maximize the amount of material a milling vise can hold for each operation. The first of four operations was to machine the main pocket of the upright. A 5-tooth, 3 inch carbide face mill was first used to face off material from the top of the stock material. Then, a 3/4 inch flat end mill was used to machine the profile of the stock to get it to its final width and height. Then, the pocket was rough machined starting with the 1/2 inch flat end mill and moving down to a 5/16 inch flat end mill. With only a small amount of material left, a 1/4 inch ball end mill was used to create large internal radiuses for stress relief and a finish pass on the walls. To create the 1/4 inch holes for the shoulder bolts supporting the rod ends, a Letter A drill was used to create a pilot hole. The hole was finished by hand reaming with a 0.2501 inch reamer.

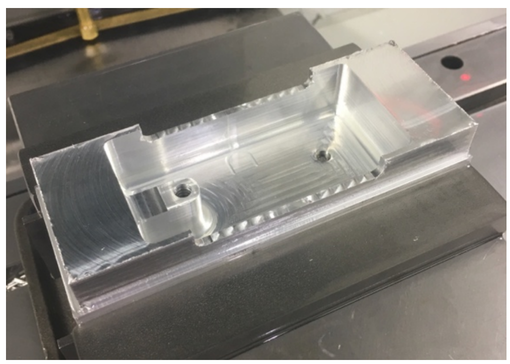


Figure 41. The upright after its first operation on the Haas VF2 CNC mill.

The second operation was relatively simple with the back face being faced and the profile contoured to match operation one. The quality of the part could have been improved by using soft jaws to line up the X and Y axes between operations, hard jaws and 1-2-3 blocks were used to align the part between operations. This caused the part to have a small visible match line, but it did not affect the performance of the part.

Machining the profile of ends where the uprights slide into the carbon tubing proved to be very difficult. With the available fixturing, the upright had to be stood up and vise grab approximately an inch from the bottom while the rest of the part was cantilevered above the vise. With the part being a thin walled channel shape, vibrations from the cutter created a large amount of chatter on the part and left a poor finish on the bond surfaces. The machine also let out a terrifying sound that closely replicated a wailing banshee because there was such a long stick out length from the vise. Although there was much chatter, the final dimension was still acceptable to bond to the carbon fiber tube.

Machining the inside of the ends to shed weight from the part also proved to be difficult. This was due to a multitude of reasons including chatter, small diameter cutter, and a long depth of cut. In the process of machining the pocket, a 1/4 inch and 5/16 inch end mill was broken do to the excessive vibrations and cutting force, even after machining parameters to mitigate the risk. In the end, a larger end mill was used to only machine half of the original depth. This made the part slightly heavier than originally designed, but it was unavoidable due to its manufacturability.

If the Supermileage team plans to manufacture more of these parts in the future, controlling the chatter will be very important. To do this, either a very tall soft jaw or a tall vise should be used to reduce the stick out length. A tall soft jaw would be able to wrap around more material and grip the part more effectively. Another option would be to rotate a standard milling vise sideways. A 90˚ adapter block would be required for this configuration, but holding the entire length of the upright would significantly reduce chatter, improve part quality, and tool life.

6.2.2 Corner Lugs

The corner lugs were also machined on the Haas VF2 mill. Machining the corner lugs presented unique challenges as a rectangular block was turned into a hollow, L-shaped part. Many of the issues concerning a long depth of cut with a small diameter cutter were present as well throughout many of the operations.

Figure 42. The completed corner lug shortly after finishing its last operation.

In the first operation, one side of the "L" was machined. Both the profile and inside pocket were done in one operation. Then, the part was flipped to machine the profile of the bottom side. Care was taken to grip as much material as possible since one of the earlier attempts dislodged the part from the vise and threw it against the inside of the mill. In the next two operations, the other side of the "L" was machined to size.

Again, customized soft jaws would help improve the quality of the part. There were small match lines between each operation from slight shifts in the part origin between operations. A soft jaw would eliminate these slight shifts as well as hold the part more securely.

6.2.3 Carbon Tubes

The RockWest composites rectangular tubes were cut per the drawings using the tile saw in Mustang '60; the best tool available for cutting carbon fiber laminates. Both the rectangular stock for the subframe and the circular tubes for the tie rods were cut to the required length on the tile saw.

To miter the rectangular tubes, an angle guide was used on the wood belt sander and then sanded down to the required 45°. The angle on the guide needed to be confirmed with an angle measuring tool as the mitering jig was not producing the stated 45°. After test fitting the mitered carbon tubes with the corner lugs, the fit was found to be satisfactory enough to go ahead with bonding.

6.2.3 Subframe Construction

The subframe pieces were bonded together using an epoxy resin. In order to improve the strength of the bond, the aluminum pieces were first surface prepped using a procedure developed by Henkel products. This involved first soaking the aluminum bonding surfaces in Turco® AlumiPrep™ 33 in order to remove the aluminum oxide coating. The pieces were then placed in Alodine® 1201™ to create a chrome conversion surface to help provide a better bonding surface for the epoxy. This also had the effect of turning the surfaces a gold/tan color as seen in Figure 43.

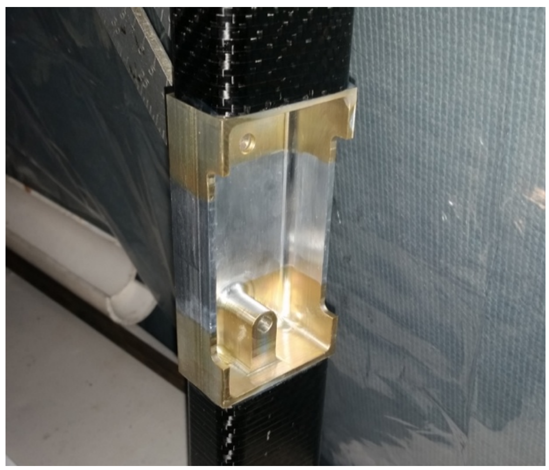


Figure 43. Aluminum Uprights with Alodine 1201 created chrome conversion surface

This surface preparation was done on the uprights, the corner lugs and the tie rod bungs to ensure a better bonding surface. The pieces were then all epoxied into their respective carbon tubes using Loctite EA E-20HP epoxy fed from an epoxy gun using a mixing tube. The gluing pieces were then clamped to ensure that they would not move and were left to dry overnight. All remaining hardware including bolts and rod ends were then installed on the uprights.

6.3 Axle Assembly Manufacturing

The main components that needed to be manufactured for the Axle Assembly were two knuckles, two spindles and two Ackerman arm mounts.

6.3.1 Knuckles

The knuckles were machined using several of the mills in the Hangar and Mustang '60, including a Kearny mill, a Lagun mill, and the Bridgeport mills. A 5/8 inch end mill was used to square up two pieces of aluminum stock. The 1.45 inch and 1.90 inch dimensions were machined to within tolerance during the squaring operation. About 1.60 inch were left for the 1.41 inch height in order to be able to hold the part in the vice for later milling of the flanges.

The two front-facing, 0.266 inch holes were located and center drilled using a Bridgeport mill and drilled using an H drill. The threaded 8-32 holes were drilled using a #29 drill. These tapped holes were centered on the part by taking the side dimension and dividing by two. The right, tapped hole was drilled through to the 0.266 inch hole, while the left hole was drilled to a depth of about half an inch. They were vertically located using the bottom edge rather than the top edge, as the final height was not yet completed. The 0.323 inch hole was center drilled, then through-drilled using a letter P drill. The 0.63 inch hole was then drilled from the top side using a 5/8 inch drill bit. The extra material length had to be added to the one inch depth.

Once all holes were completed, the 0.10 inch wide flanges were machined out of the 1.45 inch sides. The part was placed on one side, one flange was milled, then the part was flipped over and placed on two parallels on the newly milled side. The last flange was then milled. The completed knuckles can be seen in Figure 44.

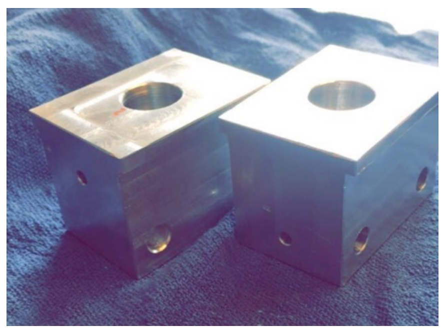


Figure 44. Completed Knuckles

The extra material was not necessary as the operation to mill the flanges had the part on its side rather than on its top. For future manufacturing of a knuckle, the outer dimensions can be machined to within tolerance while squaring up the stock before continuing with the rest of the operations.

6.3.2 Spindles

The spindles were machined on a Haas CNC tool room lathe. Instead of posting code through a CAM program, the part was programmed using conversational programming since the geometry was rather simple. A surface speed of 500 feet per minute was chosen based on the hardness of the 4340 steel being used and the type of carbide the cutter insert was made from. To maintain a good surface finish, a feed rate of 0.010 inches per revolution was used. Initially, the depth of cut was run at 0.030 inches, but to reduce chatter, this was later changed to 0.015 inches.

Machining this part was very smooth. Due to time constraints, the thinner middle section was not machined. There was some chatter initially, but a shallower depth of cut completely mitigated it. The surface finish and part tolerances were really good, and the wheel bearings fit very smoothly onto the spindle. The limiting factor to machining this part was that the lathe's maximum spindle speed was 2000 RPM which did not allow the surface speed to keep up to the smaller diameter sections.

After the spindles were CNC manufactured, they were then tapped for the required bolting hardware. There was some concern that the M10x1.0 tapped hole would have threads too fine which would crack during quenching, as the stress concentrations at those threads was fairly high. In order to test this, a failed spindle was tapped and subsequently heat treated using the process outlined below. It was found that the threads were perfectly fine after heat treat so the team went ahead and tapped and then heat treated all of the axles following a process as per the specifications outlined by the Materials Engineering Student Society report.

Figure 45. The hangar furnace. It is capable of reaching temperatures up to 2000°F which makes it perfect for heat treating.

The furnace in the Hangar machine shop, as seen in Figure 45, was turned on to a set point of 1550°F with the old Baja drive shaft to serve as an oil heater. When the set temperature of 1550°F was reached, the Baja drive shaft was removed and placed in the oil quench tank to preheat the oil and the three spindles were transferred into the furnace. After 20 minutes, the spindles were removed from the furnace and quenched in oil for 45 seconds to one minute and then placed on the metal work table. After they had cooled to where they could be touched, the spindles were cleaned of slag and scale produced during the quench using a Scotch Brite pad.

The following day, the hangar furnace was turned on to 930°F. When the furnace reached the set point, the three spindles were put in and allowed to temper for two hours. They were then removed and allowed to air cool for two hours as the five-hour suggestion was deemed unnecessary by the team. The 930°F cycle was then repeated and the spindles were tempered for another two hours and then allowed to air cool. The spindles were then cleaned of slag and scale produced during the temper using a Scotch Brite pad.

6.3.3 Ackerman Bosses

The Ackerman bosses were originally planned to be selective laser melting (SLM) metal 3D printed on Cal Poly's new SLM machine. However, we were not able to print a successful part on the SLM machine due to the unpredictable nature of the process and the reliability of the machine. Figure 46 shows an example of a failed print due to an erroring the machine. Further experimentation with print parameters will be required to be able to print the parts as originally designed. Because of this, a simplified version of the Ackerman boss was designed and we opted for a machined version of the part using the Kearny and Bridgeport mills in the hangar. These parts are less "cool" than the printed Ackerman boss, but it was required for testing and assembly.

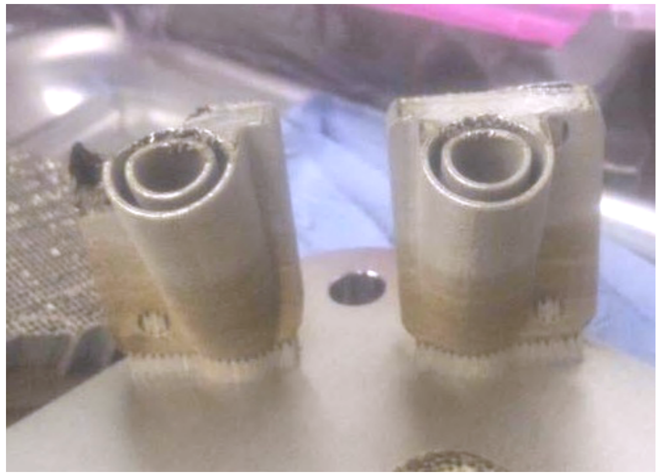


Figure 46. A failed print of the Ackerman bosses on the SLM metal 3D printer. An error in the machined caused the top portions of the parts to melt and become unusable.

The redesigned Ackerman boss can be seen in Figure 47. The geometry has been simplified to make it machinable on a mill. The outwards angle of the Ackerman arm was achieved by drilling a hole at 22º from vertical by tilting the mill. To create the inboard angle, the previously two vertical tapped holes were offset to create the 3.1º angle. The outer dimensions of 1.22 inches x 1.25 inches x 1.75 inches were machined using the Kearny mill with a 5/8 inch end mill spinning at 2000 RPM. The 1/4”-20 tapped holes were drilled using a #7 drill bit spinning at about 600 RPM. The holes were located from the top edge. Care was taken when drilling the bottom #7 hole, since the drill bit can rub up against the parallel the part is resting on.

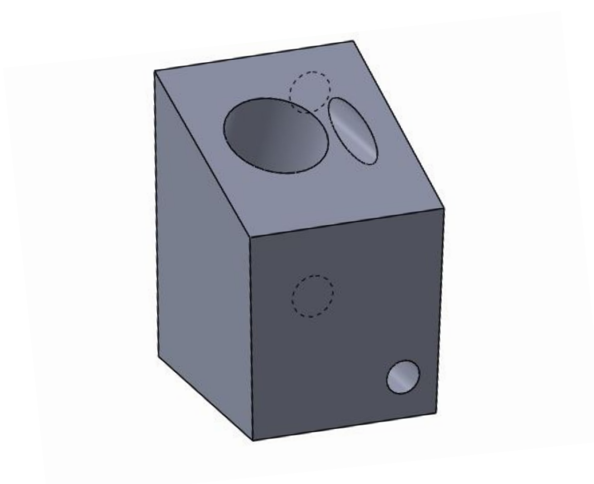


Figure 47. The redesigned Ackerman boss designed to be made on a mill.

Achieving the angled face and drilled hole was slightly challenging. The Bridgeport mills in the machine shops have heads that can be tilted at different angles. Four bolts are loosed on the front of the mill head and a bolt on the side of the head is then used to rotate the head. Since the riveted angle plates have a tendency to be inaccurate, a magnetic angle finder was placed on the quill to find the 22° angle. Once the angle was correct, the four bolts were tightened and a 5/8 inch end mill was used to machine the angled surface. The angled surface was machined until it created a razor edge with the top right side.

Machining the 19/32 inch hole was the most difficult operation. To locate the hole, the razor edge was used to edge find the angled face while the mill head was still at 22°. Then, the X- and Z-axis were used to locate the 0.62 inch dimension. The sine and cosine of 0.62 inch and the radius of the edge finder were used to determine the distance needed to travel in the X and Z direction. The hole distance needed 0.57 inches in the X-direction and 0.23 inches in the Z-direction. This was added to the X- and Z-distance needed for the edge finder radius. The 0.73 inch location from the side was easier to locate, as only the Y-direction needed to be used. Before drilling, the head of the mill was tilted to 22º as shown in Figure 48. After center drilling each hole, a 1/8 inch drill bit spinning at about 800 RPM drilled a hole through the part. The 1/8 inch drill bit was then replaced with a 19/32 inch drill bit spinning at about 1900 RPM to make the final hole size.

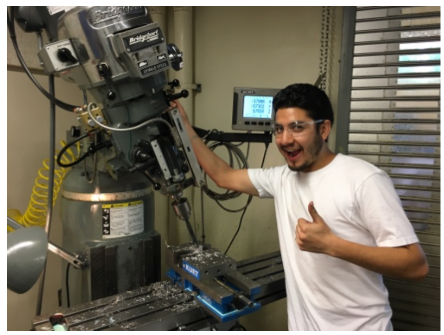


Figure 48. Gio machining the alternate Ackerman boss. To drill the angled hole, the head of the mill had to be rotated.

The material that could not be removed by the drill bit was removed using a belt sander and a deburring tool. The 1/4-20 holes were then tapped as well. Finally, the side of the Ackerman boss was sanded down to prevent interference with the knuckle flange.

There were several ways the angled face could have been machined down. This way involved a small amount of trigonometry to properly machine the angled face and locate the 19/32 inch hole. Alternatively, an angled vise can be used to perform these two operations. If angling the vice rather than the mill head, it is suggested that one use extra aluminum material to hold the part in the vise, in order to be able to drill the hole through without hitting the parallels or vise.

6.3.4 Axle Assembly Construction

After all components were manufactured, the Axle assembly was then made by using the appropriate bolt hardware outlined to attach all the pieces together. The two completed Axle Assemblies can be seen in Figure 49.

Figure 49. Left and right Axle Assemblies completely manufactured.

6.4 Tie Rod Manufacturing

The main component that needed to be manufactured for the tie rods were the four aluminum bungs.

6.4.1 Aluminum Bungs

The aluminum bungs are used for mounting the #10-32 male rod ends to either ends of the carbon fiber tube tie rods. These bungs were machined from 6061 aluminum 5/8 inch rod stock and then tapped and bonded into the carbon rods.

To make the inserts, the rod was mounted on the lathe and set to an RPM of around 1600. The rod was first faced and center drilled and then drilled as much as possible with a #24 drill for the #10-32 tap. The part was then drilled again with the 3/8 inch drill to the required depth and then turned down to the ID of the carbon tubes. The piece was then parted off at about 250 RPM and turned around in the lathe so that the #24 drill hole could be drilled the rest of the way through. This process was repeated three more times for a total of four bungs.

Figure 50. Aluminum tie rod bungs treated with AlumiPrep and Alodine to produce a better bonding surface.

Two bungs were then tapped using a #10-32 RH tap and two were tapped with a #10-32 LH tap. During the sessions where the subframe was bonded together, the bungs were also treated as seen in Figure 50 to produce the surface coating and they were bonded inside the carbon tubes.

6.5 Lessons Learned from Manufacturing

One of the big lessons learned when machining parts was to minimize the number of operations required for a CNC part. If a part can be designed in such a way that it only requires one or two operations, it can significantly reduce machining time as set-up can be a significant portion of one-off parts. Another design consideration is to minimize depth of cut. When machining, several tools were broken because of the long bits required for some of the operations. Not requiring long depths of cuts will also allow for the use of shorter length tools, reducing chatter, dimensions, and improving surface finish. Finally, a huge improvement can be made from making soft jaws for each piece to properly align parts after each operation.

While the best tool to cut carbon laminates, the Mustang 60 tile saw will still fray the ends of unidirectional carbon fiber tubes. Going slowly on the tile saw may help reduce fraying of the carbon and should be tried next time. If the strands do fray on the ends of the tubes, secure them in place with epoxy to prevent the tube from falling apart and to reduce the likelihood of receiving splinters. The rectangular tubes with 6k fabric on the outside and uni on the inside did not fray, likely due to the 6k fabric holding the laminate together.

When the axles were finished with CNC manufacturing and ready for heat treat, care was put into preventing crack propagation in the threads during heat treat. A test axle was tapped with size M10x1.0 and 5/16-24 threads which did not crack or deform during the heat treat quench in oil. From this, it can be reasoned that if the team was to use any 43xx series steel again for a part, they would be able to tap threads up to a similar thread pitch without fear of cracking the threads.

In the pursuit of achieving the designed steering geometry, locating and drilling holes correctly in the knuckle and Ackerman boss is important. Once manufacturing was completed, the team noticed the tapped holes, used to attach the knuckles to the uprights, were incorrectly located. The hole locations were measured and determined to be off by more than 0.1 inches. Both holes on each knuckle had this issue, which made it difficult to notice the manufacturing error. It was only noticed by comparing the final knuckle assembly to the CAD assembly. The takeaway from this error, is to be absolutely sure the process of edge finding is done correctly. It is possible that when edge finding, the radius of the edge-finder was not accounted for, or the edge itself was not found correctly. It’s also possible that the wrong edge was used to locate the hole. In future manufacturing of the knuckles, triple check that the holes are located correctly. This also applies to the Ackerman bosses, if they are manufactured in-house.

7.0 Design Verification

To verify the design, several tests were designed to test the strength and reliability of the steering system. The following section will detail the tests that the team was able to perform along with their results. To perform the tests, a test cart that mimics the geometry of the final vehicle was used to mount the steering system for the tests shown in Figure 51. The test cart featured a heavy duty welded steel frame to ensure that any deflections seen originated from the steering system. As all the tests were planned to be performed while still or rolling very slowly, the cart does not have an engine or drivetrain. The design validation plan and report (DVPR) and test prodecures used to verify final manufacturing can be found in Appendix K.

Figure 51. The steering test cart used for testing.

7.1 Initial Tests and Results

The tests that were performed on the test cart were:

- Geometry verification
- Turning radius
- Disassembly time
- Total weight
- Drop test
- Size testing
- Steering force

7.1.1 Geometry Verification

Before starting the planned tests, the geometry was measured on an unloaded test cart to see if the machined parts met our goals. After assembling the steering system to the test cart, the geometry was verified with a digital inclinometer. Caster on the right side measured 5.8º while the left side measured 5.7º, very close to the target 6.0º. Camber measured approximately 3º on each side, much higher than the planned 0.5º. To troubleshoot this, we measured the final dimensions on the components, and found the vertical 10-32 holes on the knuckles were in slightly wrong places. The top holes were approximately 0.05 inch shifted while the bottom holes were approximately 0.1 inch shifted. This is the likely reason that the camber was slightly off nominal.

7.1.2 Turning Radius Test

The turning radius was tested by first marking an 8 meter radius arc in front of the hangar doors on the flat concrete area. The outside wheel was first lined up on inside of the arc. Then, the steering wheel was turned as far to the right as possible and the cart was pushed forward while the steering wheel was locked to the right. When the cart reached the end of the arc, the test was performed in reverse for the left side.

The cart passed the turning radius test with flying colors with an actual turning radius of approximately 7.6 meters. The test proved that the steering system as designed will be able to physically make the turn without any of the components interfering with its operation. In the actual vehicle, the turning radius may slightly change from the cart due to the chassis geometry blocking the wheels from turning further. However, as designed in CAD, the chassis should still allow for an 8 meter turning radius.

7.1.3 Disassembly time

For this test, Lucas and Gio disassembled the entire steering system while Sean kept time. First, all tools required were gathered and then the time was started. The two disassembled all components as far as they could without damaging them (i.e. epoxied components were not disassembled). The specification for this test was 10 minutes.

The disassembly was performed in 8:06.95. This was approximately 2 minutes faster given specification. This test also disassembled the steering more than it would in a competition or testing scenario. This fast disassembly time will surely aid in repairs at competition when time is of the essence.

7.1.4 Total Weight

Each subsystem was measured separately on the scale. The following table lists the projected and actual weights of the manufactured components. All actual components weighed more than the projected weights as expected. The added weight to the subframe stems from the extra material left on the upright from machining and the epoxy. The extra weight on the knuckle is from the make shift Ackerman boss being larger than the original design and the spindle also weighing more than the CAD due to material being left on the spindle body. The tie rods CAD did not account for the epoxy as well. Despite this, the total weight of the steering system is 5.85 lbs which still met the design specification of 6 lbs.

Table 9. Actual weights of assembled components compared to their CAD counterparts.

Category	CAD Weight [lbs]	Actual Weight [lbs]	% Difference
Subframe Assembly	1.635	2.00	+20.1%
Steering Column Assembly	0.157	1.50	+162%
Knuckle Assembly (Both)	1.667	2.01	+18.7%
Tie Rods Assemblies	0.170	0.342	+67.2%
Total	**3.629**	**5.85**	**+46.9%**

7.1.5 Drop Test

The first drop test was performed by raising the front end of the test cart 6 inches from the ground to the bottom of the wheel. Unlike the original test plan, the test was performed while unloaded except for the cart that weighted 75 lbs. The cart was released from the set up position and allowed to fall to the ground. Unfortunately, as soon as the wheels hit the ground, both uprights pulled out of the bottom carbon tube and failed the test.

Figure 52. The broken steering system after drop test. The uprights pulled out of the button tubes.

Further inspection showed that the epoxy did not properly bond to the inside of the carbon tube. This could have been due to numerous reasons including poor surface preparation and insufficient bond line thickness. The inside of the carbon fiber tubes were cleaned with acetone before the bonding operation, but was left smooth which may have lowered the adhesion strength.

Figure 53. The uprights pulled out of the bottom support due to poor surface prep and an inadequate bond line thickness.

Preparing the carbon surface by sanding or plasma before bonding could have increased the adhesion, however, we do not know if this would have been enough to solve the issue. The other component to the low bond strength is the insufficient bond line thickness of the epoxy. The bond line thickness is the thickness of the epoxy between the two bonding surfaces. Due to the tolerances in machining, the gap between the carbon and aluminum was smaller than initially planned. This made the gap too small for the epoxy to reach its maximum strength.

7.1.6 Size Testing

Testing for the size of the steering system was performed in both CAD and taking real measurements. Since the 2018 Super mileage chassis was not yet built, CAD was used to verify that the wheels turned to the required angle without interfering with the chassis. The minimum distance between the chassis and wheel while turned was 0.64 inch, passing the 0.5 inch specification. The window coverage also tested in CAD for the same reason. The viewport was adjusted to the driver's eye level and pointed in the forward direction. The overlap between the steering system, and window was 0%, exceeding the 25% specification. The steering system remained completely out of the effective field of view of the driver outside the vehicle.

Figure 54. Size testing performed in CAD. Both passed the specification with the minimum distance to the chassis being 0.64 inch and no interference with visibility.

The driver clearance was performed in real life with Sean assuming the driver position. It was difficult to measure an exact distance from the subframe to the legs as clothes and flesh is soft. However, a gap was still able to be measured between 0.25 and 0.5 inch. Since he is much larger than the drivers, the fact that the steering system was wide enough for him passes this test.

7.2 Redesign and Retesting

After the disappointing results from initial testing, the team made modifications to the subframe to repair the structure and continue testing. First, the parts of the subframe that become unbonded were screwed down with 8, 1/4-20 screws that passed through 1/16 inch aluminum washer plates, through the carbon tube, and into the upright as shown in Figure 55.

Figure 55. Modifications made to the subframe to increase its reliability and strength.

The aluminum washer plates were epoxied to the carbon tubes to minimize the amount of bearing load taken directly by the carbon fiber. The holes in the upright flange were tapped so that the screws can directly mount into them from both sides. With these modifications, some of the tests were redone, including the drop test. This modification also provided an added benefit of the steering system being easily removable. This will allow the team to access components easily when assembling or adjusting components.

7.2.1 Geometry Reverification

With the new modifications in place, the team measured all of the geometry before and after load was applied to the cart. This was to ensure that no play or misalignment was introduced from our modifications.

Following test procedure 1, the angle of vertical parts of the subframe, shown in Figure 56, was measured before and after load. There was zero change in the angle before and after the cart was loaded. This was a good indication that the modifications provided adequate support so the team moved on the drop test.

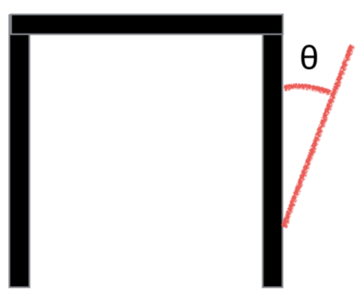


Figure 56. The angles measured during geometry reverification.

Although this was not part of the test procedure, the change in camber at the wheels after loading was also measured. Both sides' camber slightly increased by approximately 1º after being loaded. However, this deflection can also come from the wheels bending and also the wheels slightly turning so it may not be an accurate representation of the deflection in the steering system.

7.2.2 Drop Retest

Drop test was conducted again to verify the strength of the steering system. Because the last test failed without load, the drop test was initially conducted without load as well. When the cart was dropped, there was no sign of visible damage to any of the components. With this result, Sean climbed onto the cart to provide the rest of the load according to the test procedure and the cart was once again dropped from 6 inches. The cart once again survived the drop and was able to roll around without any signs of damage. The cart was disassembled to check for any damage after the loaded drop test, but once again, none of the components were broken or damaged. This was very good news as the steering system will no doubt need to survive abuse in the future and it meant that the components manufactured were capable of surviving this test. It confirmed our suspicions that the initial drop test failed because of the incorrectly assembled subframe.

7.2.3 Reliability Testing

Due to an incomplete steering column assembly, reliability testing was not performed to the full test procedure, however, the test cart was rolled around quite a bit to double check steering radius and to check for any glaring signs of damage.

The steering system seemed to hold up well for the “driving” the team did, however, the team highly recommends that Loctite or other thread locker is used to make sure that components do not come loose during operation. Some of the key joints that require thread locker is the 10-32 bolts that are in the top and bottom of the knuckle, rod ends on the end of the tie rods, and the 1/4-20 bolts that screw into the Ackerman boss. This should prevent road vibrations from loosening the components.

7.2.4 Steering Force

Although the actual steering force could not be measured because a proper steering column mount and steering wheel fell out of the scope of the project, the steering force at the end of the tie rod that connects to the steerer was measured while turning. The force in both directions was approximately 26 lbs measured with a digital linear force gauge. This data can now be used to design a steering wheel and adjust the steering ratio accordingly.

8.0 Conclusions and Recommendations

Throughout this year, the senior project team worked hard to design and build a steering system to the best of our abilities for the 2018 Supermileage vehicle. The team worked to identify design requirements to satisfy the Supermileage team, driver, and competition rules. From these requirements, the best design was brought up through several ideation and early prototyping sessions. This design was then further analyzed and modeled over several weeks and manufactured. The senior project team was ultimately able to assemble a steering system, despite running into issues during manufacturing. However, some of the issues in manufacturing set back testing which did not allow the project team to do any major redesigns when the steering system failed during initial testing. The team was able to repair the sub frame and retest the steering system with modifications which were able to meet performance requirements. From our learnings, the team has many recommendations so that the steering system can be successfully implemented into the 2018 vehicle.

First, the team needs to finalize a size for the steering column that will be implemented into the steering system. The current steering column does not allow wires from the steering wheel to be routed through easily. If the diameter of the column is changed, then a new mounting system must be designed and implemented. This is also dependent on possible revisions to the steering wheel as a result of competition in 2017. This will be decided during the 2017-2018 school year. Thankfully, the steering system can implement steering columns of up to approximately 0.75 inches in outer diameter so there is some room to implement changes to the system. With that in mind, the steering wheel should be designed to provide enough mechanical advantage to easily turn the vehicle. When designing the column, keep in mind that the end of the steerer will see a 26 lb force at low speeds that needs to be overcome.

The Supermileage team also needs to remanufacture or modify the brake bosses for the knuckles. The steering system was designed to work with the current brake bosses, however, it was found late in the assembly process that the dimension between the holes that mount to the knuckles was 1.5 inches rather than 1.25 inches. This was due to the project team basing the knuckle design off of the CAD of the brake boss rather than measuring the actual part that was installed on the vehicle. Fortunately, this part is relatively easy to machine from aluminum angle stock.

Despite a few modifications that will be needed before implementation this senior project was able to provide a good foundation that can be implemented into the new vehicle. The lessons learned from the manufacturing will provide important insights for the team to avoid issues faced during the senior project and to effectively design any future components on the Supermileage vehicle. This steering system prototype will allow the club to dedicate importance resources to the other aspects of the vehicle, such as the chassis, before competition in 2018.

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Appendices List

A. House of Quality
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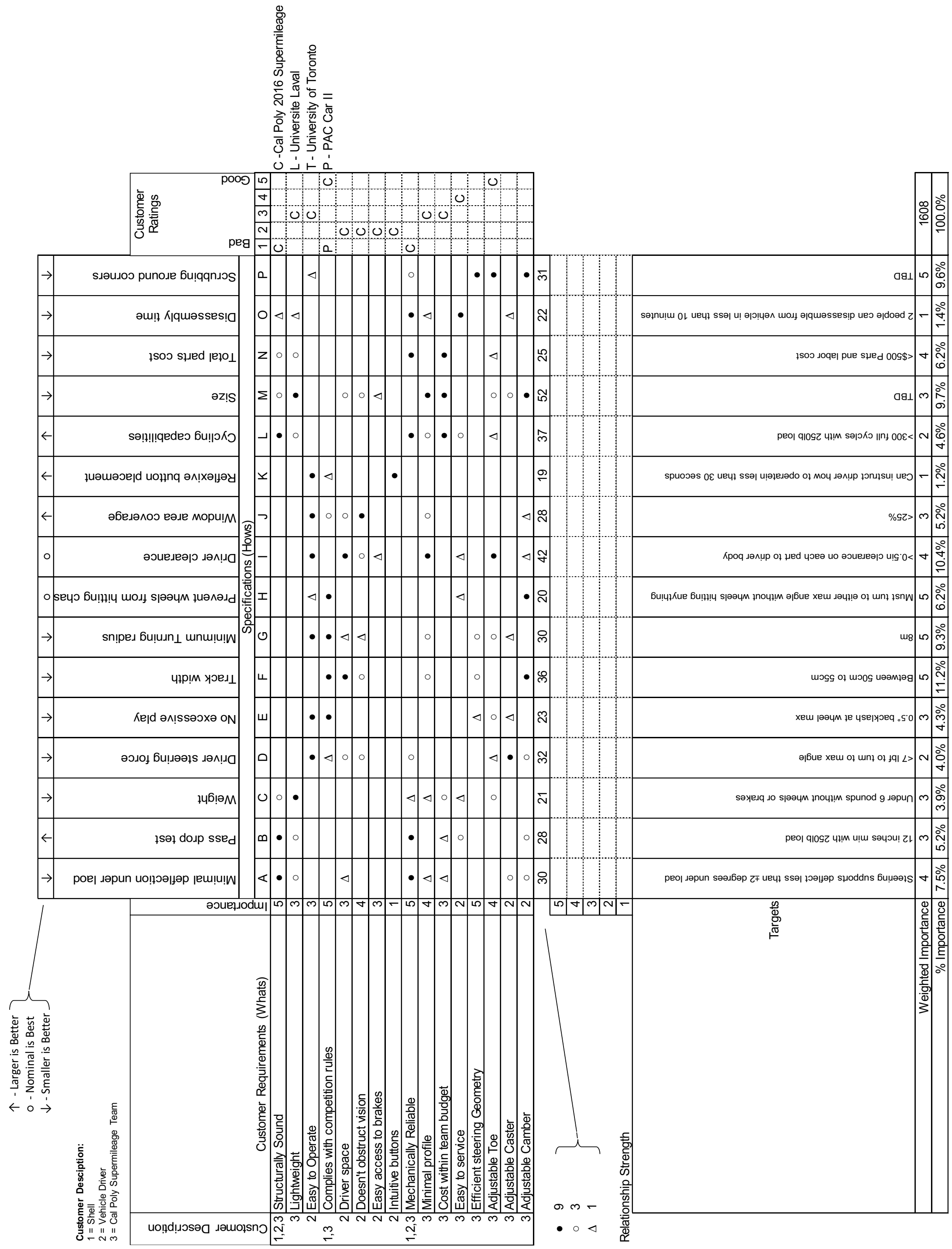
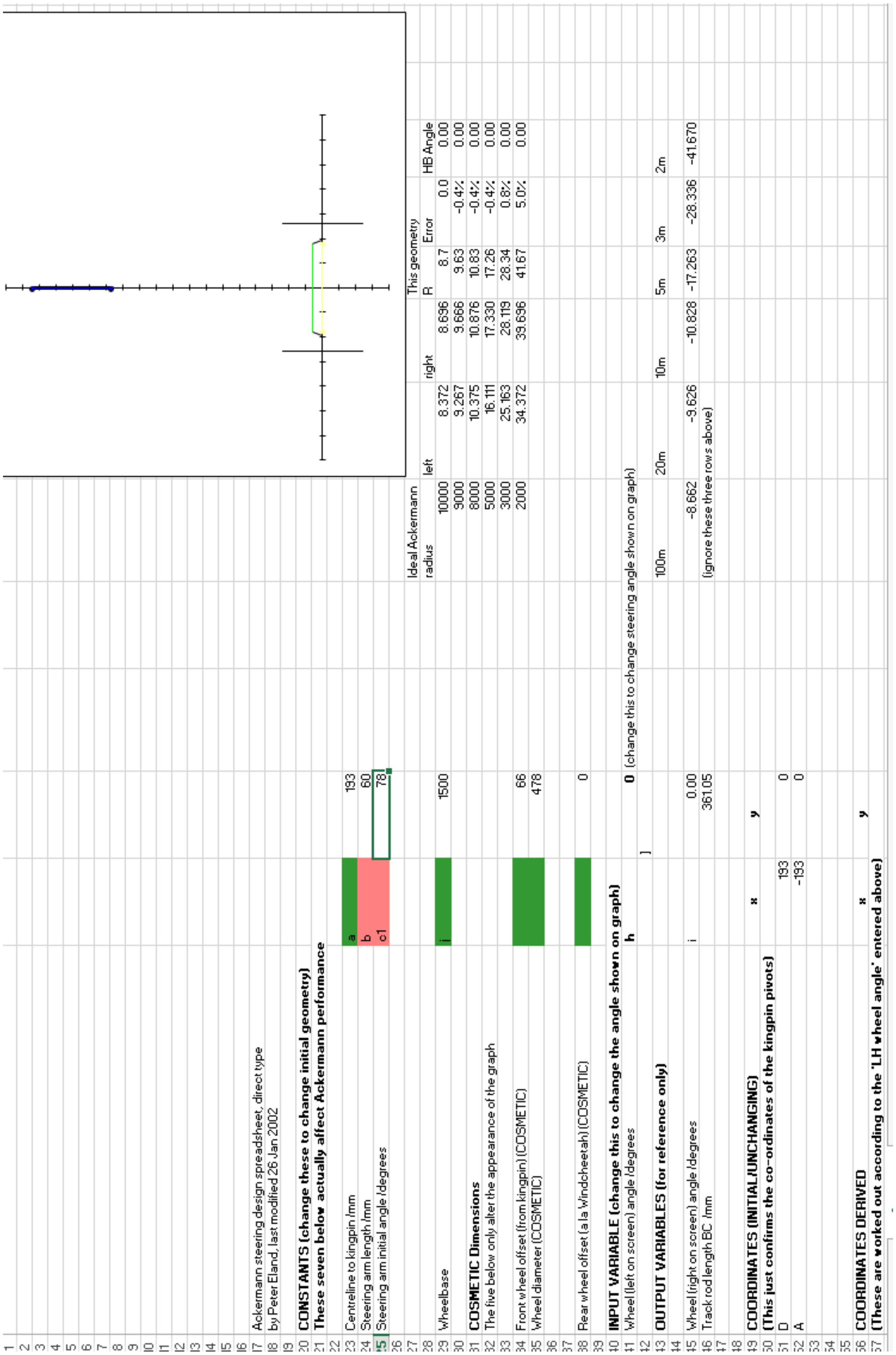
Appendix A – House of Quality



Appendix B – Excel Ackerman Steer Model



Ackermann steering design spreadsheet, direct type
by Peter Eland, last modified 26 Jan 2002

CONSTANTS (change these to change initial geometry)
These seven below actually affect Ackermann performance

Centreline to kingpin /mm	a	193
Steering arm length /mm	b	60
Steering arm initial angle /degrees	c1	78
Wheelbase	j	1500

COSMETIC Dimensions
The five below only alter the appearance of the graph

Front wheel offset (from kingpin) (COSMETIC)		66
Wheel diameter (COSMETIC)		478
Rear wheel offset (a la Windcheetah) (COSMETIC)		0

INPUT VARIABLE (change this to change the angle shown on graph)

Wheel (left on screen) angle /degrees	h	**0**	(change this to change steering angle shown on graph)

OUTPUT VARIABLES (for reference only)

Wheel (right on screen) angle /degrees	i	0.00
Track rod length BC /mm		361.05

Ideal Ackermann			This geometry		
radius	left	right	R	Error	HB Angle
10000	8.372	8.696	8.7	0.0	0.00
9000	9.267	9.666	9.63	-0.4%	0.00
8000	10.375	10.876	10.83	-0.4%	0.00
5000	16.111	17.330	17.26	-0.4%	0.00
3000	25.163	28.119	28.34	0.8%	0.00
2000	34.372	39.696	41.67	5.0%	0.00

100m	20m	10m	5m	3m	2m
-8.662	-9.626	-10.828	-17.263	-28.336	-41.670

(ignore these three rows above)

COORDINATES (INITIAL/UNCHANGING)
(This just confirms the co-ordinates of the kingpin pivots)

	x	y
D	193	0
A	-193	0

COORDINATES DERIVED x y
(These are worked out according to the 'LH wheel angle' entered above)

Appendix C – Excel Load and Force Calculations

Vehicle Parameter			
L	Wheelbase	150	cm
T	Track	52	cm
x_{cg}	CG to rear axle	109.5	cm
P	Tire pressure	70	psi
Wt	Total weight	220	lb_f
h	CG Height	25.2	cm
f_r	Rolling Resistance	0.001	-
V	Vehicle Speed	15	mph
R	Turn radius	800	cm
g	Gravity	32.2	ft/s^2

Pacejka Magic Equation	
a30	57.806
a31	15.101
a40	-0.082
a41	0.186

Pacejka Magic Equation	
c30	1.802
c31	-0.201
c40	-1.804
c41	0.197
c50	-2.927
c51	-0.047

Lateral Acceleration		
At CG	0.5729	g

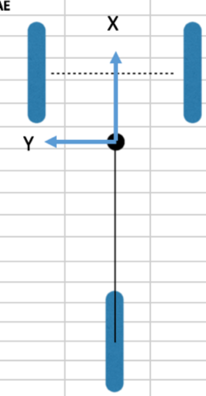
Ackerman Angles	
Inside	
11.339	deg
Outside	
10.620	deg

Max Speed for Rollover	
28.131	mph

For Left Turn

NOTE: Axis convention is not standard SAE

Inner Wheel		
Static Wt	-80.300	lb_f
LLT	22.295	lb_f
Net F_z	-58.005	lb_f
α_i	-1.704	deg
$C_{\alpha i}$	-16.896	lbf/deg
G_{zi}	0.021	lbf-in/deg
F_{yi}	28.789	lb_f
F_{xi}	0.058	lb_f
M_{zi}	-0.036	lb_f-in



Outer Wheel		
Static Wt	-80.300	lb_f
LLT	-22.295	lb_f
Net F_z	-102.595	lb_f
α_o	-2.525	deg
$C_{\alpha o}$	-25.038	lbf/deg
G_{zi}	0.023	lbf-in/deg
F_{yo}	63.221	lb_f
F_{xo}	0.103	lb_f
M_{zo}	-0.040	lb_f

Bicycle Model		
Static Wt	-160.600	lb_f
α_o	-3.159	deg
$C_{\alpha o}$	-29.125	lbf/deg
G_{zi}	0.019	lbf-in/deg
F_{yo}	92.010	lb_f
F_{xo}	0.161	lb_f
M_{zo}	-0.032	lb_f-in
δ	11.92734	deg

Rear		
F_{zr}	59.4	lb_f
α_r	-1.976	deg
$C\alpha_r$	17.226	lb_f/deg
$F_{y\ req}$	34.031	lb_f
F_{xr}	0.059	lb_f

Properties

SAI	14	deg
Top rod end L	0.857	in
Bot Rod end L	1.570	in
base to top	6.283	in
base to bot	4.243	in
Subframe ht	10	in
Subframe wd	12	in
Driver push	35	lbf
Caster	6	deg
Rw	10	in
h-knuckle	2	in
L-axle	3.5	in
h-ackerman	4.5	in
L-ackerman	3	in
Rotor to center	0.825	in
Rotor Radius	2.76	in

Forces at Right Wheel Only

	Cornering and Braking (Left turn)		Cornering Only (Left turn)		Cornering and Braking (right turn)		Cornering Only right turn)		Static/Stright Line	
Fz	102.59	lbf	102.59	lbf	58.01	lbf	56.50	lbf	80	lbf
Fy	63.22	lbf	63.22	lbf	-28.79	lbf	-28.79	lbf	0	lbf
Fb	40.00	lbf	0.00	lbf	40.00	lbf	0.00	lbf	0	lbf
Turn angle	10.13	deg	10.13	deg	11.65	deg	11.65	deg	0	deg

Reactions on Knuckle

	Cornering and Braking (Left turn)		Cornering Only (Left turn)		Cornering and Braking (right turn)		Cornering Only right turn)		Static/Stright Line		MAX VALS	
Rxa	10.45	lbf	-44.97	lbf	-78.70	lbf	-23.36	lbf	4.20	lbf	78.70	lbf
Rya	24.25	lbf	37.69	lbf	-210.60	lbf	-195.06	lbf	-114.05	lbf	210.60	lbf
Rza	-142.59	lbf	-102.59	lbf	-98.01	lbf	-56.50	lbf	-80.00	lbf	142.59	lbf
Max Shear	26.40	lbf	58.68	lbf	224.83	lbf	196.45	lbf	114.13	lbf	224.83	lbf
Rxb	0.67	lbf	56.10	lbf	84.52	lbf	29.18	lbf	-4.20	lbf	84.52	lbf
Ryb	-109.37	lbf	-123.95	lbf	250.97	lbf	234.10	lbf	123.72	lbf	250.97	lbf
Rzb	0.00	lbf	0.00	lbf	0.00	lbf	0.00	lbf	0.00	lbf	0.00	lbf
Max Shear	109.37	lbf	136.05	lbf	264.82	lbf	235.92	lbf	123.79	lbf	264.82	lbf
Fa	22.89	lbf	24.03	lbf	-12.17	lbf	-10.85	lbf	-9.67	lbf	24.03	lbf

Reactions on Base

	Cornering and Braking (Left turn)		Cornering Only (Left turn)		Cornering and Braking (right turn)		Cornering Only right turn)		Static/Stright Line		MAX VALS	
Rxo	11.12	lbf	11.12	lbf	5.82	lbf	5.82	lbf	0.00	lbf	11.12	lbf
Ryo	-85.12	lbf	-86.26	lbf	40.36	lbf	39.04	lbf	9.67	lbf	86.26	lbf
Rzo	-142.59	lbf	-102.59	lbf	-98.01	lbf	-56.50	lbf	-80.00	lbf	142.59	lbf
Mxo	-433.90	lbf-in	-377.04	lbf-in	-342.36	lbf-in	-280.68	lbf-in	-260.17	lbf-in	433.90	lbf-in
Myo	68.52	lbf-in	-44.54	lbf-in	-135.88	lbf-in	-22.98	lbf-in	8.58	lbf-in	135.88	lbf-in
Mzo	10.01	lbf-in	49.53	lbf-in	65.25	lbf-in	25.79	lbf-in	-3.00	lbf-in	65.25	lbf-in

Shoulder Bolt Failure Stainless

Shear		
Su	70000	psi
Ssu	35000	psi
Shoulder Dia	0.25	in
Shear Stress	4580.17	psi
Design Factor	15.28	
Tensile failure		
Max force	250.97	lbf
Minor dia area	0.0175	in^2
Stress	14340.90	psi
DF	4.88	
Hole yield inside	**6061-T6**	
Sy	40000	psi
dia	0.25	in
Thickness	0.10	in
Stress	8993.14	psi
DF	4.45	
Hole yield surface	**6061-T6**	in
Head dia	0.375	in
Head dia area	0.110	in^2
Stress	2700.1059	psi
DF	14.81	

Rod End Failure Alloy Steel

Thrust		
Thrust load cap	540.00	lbf
Max load	142.59	lbf
DF	3.79	
Bending	Alloy steel	
Sy	120000	psi
Max lateral force	224.83	lbf
Thickness	0.3125	in
Width	0.40625	in
Length	1.125	in
Major Dia	0.19	in
Stress	40777.57	psi
MOI	0.00096918	in^4
DF	2.94	
Deflection		
E	2.90E+07	psi
SF	1	
Deflection	0.004	in
Rotation	0.2900	deg

Knuckle Bolt

Shear		
Su	70000	psi
Ssu	35000	psi
Shoulder Dia	0.17	in
Shear Stress	11708.19	psi
Design Factor	2.99	

Upright bending

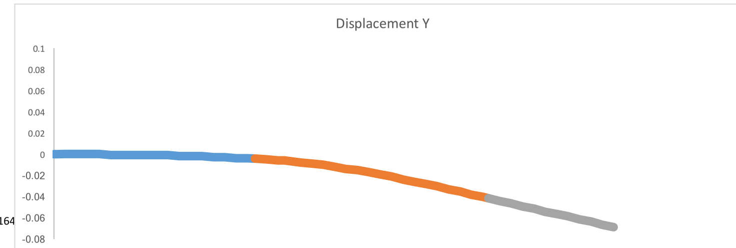
y_max	0.6065	in
c	0.2185	
M_max	285.6	lbf-in
I_weak	0.0212	in^4
I_strong	0.228	in^4
Sy	40000	psi
VM Stress	8170.6	psi

Section 1		
F1	44.40	lbf
M	-960.16	lbf-in
a	3.533	in

Section 2		
F1	361.00	lbf
F2	-316.60	lbf
M	-134.757163	lbf-in
a	0.52	in
b	3.2	
L	4.1	

Properties		
E*I_carbon	1297828.51	lbf*in^2
I_carbon	1	-
E_alum	1.00E+07	psi
I_alum	0.0211	in^4
SF	1	-
L	10	in

X_sec	X_global	Y1	Y2	Y3	SUM	
0	0	0.00E+00	0.00E+00		0.0000000	
0.2	0.2	2.37E-06	-1.48E-05		-0.0000124	
0.4	0.4	9.30E-06	-5.92E-05		-0.0000499	
0.6	0.6	2.05E-05	-1.33E-04		-0.0001126	
0.8	0.8	3.58E-05	-2.37E-04		-0.0002010	
1	1	5.47E-05	-3.70E-04		-0.0003152	
1.2	1.2	7.72E-05	-5.33E-04		-0.0004555	
1.4	1.4	1.03E-04	-7.25E-04		-0.0006222	
1.6	1.6	1.31E-04	-9.47E-04		-0.0008156	
1.8	1.8	1.63E-04	-1.20E-03		-0.0010360	
2	2	1.96E-04	-1.48E-03		-0.0012835	
2.2	2.2	2.32E-04	-1.79E-03		-0.0015586	
2.4	2.4	2.69E-04	-2.13E-03		-0.0018614	
2.6	2.6	3.08E-04	-2.50E-03		-0.0021923	
2.8	2.8	3.49E-04	-2.90E-03		-0.0025515	
3	3	3.90E-04	-3.33E-03		-0.0029392	
3.2	3.2	4.32E-04	-3.79E-03		-0.0033559	
3.4	3.4	4.75E-04	-4.28E-03		-0.0038016	theta tip
3.533	3.533	5.03E-04	-4.62E-03		-0.0041143	-0.002351164
0	3.533	0.000E+00	0.000E+00	0.00E+00	-0.0041143	
0.2	3.733	1.551E-05	-9.403E-05	-1.28E-05	-0.0046759	
0.4	3.933	5.292E-05	-3.681E-04	-5.11E-05	-0.0054211	
0.52	4.053	8.019E-05	-6.140E-04	-8.63E-05	-0.0059571	
0.8	4.333	1.450E-04	-1.408E-03	-2.04E-04	-0.0074631	
1	4.533	1.912E-04	-2.151E-03	-3.19E-04	-0.0087443	
1.2	4.733	2.375E-04	-3.025E-03	-4.60E-04	-0.0101831	
1.4	4.933	2.837E-04	-4.019E-03	-6.26E-04	-0.0117674	
1.6	5.133	3.300E-04	-5.122E-03	-8.17E-04	-0.0134853	
1.8	5.333	3.763E-04	-6.320E-03	-1.03E-03	-0.0153248	
2	5.533	4.225E-04	-7.602E-03	-1.28E-03	-0.0172739	Average angle
2.2	5.733	4.688E-04	-8.957E-03	-1.55E-03	-0.0193205	-0.009638842
2.4	5.933	5.151E-04	-1.037E-02	-1.84E-03	-0.0214527	-0.552264989
2.6	6.133	5.613E-04	-1.183E-02	-2.16E-03	-0.0236585	
2.8	6.333	6.076E-04	-1.333E-02	-2.50E-03	-0.0259258	
3	6.533	6.538E-04	-1.485E-02	-2.87E-03	-0.0282427	
3.2	6.733	7.001E-04	-1.639E-02	-3.27E-03	-0.0305971	
3.4	6.933	7.464E-04	-1.793E-02	-3.69E-03	-0.0329790	
3.6	7.133	7.926E-04	-1.946E-02	-4.14E-03	-0.0353866	
3.8	7.333	8.389E-04	-2.100E-02	-4.61E-03	-0.0378196	
4	7.533	8.852E-04	-2.254E-02	-5.11E-03	-0.0402782	theta tip
4.1	7.633	9.083E-04	-2.330E-02	-5.37E-03	-0.0415171	-0.012388214
0	7.633				-0.0415171	-0.709792388
0.2	7.833				-0.0439948	
0.4	8.033				-0.0464724	
0.6	8.233				-0.0489500	
0.8	8.433				-0.0514277	
1	8.633				-0.0539053	
1.2	8.833				-0.0563830	
1.4	9.033				-0.0588606	
1.6	9.233				-0.0613383	
1.8	9.433				-0.0638159	
2	9.633				-0.0662935	
2.2	9.833				-0.0687712	
2.367	10				-0.0708400	



Appendix D – Composite Tube Calculations

```
%
%

% Simple CLT File
% This one includes hygrothermal
%

clear all
close all

%set up a diary file
diary RockRec.dat


%units are US customary (lb, in, E in psi)

% total laminate definition in matrix below
% [ply angles, thicknesses, matl. #]

%Set up for two materials

% Data in there now is
%1-carbon
%2-cloth


%Laminate is defined in this matrix l (sorry it looks like a one)
% [ angle  thick  matl #]
 l=[ 0     0.0075    1;
     0     0.0075    1;
     -45   0.0075    1;
     45    0.0075    1;
     45    0.0075    1;
     -45   0.0075    1;
     0     0.0075    1;
     0     0.0075    1;]


% this is the total laminate
% cut, paste, edit above to study your laminate of choice

%delta temp
DT = 0.0


% size command to get number of plies
n = size(l,1)
```

```
%      Lamina Properties
%      matrix for engineering constants
      %E1     E2    v12  G12   a11     a22
 E = [33.0e6 1.4e6  .30   .93e6  -.5e-6  15e-6; %DRAGONPLATE
      10.0e6 10.0e6 .050  .93e6  1.0e-6  1.0e-6] %carbon cloth need to fix CTE
 % a's are CTE's


%intiialize the ply distance and ABD matrices
NT = zeros(3,1);
MT = zeros(3,1);

h = zeros(n+1,1);
A = zeros(3);
B = zeros(3);
D = zeros(3);
% Form R matrix which relates engineering to tensor strain
R = [1  0  0;
     0  1  0;
     0  0  2];

% find the total thickness
total = sum(l,1);
thick = total(1,2)



% locate the bottom of the first ply
h(1) = -thick/2.;
imax = n + 1;
%loop for rest of the ply distances from midsurf
for i = 2 : imax
   h(i) = h(i-1) + l(i-1,2);
end

%loop over each ply to integrate the ABD matrices
for i = 1:n

   %ply material ID
   mi=l(i,3);
   v21 = E(mi,2)*E(mi,3)/E(mi,1);
   d = 1 - E(mi,3)*v21;

   %Q12 matrix
   Q = [E(mi,1)/d          v21*E(mi,1)/d      0;
        E(mi,3)*E(mi,2)/d   E(mi,2)/d          0;
        0                 0               E(mi,4)];


   %ply angle in radians
```

```
   a1=l(i,1)*pi/180;

         %Form transformation matrices T1 for ply
         T1 = [(cos(a1))^2       (sin(a1))^2               2*sin(a1)*cos(a1);
         (sin(a1))^2        (cos(a1))^2              -2*sin(a1)*cos(a1);
        -sin(a1)*cos(a1)    sin(a1)*cos(a1)   (cos(a1))^2-(sin(a1))^2 ];


   %Form Qxy
   Qxy = inv(T1)*Q*R*T1*inv(R);

         % build up the laminate stiffness matrices
   A = A + Qxy*(h(i+1)-h(i));
   B = B + Qxy*(h(i+1)^2 - h(i)^2);
   D = D + Qxy*(h(i+1)^3 - h(i)^3);

   %load alphs into and array
   a=[E(mi,5); E(mi,6); 0.0];

   %transform cte's mult by DT to get thermal strain exy
   exy = (R*inv(T1)*inv(R)*a)*DT;
   %build up thermal load as well now
   NT = NT +  Qxy*exy*(h(i+1)-h(i));
   MT = MT + .5*(Qxy*exy*(h(i+1)^2 - h(i)^2));



%end of stiffness loop
end

%change the display format for compliance matrix
format short e

A = 1.0*A
B = .5*B
D = (1/3)*D

%
%
K = [A, B;
     B, D]


%wall
t = thick

Ho = 2
bo = 1.01

H= Ho + t
```

```
b = bo + t

%section properties

A = 2*(H+b)*t
Iweak= 2*(b/2)^2*H*t


gamma = .06
wtlength = gamma*A

%design moment alum equiv
% M = 5120

%Max torque alum equivalent
%T=11,500

%max shear load
% V=100

% line load from bending
%Nxmax=M/(pi*R^3)

%direct shear line load
% Nxymax=V/(pi*R)

%add in torsion CHECK...
%Nxytors = T/(2*pi*R^2)

%Moment carried by couple of line loads on h
M = 435 %in-lb

Nax=M/(b*H)

%
  Nx=Nax
  Ny=0.0
  Ns=0.0
  Mx=0.0
  My=0.0
  Ms=0.0



%
% superimpose mech and thermal loads
load = [ NT(1) + Nx;
         NT(2) + Ny;
         NT(3) + Ns;
         MT(1) + Mx;
         MT(2) + My;
```

```
         MT(3) + Ms]

C = inv(K)
%

% Effective tube axial modulus
Ex = 1/(C(1,1)*thick)

%effective tube shear modulus
Gxy=1/(C(3,3)*thick)

%effective stiffness parameters

%Bend
EI = Ex*Iweak
%axial
EA =Ex*A

%
%compute the strains = compliance times load
e = C*load
%
%
% reduction factor for ultimate (pseudo A-basis use .80
% reduce for CALPOLY Made
RF=.80
%
%
% allowable strains reduced to account for ultimate strength after impact
% row1 is carbon
% row2 is E-glass
% transverse prperties assumed same
% load allowable strains into array
%
% load allowable strains into array
%     ELU        ELUP       ETU      ETUP     ELTU
ea = [RF*.012   RF*.011   RF*.010   RF*.031  RF*.0296;%fix this???
      RF*.010   RF*.010   RF*.010   RF*.010  RF*.025]%cloth
%
%zero out results array
ERES = zeros(2*n,6);
SRES = zeros(2*n,6);

% loop over each ply and calculate strain
for i=1 : n;
   %loop over top and bottom of each ply
   for j=1 : 2;
   % one is bottom two is top for loc
   ply = i;
   loc = j;
```

```
   z = h(i-1+j);

   %ply strain from midplane strain
   el= [ e(1)+z*e(4);  e(2)+z*e(5);  e(3)+z*e(6)];

   %ply material ID
   mi=l(i,3);
   v21 = E(mi,2)*E(mi,3)/E(mi,1);
   d = 1 - E(mi,3)*v21;

   %Q12 matrix
   Q = [E(mi,1)/d          v21*E(mi,1)/d      0;
        E(mi,3)*E(mi,2)/d   E(mi,2)/d          0;
        0                 0               E(mi,4)];

   %
   %ply angle in radians
   a1=l(i,1)*pi/180;

        %Form transformation matrices T1 for ply
        T1 = [(cos(a1))^2       (sin(a1))^2               2*sin(a1)*cos(a1);
        (sin(a1))^2        (cos(a1))^2              -2*sin(a1)*cos(a1);
        -sin(a1)*cos(a1)    sin(a1)*cos(a1)   (cos(a1))^2-(sin(a1))^2 ];

   % load alpha for the ply
   a=[E(mi,5); E(mi,6); 0.0];

   % tranform to 1,2
   % subtract off alpha delta T to get mech strain that causes stress
   ep = R*T1*inv(R)*el - a*DT;

   %calculate stress in 1,2 coords
   sp = Q*ep;

%failure index now looks at two different materials

   if ep(1) > 0.0;
      FI = ep(1)/ea(mi,1);
      FIF=FI;
     elseif ep(1) < 0.0;
        FI = abs( ep(1) )/ea(mi,2);
        FIF=FI;
   end

   if ep(2) > 0.0;
     F1 = ep(2)/ea(mi,3);
   elseif ep(2) < 0.0;
     F1 = abs( ep(2) )/ea(mi,4);
   end
```

```
%

  if F1 > FI;
   FI = F1;
  end
%
%
   F1 = abs( ep(3) )/ea(mi,5);
  if F1 > FI ;
   FIe = F1;
  elseif F1 < FI;
   FIe = FI;
  end


   %load the results array
   % note top and botom of every ply!

   %strain results, FI based on Max Strain
   %angle,eps1,eps2,gamma12,FI, FIfiber
    ERES(2*i+j-2,1)=l(i);
    ERES(2*i+j-2,2)=ep(1);
    ERES(2*i+j-2,3)=ep(2);
    ERES(2*i+j-2,4)=ep(3);
    ERES(2*i+j-2,5)=FIe;
    ERES(2*i+j-2,6)=FIF;

   %stress results, FI based on max strain
   %angle,Sigma1,Sigma2,Tau12, FI, FIfiber
    SRES(2*i+j-2,1)=l(i);
    SRES(2*i+j-2,2)=sp(1);
    SRES(2*i+j-2,3)=sp(2);
    SRES(2*i+j-2,4)=sp(3);
    SRES(2*i+j-2,5)=FIe;
    SRES(2*i+j-2,6)=FIF;


end
%
end
ERES=ERES*1
SRES=SRES*1


diary off
%
%
```

```
EI =   1.2978e+06


ERES =

           0   1.7932e-04  -1.3370e-04   5.7741e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04   4.3306e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04   4.3306e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04   2.8871e-21   1.8679e-02   1.8679e-02
 -4.5000e+01   2.2808e-05   2.2808e-05   3.1302e-04   1.3219e-02   2.3758e-03
 -4.5000e+01   2.2808e-05   2.2808e-05   3.1302e-04   1.3219e-02   2.3758e-03
  4.5000e+01   2.2808e-05   2.2808e-05  -3.1302e-04   1.3219e-02   2.3758e-03
  4.5000e+01   2.2808e-05   2.2808e-05  -3.1302e-04   1.3219e-02   2.3758e-03
  4.5000e+01   2.2808e-05   2.2808e-05  -3.1302e-04   1.3219e-02   2.3758e-03
  4.5000e+01   2.2808e-05   2.2808e-05  -3.1302e-04   1.3219e-02   2.3758e-03
 -4.5000e+01   2.2808e-05   2.2808e-05   3.1302e-04   1.3219e-02   2.3758e-03
 -4.5000e+01   2.2808e-05   2.2808e-05   3.1302e-04   1.3219e-02   2.3758e-03
           0   1.7932e-04  -1.3370e-04  -2.8871e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04  -4.3306e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04  -4.3306e-21   1.8679e-02   1.8679e-02
           0   1.7932e-04  -1.3370e-04  -5.7741e-21   1.8679e-02   1.8679e-02
```

Appendix E – Bill of Materials

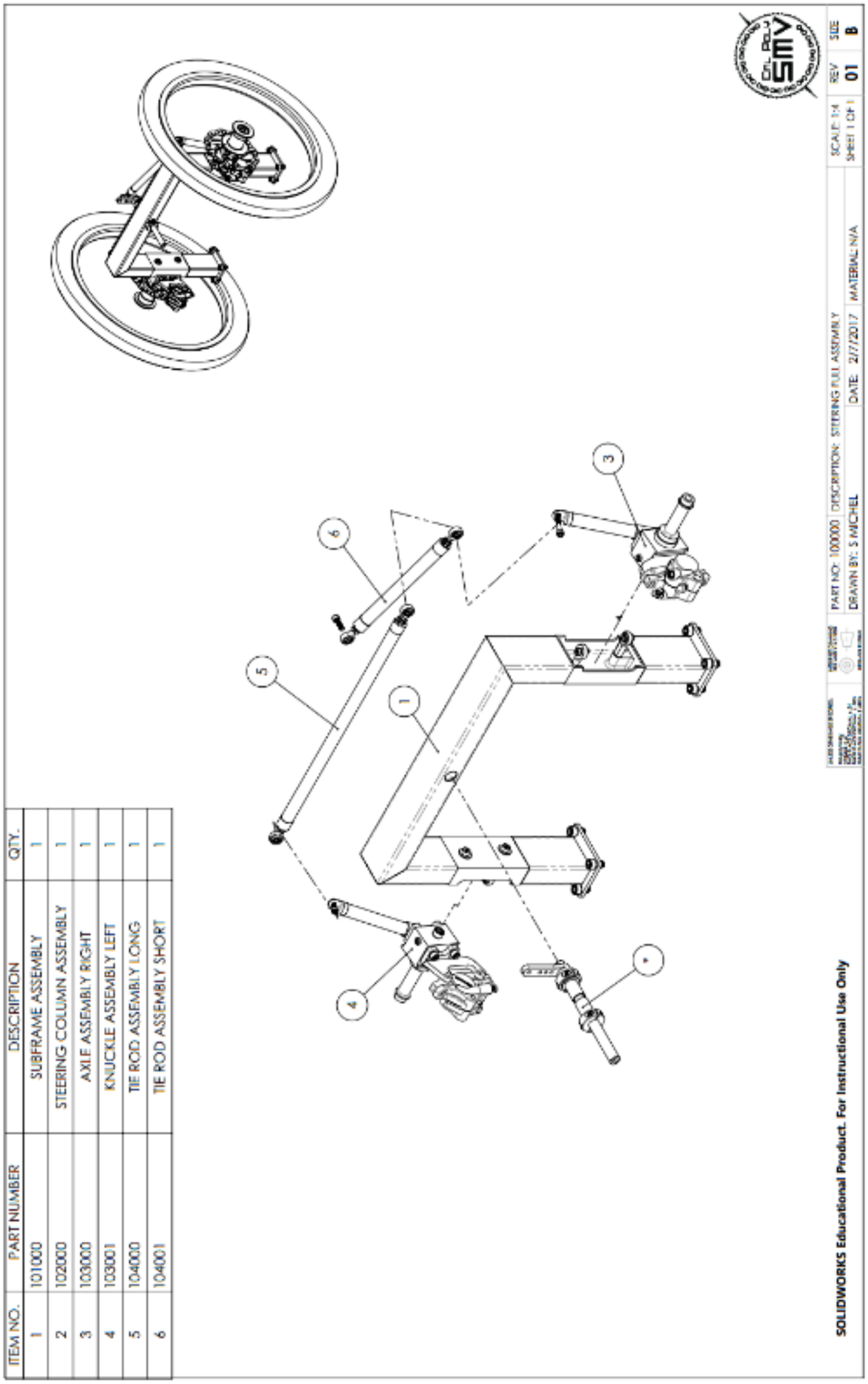
Indented Bill of Material (BOM)

2018 Supermileage Steering System

Part Number	Description (Lvl0 / Lvl1 / Lvl2)	MFG Notes	Vendor	Part #	Qty Needed	Cost	Line Cost	Notes	Matl	Weight [lb]	Line Wt
100000	Full Assembly										
101000	Subframe Assembly										
101010	#10-32 RH Female Thrust Rated Rod End (3/16" Ball, 9/16" thread)		McMaster Carr	8405K291	2	$ 6.84	$ 13.68		Alloy Steel	0.0300	0.0600
101020	#10-32 RH Female Steel Ball Joint Rod End (3/16" ball, 1/2" thread)		McMaster Carr	60645K311	2	$ 3.32	$ 6.64		Alloy Steel	0.0300	0.0600
101030	Upright - Left (2.25" X 1.25")	CNC'd from aluminum stock	McMaster Carr	8975K955	1	$ 22.52	$ 22.52	1 ft stock	Al 6061-T6	0.2792	0.2792
101040	Upright - Right (2.25" X 1.25")	CNC'd from aluminum stock	McMaster Carr	8975K955	1	-----	-----	purchased above	Al 6061-T6	0.2792	0.2792
101050	3/16"x3/8" Shoulder Screw		McMaster Carr	93985A204	4	$ 2.97	$ 11.88		416 Stainless	0.0070	0.0280
101060	1/4"x5/32" Shoulder Screw		McMaster Carr	94035A176	2	$ 2.47	$ 4.94		18-8 Stainless	0.0044	0.0088
101070	Carbon Frame Cross Bar (1.01X1.13 - 2.00X2.13)	Cut to length and mitered	Rockwest	25507-36	1	$ 163.99	$ 163.99	36" length tube	carbon fiber	0.0310	0.0310
101071	Carbon frame Top Piece (1.01X1.13 - 2.00X2.13)	Cut to length and mitered	Rockwest	25507-36	2	-----	-----	Purchased above	carbon fiber	0.0056	0.0112
101072	Carbon frame Bottom Piece (1.01X1.13 - 2.00X2.13)	Cut to length	Rockwest	25507-36	2	-----	-----	Purchased above	carbon fiber	0.0081	0.0162
101080	1/4"x7/8" Shoulder Screw		McMaster Carr	92012A597	2	$ 7.62	$ 15.24		Alloy Steel	0.0190	0.0380
101090	1/4" Washer		McMaster Carr	92141A029	4	$ 3.37	$ 3.37	Pack of 100	18-8 Stainless	0.0039	0.0156
101100	Base bracket	CNC'd from aluminum stock	McMaster Carr	8975K39	2	$ 20.79	$ 20.79	1ft stock	Al 6061-T6	0.1400	0.2800
101120	5/16-18X0.5" SHCS		McMaster Carr	91251A378	8	$ 11.12	$ 11.12	Pack of 50	Alloy Steel	0.0208	0.1664
101130	Corner Lugs (1.5"x1.5" Stock)	Machined from aluminum	Online Metals	Link to Stock	2	$ 14.31	$ 14.31	1ft stock	Al 6061-T6	0.1420	0.2840
102000	Steering Column Assembly										
102010	1/2" Clamping Two-Piece Shaft Collar		McMaster Carr	6436K71	2	$ 5.15	$ 10.30		Al 2024	0.0116	0.0232
102020	1/2" Flanged sleeve bearings		McMaster Carr	6294K448	2	$ 2.05	$ 4.10		MDS-filled nylon	0.0046	0.0093
102030	1/2" Steering shaft (ID=0.260", t=0.120")		McMaster Carr	1968T23	1	$ 14.33	$ 14.33	1 ft stock	Al 2024-T3	0.0845	0.0845
102050	Steerer (3/4" stock)	CNC machined	McMaster Carr	9008K12	1	$ 3.00	$ 3.00	1/2 ft stock	Al 6061-T7	0.0353	0.0353
102060	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	$ 6.13	Package of 25	black oxide alloy steel	0.0044	0.0044
103000	Knuckle Assembly Right										
103010	Knuckle body (1.25"X1.25" stock)	CNC'd from 6061 stock	McMaster Carr	9008K46	1	$ 14.56	$ 14.56	1 ft stock	Al 6061-T6	0.2630	0.2630
103020	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	-----	Purchased above	black oxide alloy steel	0.0044	0.0044
103030	Stainless Steel Unthreaded Spacer	Length machined to length	McMaster Carr	92320A462	2	$ 2.17	$ 4.34		Stainless Steel	0.0030	0.0060
103040	1/4"-20 x 1-3/4" SHCS		McMaster Carr	90044A124	2	-----	$ 9.34	Package of 50	black oxide alloy steel	0.0020	0.0040
103050	Brake Boss	From current vehicle	-----	-----	1	-----	-----		Al 6061-T6	0.0756	0.0756
103060	Spindle (1.125" round stock)	CNC'd from 4340 steel stock	Online Metals	Link to Stock	1	$ 41.34	$ 41.34	2ft stock	4340 normal. Rough turned	0.3340	0.3340
103070	Ackerman Boss Right	Metal 3D printed	Divergent	Website	1				316 Stainless	0.1251	0.1251
103080	Ackerman arm (ID=0.5", OD=0.59")	Cut to length and Mitered	DragonPlate	Link to Part	1	$ 36.00	$ 36.00	48" long rod	Uni carbon fiber	0.0016	0.0016
103090	0.5" Single Sided Threaded Clevis Insert		DragonPlate	Link to Part	1	$ 7.60	$ 7.60		aluminum alloy (TBD)	0.0200	0.0200
103001	Knuckle Assembly Left										
103010	Knuckle body (1.25"X1.25" stock)	CNC'd from 6061 stock	McMaster Carr	9008K46	1	-----	-----	Purchased above	Al 6061-T6	0.2630	0.2630
103020	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	-----	Purchased above	black oxide alloy steel	0.0044	0.0044
103030	Stainless Steel Unthreaded Spacer	Length machined to length	McMaster Carr	92320A462	2	$ 2.17	$ 4.34		Stainless Steel	0.0030	0.0060
103040	1/4"-20 x 1-3/4" SHCS		McMaster Carr	90044A124	2	-----	-----	Purchased above	black oxide alloy steel	0.0020	0.0040
103050	Brake Boss	From current vehicle	-----	-----	1				Al 6061-T6	0.0756	0.0756
103060	Spindle (1.125" round stock)	CNC'd from 4340 steel stock	Online Metals	Link to Stock	1	-----	-----	Purchased above	4340 normal. Rough turned	0.3340	0.3340
103071	Ackerman Boss Left	Metal 3D printed	Divergent	Website	1				316 Stainless	0.1251	0.1251
103080	Ackerman arm (ID=0.5", OD=0.59")	Cut to length and Mitered	DragonPlate	Link to Part	1	-----	-----	Purchased above	Uni carbon fiber	0.0016	0.0016
103090	0.5" Single Sided Threaded Clevis Insert		DragonPlate	Link to Part	1	$ 7.60	$ 7.60		aluminum alloy (TBD)	0.0200	0.0200
104000	Tie Rod Assembly Long										
104010	10-32 RH Male threaded shank (3/16" ball)		McMaster Carr	60645K111	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104020	10-32 LH Male threaded shank (3/16" ball)		McMaster Carr	60645K112	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104030	10-32 RH hex nut		McMaster Carr	90480A195	2	-----	$ 1.83	Package of 100	zinc-plated steel	0.0004	0.0008
104040	10-32 LH hex nut		McMaster Carr	99961A520	2	-----	$ 11.06	Package of 25	zinc-plated steel	0.0004	0.0008
104050	1/2" RH threaded end connector		Dragon Plate	Link to Part	1	$ 7.60	$ 7.60		aluminum	0.0350	0.0350
104060	1/2" LH threaded end connector (5/8" stock)	Machined in house	McMaster Carr	8974K48	1	$ 2.41	$ 2.41	1/2 ft stock	6061-T6	0.0240	0.0240
104070	Tie Rod Body Long (ID=0.5", OD=0.59")	Cut to length	Dragon Plate	Link to Part	1	$ 36.00	$ 36.00	48" long rod	carbon fiber	0.0061	0.0061
104080	10-32 X 5/8" SHCS		McMaster Carr	90128A944	1	-----	$ 6.82	Box of 25		0.0072	0.0072
104001	Tie Rod Assembly Short										
104010	10-32 RH Male threaded shank (3/16" ball)		McMaster Carr	60645K111	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104020	10-32 LH Male threaded shank (3/16" ball)		McMaster Carr	60645K112	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104030	10-32 RH hex nut		McMaster Carr	90480A195	2	-----	-----	Purchased above	zinc-plated steel	0.0004	0.0008
104040	10-32 LH hex nut		McMaster Carr	99961A520	2	-----	-----	Purchased above	zinc-plated steel	0.0004	0.0008
104050	1/2" RH threaded end connector		Dragon Plate	Link to Part	1	$ 7.60	$ 7.60		aluminum	0.0350	0.0350
104060	1/2" LH threaded end connector (5/8" stock)	Machined in house	McMaster Carr	8974K48	1	-----	-----	Purchased above	6061-T6	0.0240	0.0240
104071	Tie Rod Body Short (ID=0.5", OD=0.59")	Cut to length	Dragon Plate	Link to Part	1	-----	-----	Purchased above	carbon fiber	0.0026	0.0026
104080	10-32 X 5/8" SHCS		McMaster Carr	90128A944	1	-----	-----	Purchased above	black oxide alloy steel	0.0072	0.0072
104090	10-32 X 1-1/4" SHCS		McMaster Carr	90128A948	1	-----	$ 4.55	Box of 25	black oxide alloy steel	0.0124	0.0124
					Total part cost		**$ 543.45**			**Total weight**	**3.5513**

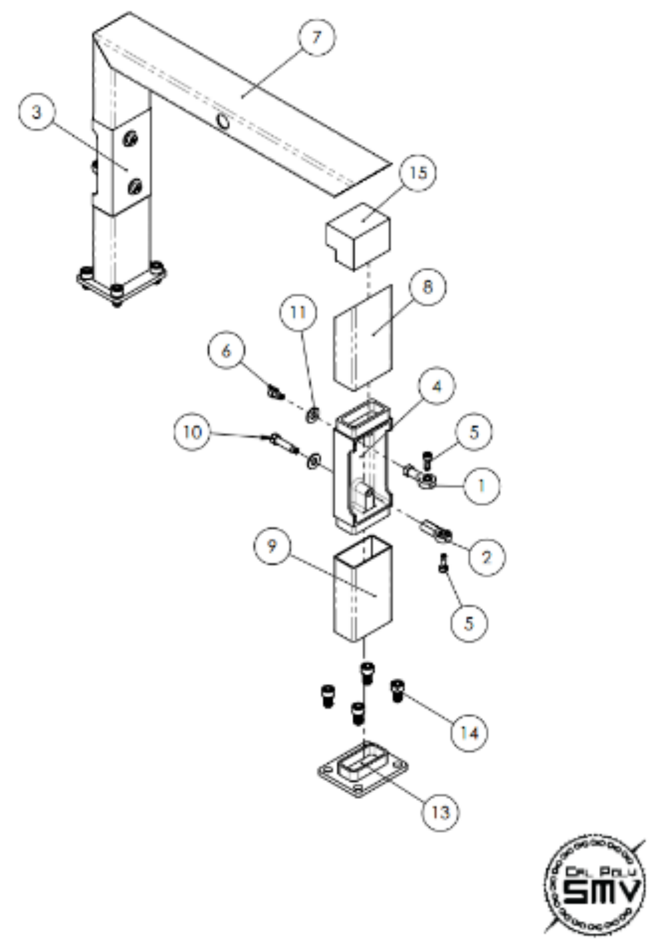
Appendix F – Specification Sheets and Drawings

Part Number: 100000



Part Number: 101000

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	101010	MCMASTER 8405K291	ALLOY STEEL	2
2	101020	MCMASTER 60645K311	ALLOY STEEL	2
3	101030	STEERING UPRIGHT LEFT	AL 6061-T6	1
4	101040	STEERING UPRIGHT LEFT	6061-T6	1
5	101050	MCMASTER 93985A204	18-8 STAINLESS	4
6	101060	MCMASTER 94035A176	18-8 STAINLESS	2
7	101070	RECTANGULAR CARBON FIBER TUBING	CARBON FIBER	1
8	101071	RECTANGULAR CARBON FIBER TUBING	CARBON FIBER	2
9	101072	RECTANGULAR CARBON FIBER TUBING	CARBON FIBER	2
10	101080	MCMASTER 92012A597	18-8 STAINLESS	2
11	101090	MCMASTER 92141A02	ALLOY STEEL	4
13	101100	BASE BRACKET	AL 6061-T6	2
14	101120	MCMASTER 91251A378	ALLOY STEEL	8
15	101130	CORNER LUG	AL 6061-T651	2



SOLIDWORKS Educational Product. For Instructional Use Only

PART NO: 101000 DESCRIPTION: SUBFRAME ASSEMBLY
DRAWN BY: S MICHEL DATE: 2/10/2017 MATERIAL:
SCALE: 1:4 SHEET 1 OF 1 REV 01 SIZE B

Part Number: 101010

Thrust-Rated Ball Joint Rod End

10-32 RH Female Shank, 3/16" Ball ID, 9/16" Long Thread

Each

ADD TO ORDER

In stock
$6.84 Each
8405K291

Shank Thread Direction	Right-Hand Threads
Shank Type	Female-Threaded
Shank Thread Size	10-32
Ball ID (A)	3/16"
Maximum Ball Swivel	36°
Overall Width (B)	11/16"
Overall Thickness (C)	5/16"
(D)	1 1/8"
Thread Length (E)	9/16"
Static Radial Load Capacity	1,910 lbs.
Thrust Load Capacity	540 lbs.
Additional Specifications	Inch Sizes
RoHS	Not Compliant

Thanks to an innovative body design that keeps the ball from being pushed out, these rod ends are able to take on thrust (side) loads. All have a zinc-plated steel housing; a steel ball; and an injection-molded, self-lubricating polyurethane insert. Temperature range is –40° to +176° F.

Part Number: 101020

Steel Ball Joint Rod End

10-32 RH Female Shank, 3/16" Ball ID, 1/2" Long Thread

Each

ADD TO ORDER

In stock
$3.32 Each
60645K311

Shank Thread Direction	Right-Hand Threads
Shank Type	Female-Threaded
Shank Thread Size	10-32
Ball ID (A)	3/16"
Maximum Ball Swivel	20°
Overall Width (B)	5/8"
Overall Thickness (C)	5/16"
(D)	1 1/16"
Thread Length (E)	1/2"
Static Radial Load Capacity	2,079 lbs.
Additional Specifications	Inch Sizes
RoHS	Compliant

Our general purpose rod ends will meet your basic connection needs.

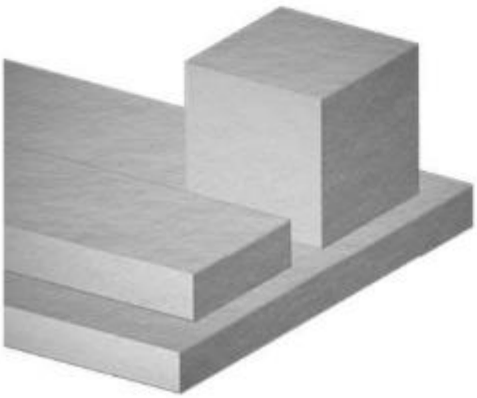
Inch sizes have a zinc-plated steel housing and chrome-plated steel ball (unless noted).

Part Number: 101030, 101040, 101100, 102050, 103010, 103050

Note: Reference Bill of Materials for aluminum stock needed for each part

Multipurpose 6061 Aluminum

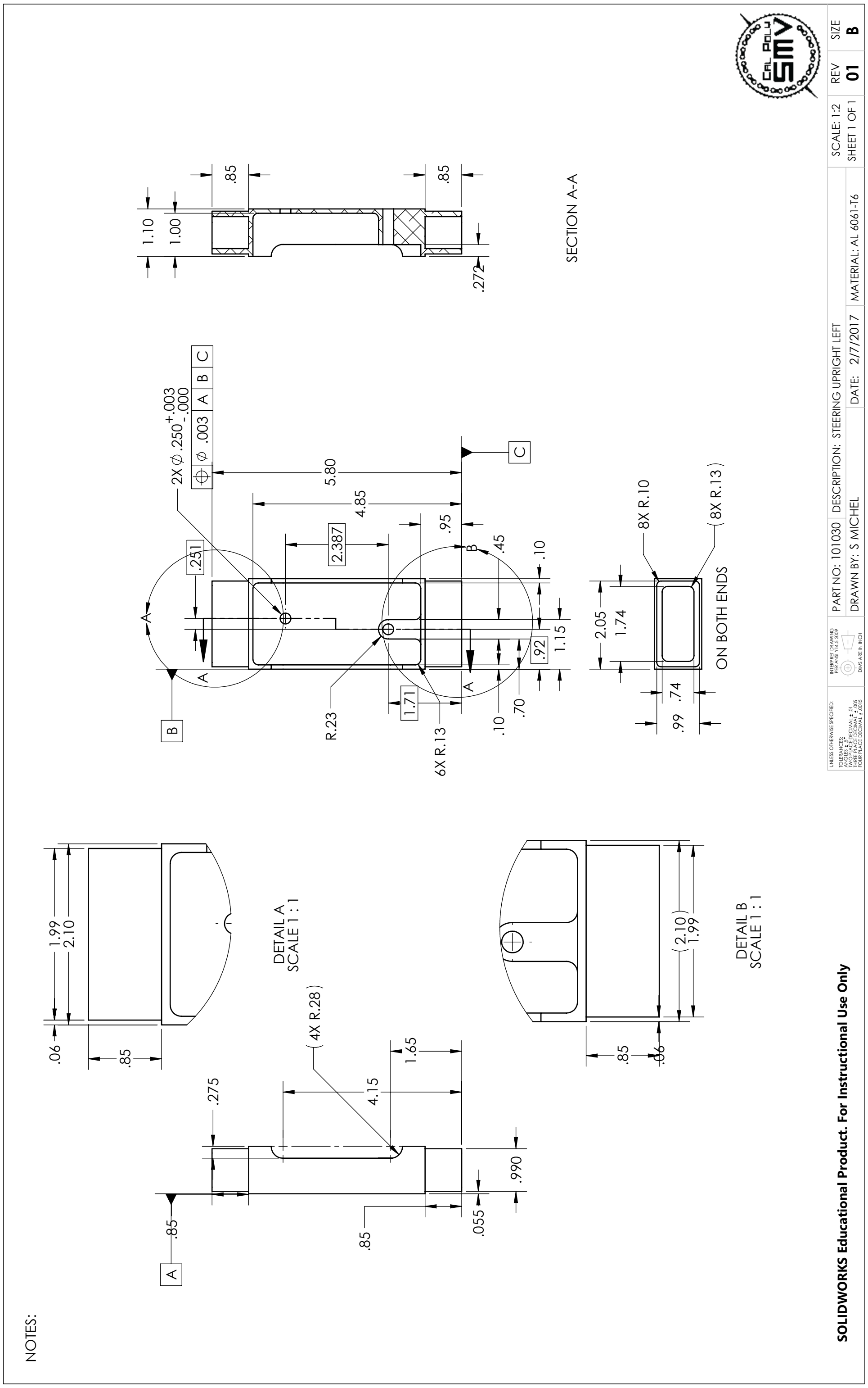
Rectangular Bar, 1-1/4" x 2-1/4"



(Web) System of Measurement	Inch
Material	6061 Aluminum
Cross Section Shape	Rectangle
Construction	Solid
Thickness	1 1/4"
Thickness Tolerance	-0.012" to 0.012"
Tolerance Rating	Standard
Width	2 1/4"
Width Tolerance	-0.034" to 0.034"
Yield Strength	35,000 psi
Fabrication	Heat Treated
Temper	T6511
Temper Rating	Hardened
Hardness	Brinell 95
Hardness Rating	Soft
Heat Treatable	Yes
Appearance	Plain
Temperature Range	-320° to 300° F
Specifications Met	ASTM B221
Straightness Tolerance	Not Rated
Magnetic Properties	Nonmagnetic
Density	0.1 lbs./cu. in.
Surface Resistivity	25 Ohm-Cir Mil/ft
Melting Point Temperature	1080° F

Modulus of Elasticity	10.0 ksi × 10^3
Thermal Conductivity	1,160 Btu/hr. × in./sq. ft./°F @ 75° F
Elongation	12.5%
Material Composition	
Aluminum	95.1-98.2%
Chromium	0.4-0.8%
Copper	0.05-0.4%
Iron	0-0.7%
Magnesium	0.8-1.2%
Manganese	0-0.15%
Nickel	0-0.05%
Silicon	0.4-0.8%
Titanium	0-0.15%
Zinc	0-0.25%
Zirconium	0-0.25%
Other	0.15%
Length Tolerance	-1" to 1"
Length	1/2 ft., 1 ft., 2 ft., 3 ft., 6 ft.
RoHS	Not Compliant

Part Number: 101030



Part Number: 101050

Type 416 Stainless Steel Tight-Tolerance Shoulder Screw

Socket Drive, 3/16" Diameter x 3/8" Long Shoulder, 8-32 Thread Size

Shoulder Fit	Precise
Shoulder Diameter	3/16"
Shoulder Diameter Tolerance	-0.001" to 0.000"
Shoulder Length	3/8"
Shoulder Length Tolerance	0.000" to 0.002"
Thread Size	8-32
Screw Size Decimal Equivalent	0.164"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A
Thread Direction	Right Hand
Thread Length	3/16"
Head Diameter	5/16"
Head Height	5/32"
Material	416 Stainless Steel
Hardness	Rockwell C26
Tensile Strength	120,000 psi
Head Type	Socket
Socket Head Profile	Standard
Head Texture	Smooth
Drive Style	Hex
Drive Size	3/32"
System of Measurement	Inch
RoHS	Compliant

These shoulder screws are about 75% stronger and as corrosion resistant as 18-8 stainless steel. These screws have a shoulder diameter that is twice as precise as general purpose shoulder screws, eliminating space between the shoulder and the surrounding material to provide smooth, accurate movement. Use them in measuring devices, optical fixtures, and laboratory equipment.

Part Number: 101060

18-8 Stainless Steel Tight-Tolerance Screw

Socket Drive, 1/4" Diameter x 5/32" Long Shoulder, 10-32 Thread Size

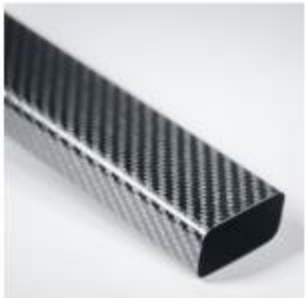
In stock
1-4 Each $2.50
5 or more $2.12
94035A176

Shoulder Fit	Precise
Shoulder Diameter	1/4"
Shoulder Diameter Tolerance	-0.001" to 0.000"
Shoulder Length	5/32"
Shoulder Length Tolerance	0.000" to 0.002"
Thread Size	10-32
Screw Size Decimal Equivalent	0.190"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 2A
Thread Direction	Right Hand
Thread Length	1/4"
Head Diameter	3/8"
Head Height	3/16"
Material	18-8 Stainless Steel
Hardness	Rockwell B55
Tensile Strength	70,000 psi
Head Type	Socket
Socket Head Profile	Standard
Head Texture	Smooth
Drive Style	Hex
Drive Size	1/8"
System of Measurement	Inch
RoHS	Compliant

18-8 stainless steel shoulder screws have good chemical resistance and may be mildly magnetic. They have a shoulder diameter that is twice as precise as general purpose shoulder screws, eliminating space between the shoulder and the surrounding material to provide smooth, accurate movement. Use them in measuring devices, optical fixtures, and laboratory equipment.

Part Number: 101070, 101071, 101072

HOME / 25507-36



TUBE - RECTANGLE - FABRIC - 1.01X1.13 - 2.00X2.13 - 36 INCH

Sku: 25507-36

$163.99

1 to 5 **$163.99**
6 to 10 **$150.79**
11+ **$139.59**

Click "**add/ customize**" to add full lengths or to select your custom cut length preferences

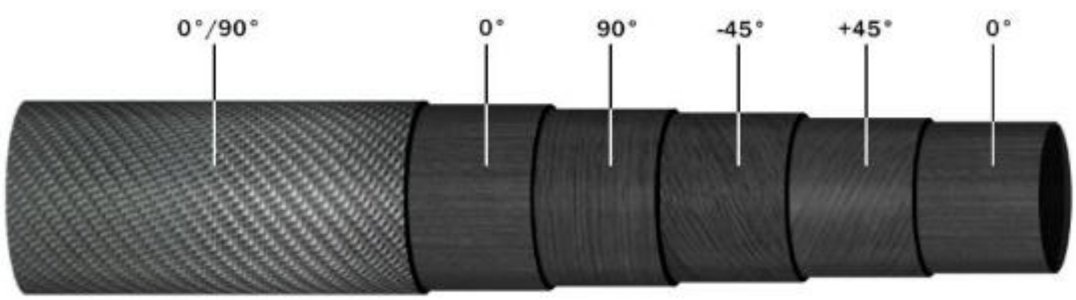
ADD / CUSTOMIZE

DESCRIPTION | ADDITIONAL INFORMATION | LAYUP ORIENTATION | TECHNICAL DATA | TOLERANCES

Unlike metals which have similar properties in all directions (isotropic), the properties of composites are varying, dependent on the orientation of the fibers in each layer.

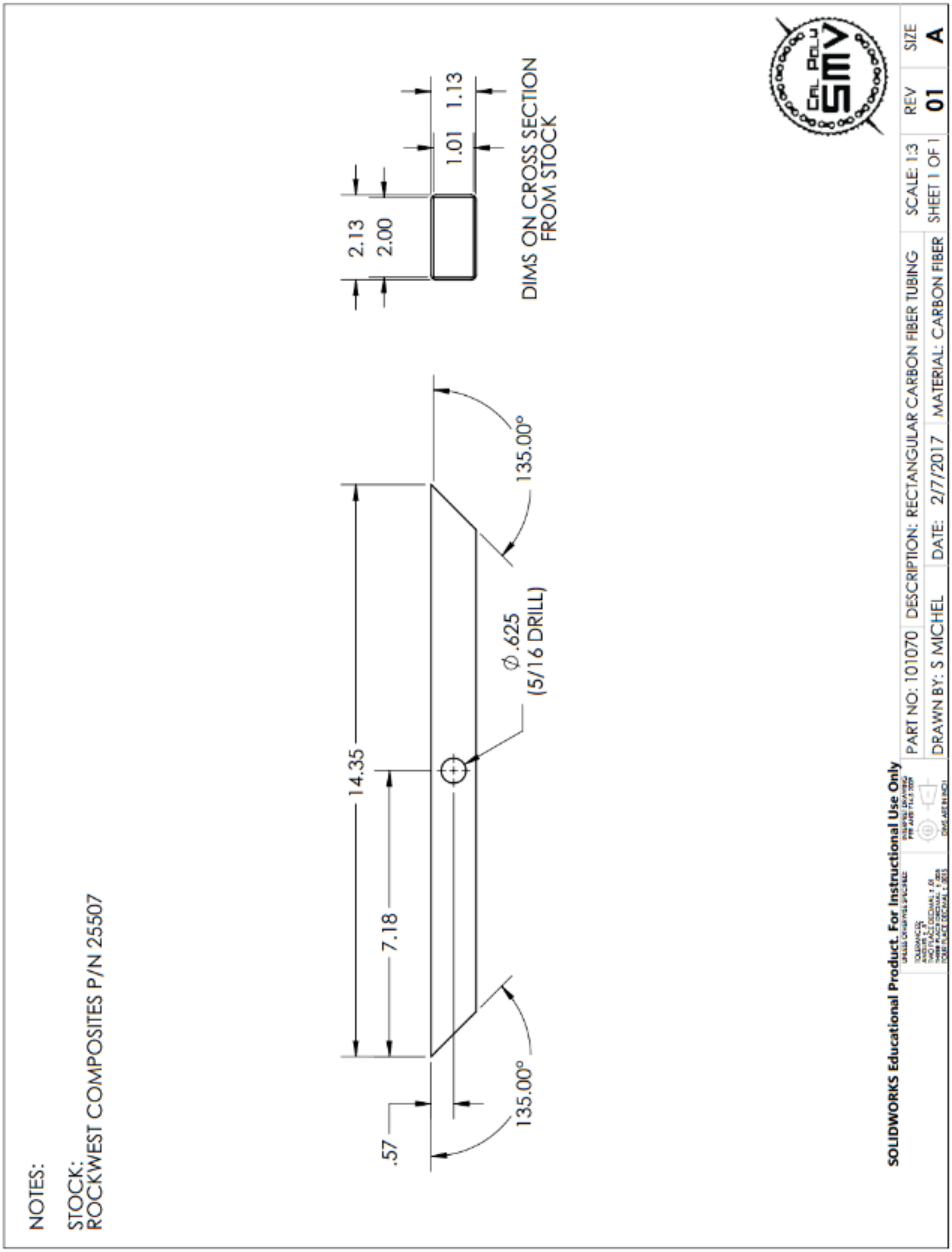
Roll wrapped tubing is manufactured using multiple layers of pre-preg carbon fiber (and if noted, other) materials. In general each layer is about 0.006 inches thick which means that a tube with a wall thickness of 0.060 inches will typically be composed of 9-10 individual layers of carbon fiber. The number of layers(plys) allows us to vary the orientation of the fibers throughout the thickness, creating a high performance, engineered product.

- **Fabric Tubing** has an outer ply of woven material (denoted below as 0°/90°). Typically this outer ply is a 2x2 twill weave (diagonal appearance seen below) but it can also be a plain weave (small checkerboard), spread tow (large format plain weave / checkerboard) or other off-axis weave such as a braid. The core of these tubes are almost always comprised of multi-directional "uni" plies.
- **Uni Tubing** is comprised of multi-directional "uni" plies just like the fabric tubes however instead of the outer ply being fabric, it is unidirectional and most typically oriented at 0° (fibers running the length).
- To learn about our Roll Wrapping Process click here.

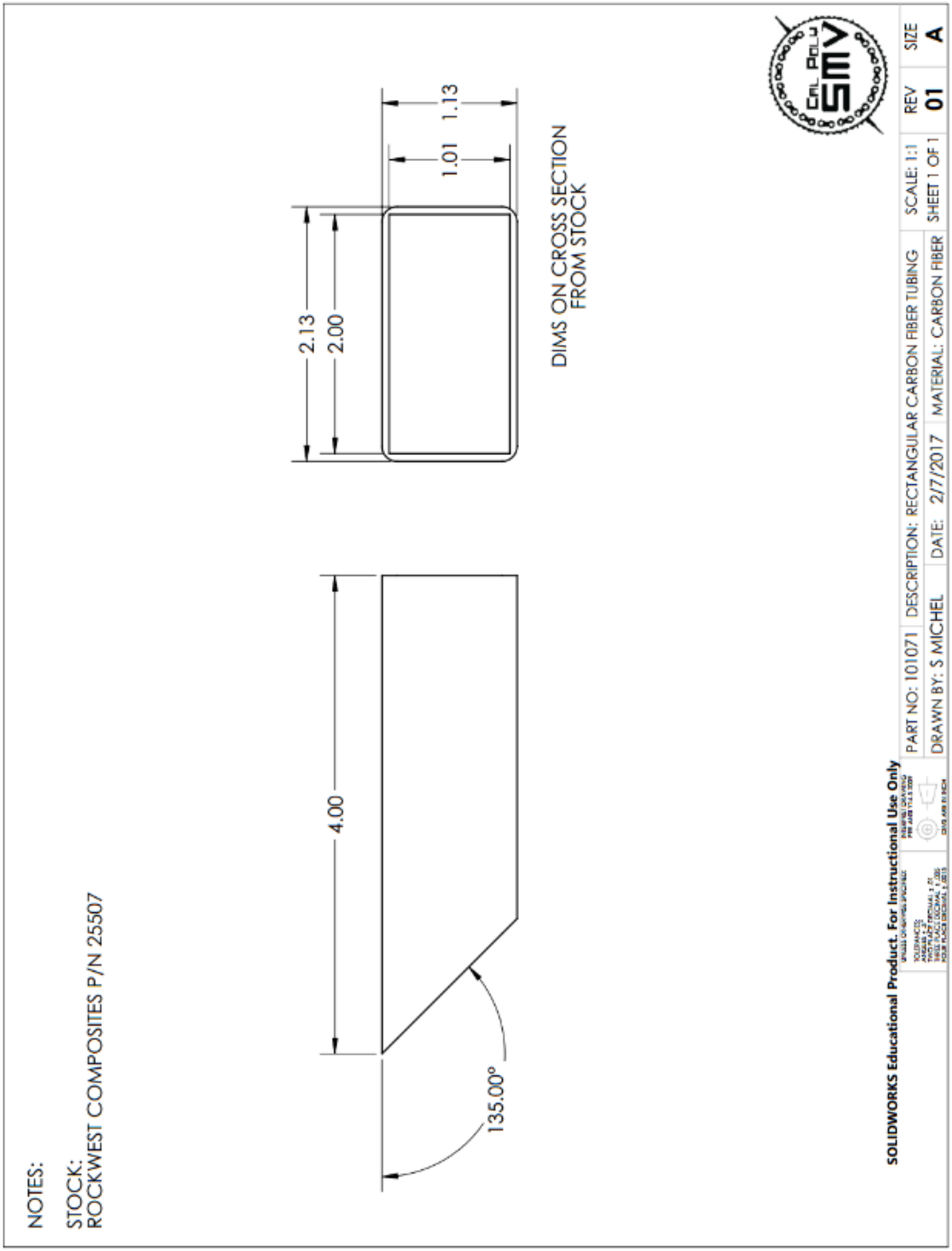


*This diagram illustrates a "generic" layup. The SKU being viewed may not have the layup schedule shown in this diagram. To view this SKU's particular layup please check out the "LAYUP ORIENTATION" tab.

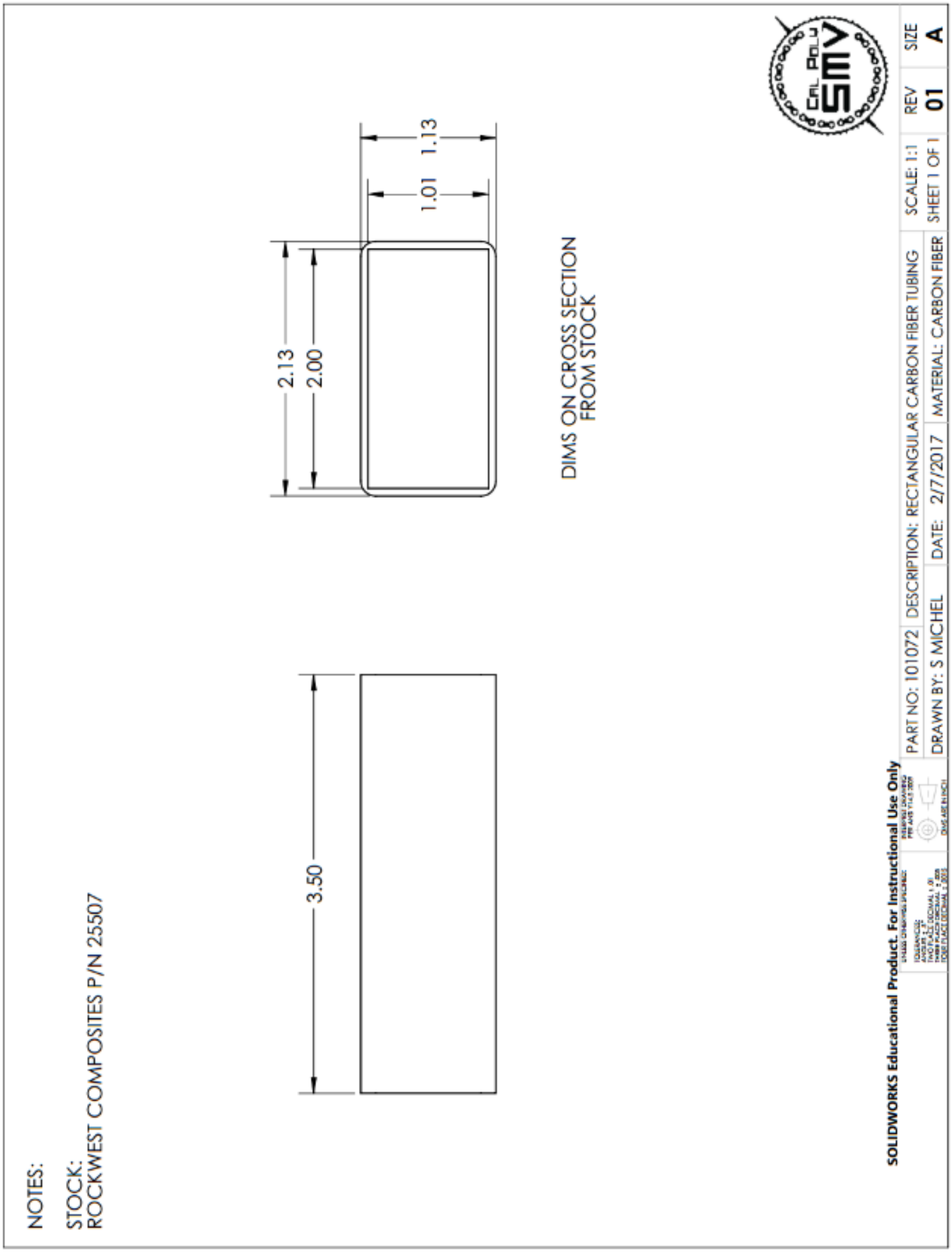
Part Number: 101070



Part Number: 101071



Part Number: 101072



Part Number: 101080

Alloy Steel Tight-Tolerance Shoulder Screw

1/4" Diameter x 7/8" Long Shoulder, 10-32 Thread Size

Each

ADD TO ORDER

In stock
1-4 Each $7.62
5 or more $6.44
92012A597

Shoulder Fit	Precise
Shoulder Diameter	1/4"
Shoulder Diameter Tolerance	-0.001" to 0.000"
Shoulder Length	7/8"
Shoulder Length Tolerance	0.000" to 0.002"
Thread Size	10-32
Screw Size Decimal Equivalent	0.190"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 2A
Thread Direction	Right Hand
Thread Length	1/4"
Head Diameter	3/8"
Head Height	3/16"
Material	Alloy Steel
Finish	Black Oxide
Hardness	Rockwell C32
Tensile Strength	140,000 psi
Head Type	Socket
Socket Head Profile	Standard
Head Texture	Smooth
Drive Style	Hex
Drive Size	1/8"
System of Measurement	Inch
RoHS	Not Compliant

These shoulder screws have a shoulder diameter that is twice as precise as general purpose shoulder screws, eliminating space between the shoulder and the surrounding material to provide smooth, accurate movement. Use in measuring devices, optical fixtures, and laboratory equipment.

Part Number: 101090

18-8 Stainless Steel Washer

for 1/4" Screw Size, 0.281" ID, 0.625" OD

Packs of 100

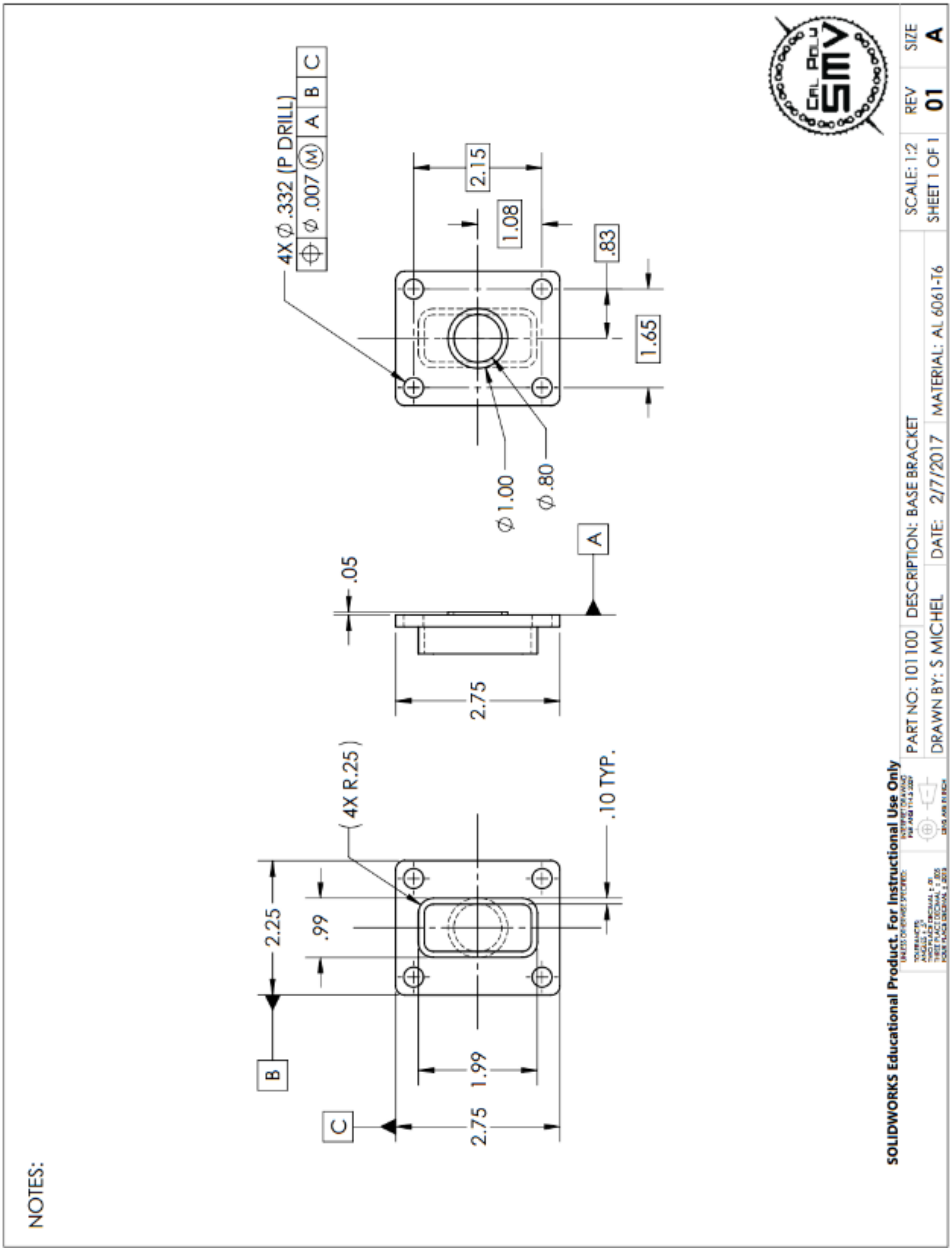
ADD TO ORDER

In stock
$3.37 per pack of 100
92141A029

Material	18-8 Stainless Steel
For Screw Size	1/4"
ID	0.281"
OD	0.625"
Thickness	0.043"-0.057"
Washer Type	Flat
System of Measurement	Inch
Hardness	Not Rated
RoHS	Compliant

18-8 stainless steel and 17-7 PH stainless steel washers have good chemical resistance and may be mildly magnetic.

Part Number: 101100



Part Number: 101120

Black-Oxide Alloy Steel Socket Head Screw

5/16"-24 Thread Size, 1/2" Long

Packs of 50

ADD TO ORDER

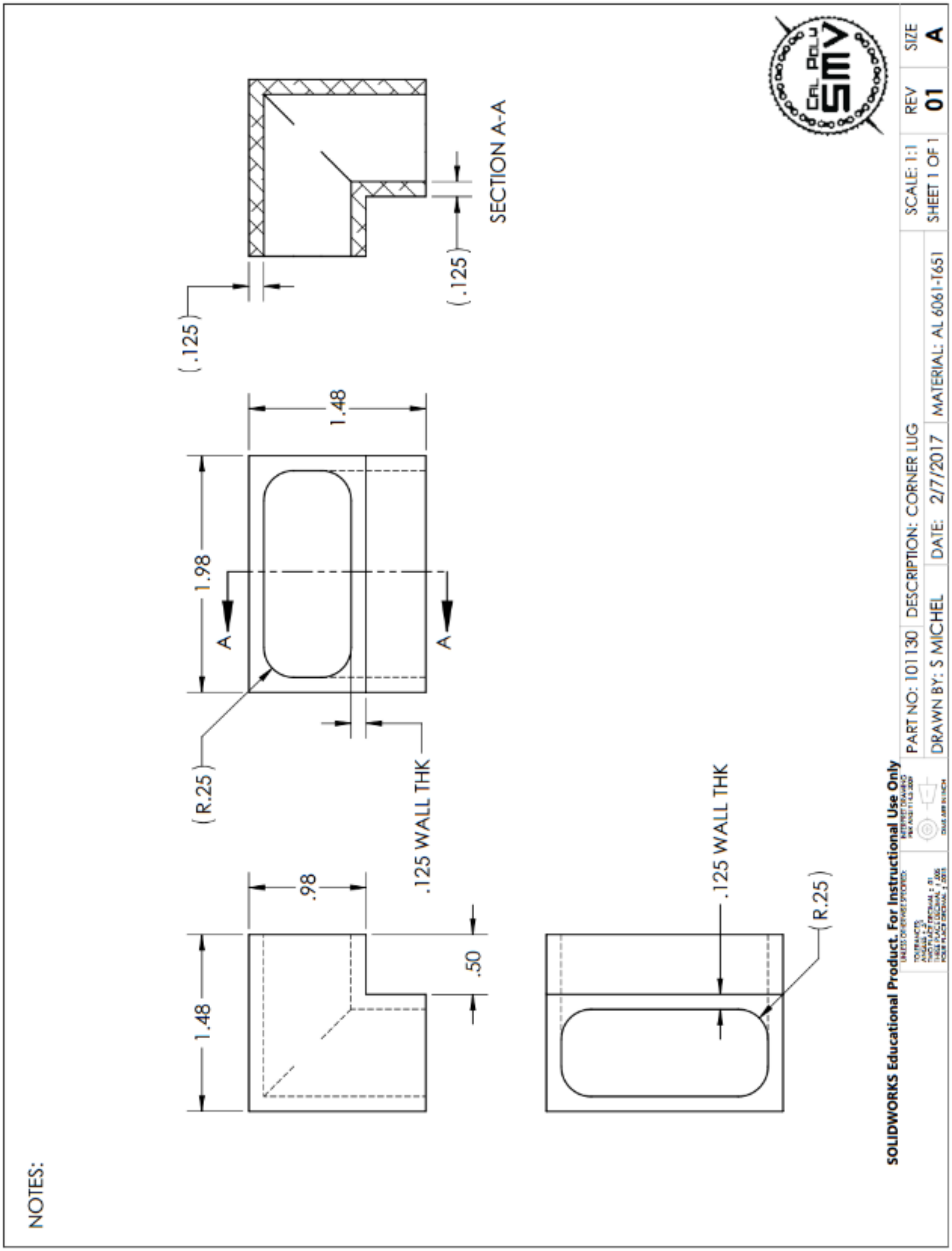
In stock
$11.12 per pack of 50
91251A378

Thread Size	5/16"-24
Length	1/2"
Threading	Fully Threaded
Head Diameter	0.469"
Head Height	0.313"
Drive Size	1/4"
Material	Black-Oxide Alloy Steel
Hardness	Rockwell C37
Tensile Strength	170,000 psi
Screw Size Decimal Equivalent	0.313"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 3A
Thread Direction	Right Hand
Head Type	Socket
Socket Head Profile	Standard
Drive Style	Hex
Specifications Met	ASTM A574
System of Measurement	Inch
RoHS	Compliant

These screws are made from an alloy steel that's stronger than Grade 8 steel. Length is measured from under the head.

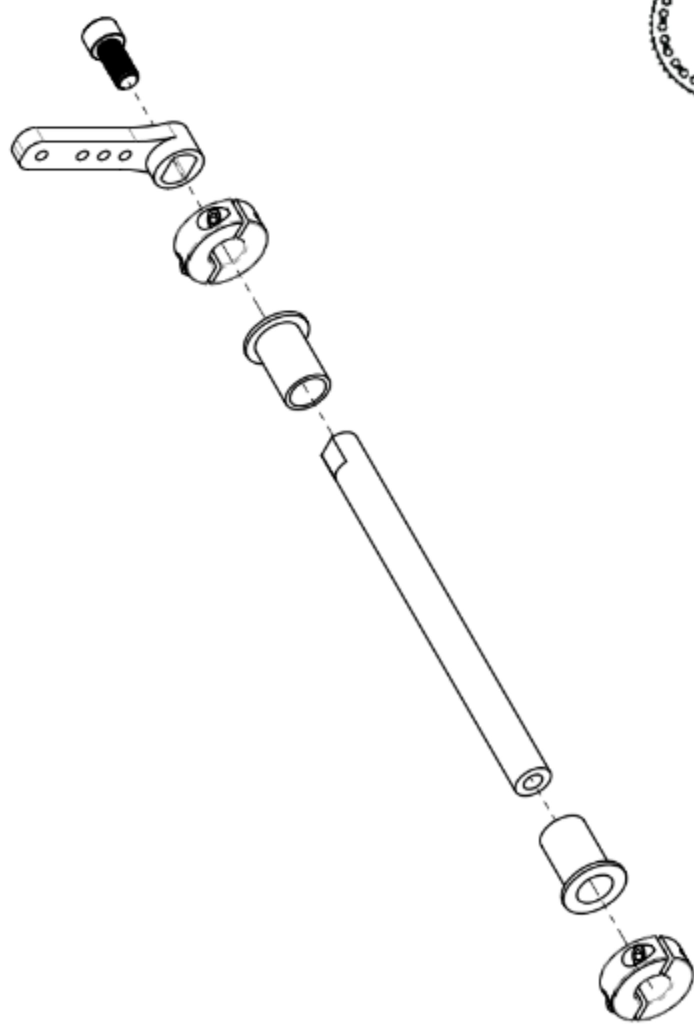
Black-oxide steel screws are mildly corrosion resistant in dry environments.

Part Number: 101130



Part Number: 102000

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Default/ QTY.
1	102010	MCMASTER 6436K71	2024 ALUMINUM	2
2	102020	MCMASTER 6294K448	MDS FILLED NYLON	2
3	102030	STEERING COLUMN	AL 2024-T3	1
4	102060	MCMASTER 91251A383	BLACK OXIDE COATED STEEL	1
5	102070	STEERER	AL 6061-T6	1



SOLIDWORKS Educational Product. For Instructional Use Only

PART NO: 102000 | DESCRIPTION: | SCALE: 1:2 | REV 01 | SIZE A

DRAWN BY: G MURILLO | DATE: 2/10/2017 | MATERIAL: | SHEET 1 OF 1

Part Number: 102010

Clamping Two-Piece Shaft Collar

for 1/2" Diameter, 2024 Aluminum

[ ] Each

ADD TO ORDER

In stock
$5.15 Each
6436K71

Material	2024 Aluminum
For Shaft Diameter	1/2"
OD	1 1/8"
Width	13/32"
Clamping Screw	
Type	Socket Head Screw
Material	Black-Oxide Steel
Number Included	2
For Shaft Type	Round
Shaft Mount Type	Clamp On
Construction	Two Piece
RoHS	Compliant

These metal collars are stronger than plastic shaft collars. The two-piece design allows you to install them anywhere on a shaft without removing components or having access to the ends of the shaft. Collars clamp evenly around the shaft to create a strong, mar-free hold. Tighten the clamping screws to secure.

Aluminum collars are lightweight and have good corrosion resistance.

Part Number: 102020

Light Duty Dry-Running Sleeve Bearing

7/8" Flange OD, MDS-Filled Nylon, 5/8" OD, 1" Length

Each	In stock $2.05 Each 6294K448

ADD TO ORDER

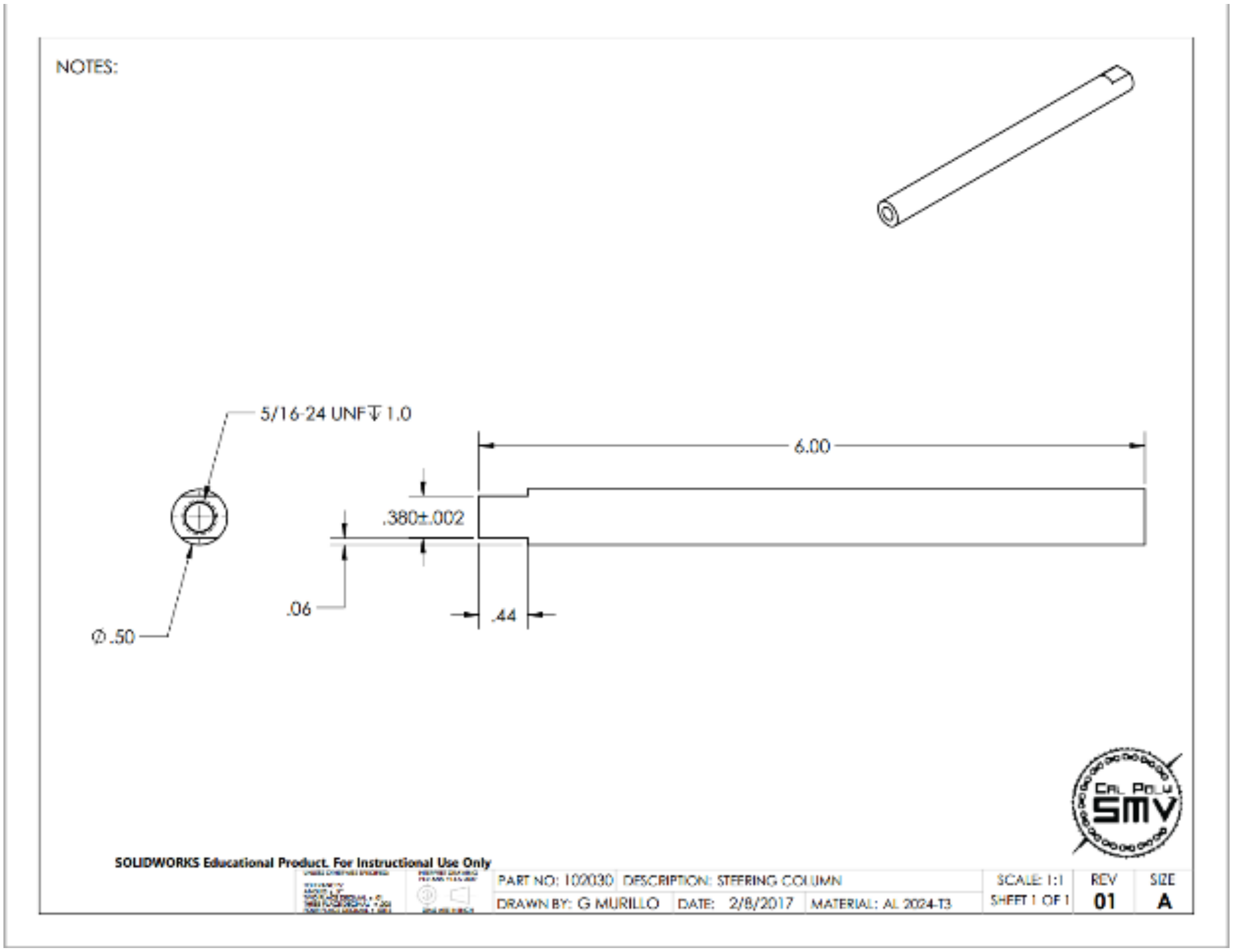
Bearing Type	Plain
Plain Bearing Type	Flanged
For Shaft Diameter	1/2"
ID	0.500"
ID Tolerance	Not Rated
OD	5/8"
OD Tolerance	Not Rated
Length	1"
Length Tolerance	0" to -0.013"
Flange	
OD	7/8"
Thickness	1/16"
Material	MDS-Filled Nylon
Color	Black
Dynamic Load Capacity	200 lbs. @ 60 rpm
For Load Direction	Radial, Thrust, Combined Radial and Thrust
Shaft Mount Type	Press Fit
Lubrication	Not Required
Temperature Range	-40° to 170° F
RoHS	Compliant

Made of slippery plastics, these bearings reduce friction without the need for lubrication.

MDS-filled nylon bearings create less friction than standard nylon bearings, making them more wear resistant.

Note: Dynamic load capacity is the maximum load a bearing can withstand at a given shaft speed. If the bearing's load and speed are below the values listed, the bearing should work for your application.

Part Number: 102030



Part Number: 102030

High-Strength 2024 Aluminum

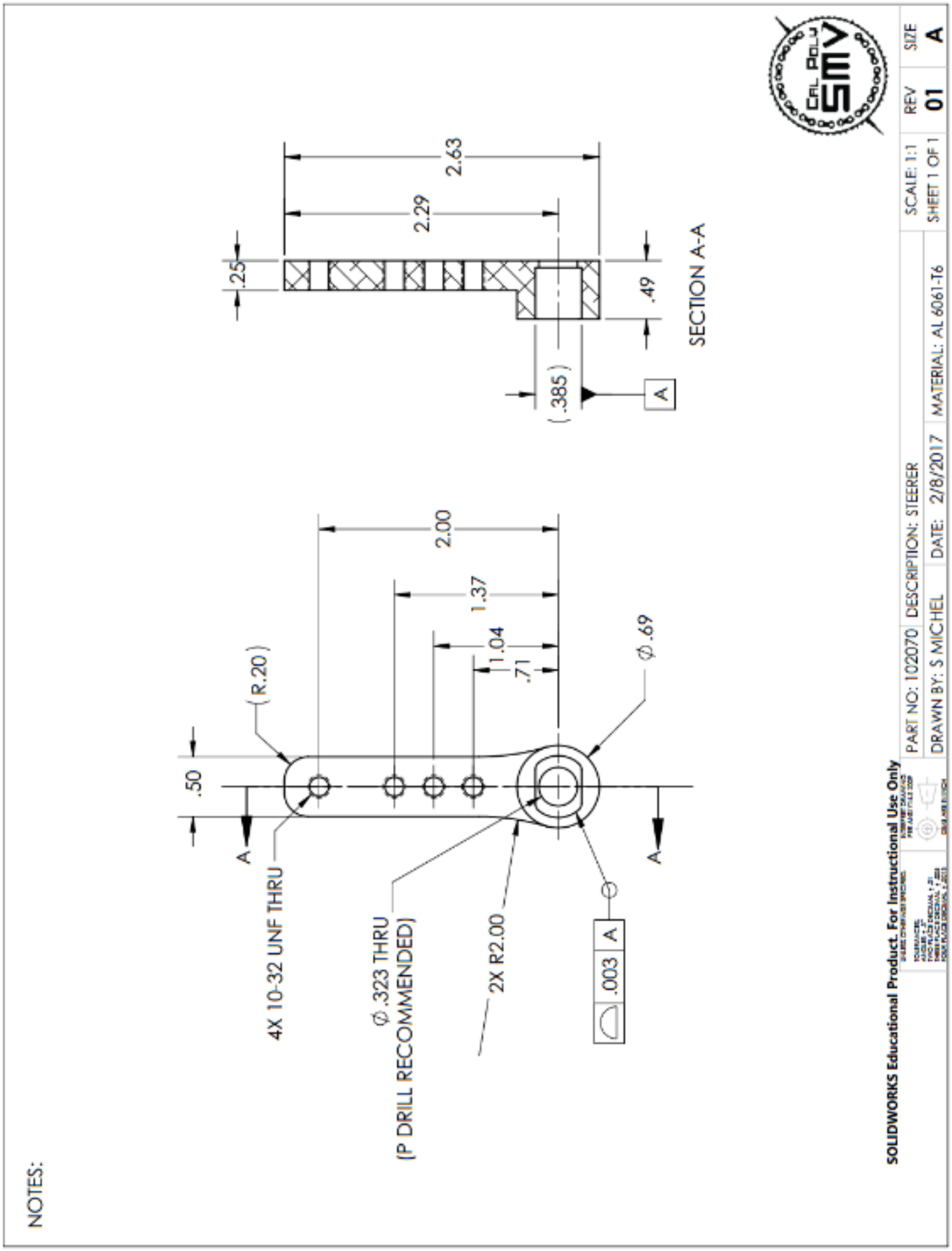
Tube, 1/2" OD, .260" ID, .120" Wall Thickness

1968T23

Material	2024 Aluminum
Cross Section Shape	Round
Construction	Hollow
Appearance	Plain
Wall Thickness	0.12"
Wall Thickness Tolerance	-0.014" to 0.014"
Tolerance Rating	Standard
OD	1/2"
OD Tolerance	-0.008" to 0.008"
ID	0.260"
Yield Strength	42,000 psi
Fabrication	Heat Treated
Temper	T3
Temper Rating	Hardened
Hardness	Brinell 120
Hardness Rating	Soft
Heat Treatable	Yes
Temperature Range	-320° to 300° F
Specifications Met	ASTM B210
Straightness Tolerance	Not Rated
Magnetic Properties	Nonmagnetic
Density	0.1 lbs./cu. in.
Surface Resistivity	30 Ohm-Cir Mil/ft
Melting Point Temperature	935° F
Modulus of Elasticity	10.6 ksi × 10^3
Thermal Conductivity	840 Btu/hr. × in./sq. ft./°F @ 75° F
Elongation	15%
Material Composition	
Aluminum	90.75-94.7%
Chromium	0-0.1%
Copper	3.8-4.9%
Iron	0-0.5%
Magnesium	1.2-1.8%
Manganese	0.3-0.9%
Silicon	0-0.5%
Titanium	0-0.15%
Zinc	0-0.25%
Other	0-0.15%
Length Tolerance	-1" to 1"
Length	1 ft., 3 ft., 6 ft.
RoHS	Compliant

2024 aluminum is used when a high strength-to-weight ratio is required, such as for gears, shafts, and fasteners. It is nonmagnetic and heat treatable.

Part Number: 102050



Part Number: 102060, & 103020

Black-Oxide Alloy Steel Socket Head Screw

5/16"-24 Thread Size, 1" Long

| Packs of 25 | In stock
$6.13 per pack of 25
91251A383 |

ADD TO ORDER

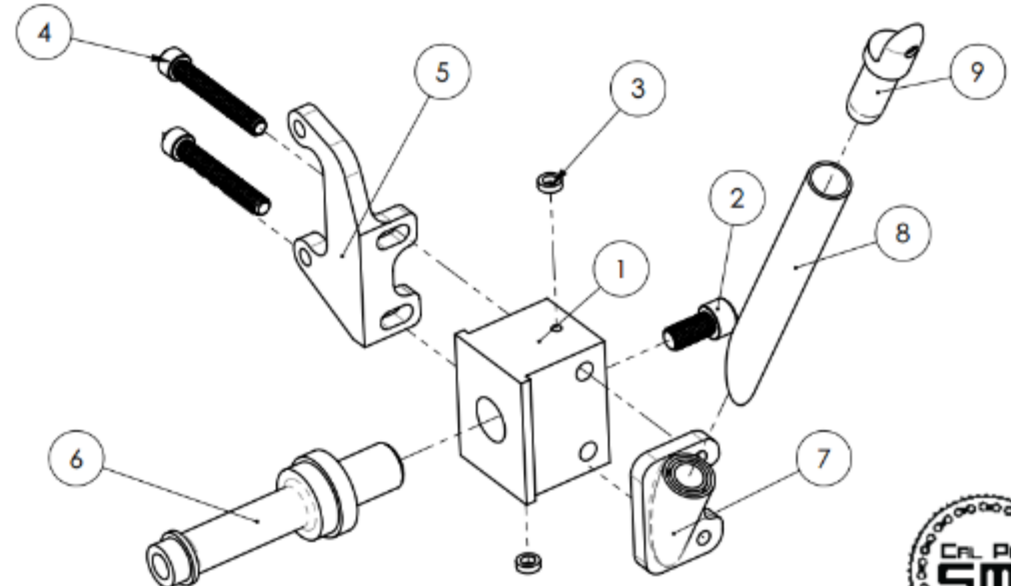
Thread Size	5/16"-24
Length	1"
Threading	Fully Threaded
Head Diameter	0.469"
Head Height	0.313"
Drive Size	1/4"
Material	Black-Oxide Alloy Steel
Hardness	Rockwell C37
Tensile Strength	170,000 psi
Screw Size Decimal Equivalent	0.313"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 3A
Thread Direction	Right Hand
Head Type	Socket
Socket Head Profile	Standard
Drive Style	Hex
Specifications Met	ASTM A574
System of Measurement	Inch
RoHS	Compliant

These screws are made from an alloy steel that's stronger than Grade 8 steel. Length is measured from under the head.

Black-oxide steel screws are mildly corrosion resistant in dry environments.

Part Number: 103000

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	103010	KNUCKE BLOCK	6061-T6	1
2	103020	MCMASTER 91251A380	BLACK OXIDE COATED STEEL	1
3	103030	MCMASTER 92320A462	18-8 STAINLESS	2
4	103040	MCMASTER 90044A124	ALLOY STEEL	2
5	103050	BRAKE BOSS	AL 6061-T6	1
6	103060	SPINDLE	AISI 4340 STEEL	1
7	103070	ACKERMAN BOSS RIGHT	3D PRINTED 316 STAINLESS	1
8	103080	CARBON ACKERMAN ARM	CARBON FIBER	1
9	103090	0.5" SINGLE SIDED THREADED CLEVIS INSERT	6061-T6	1

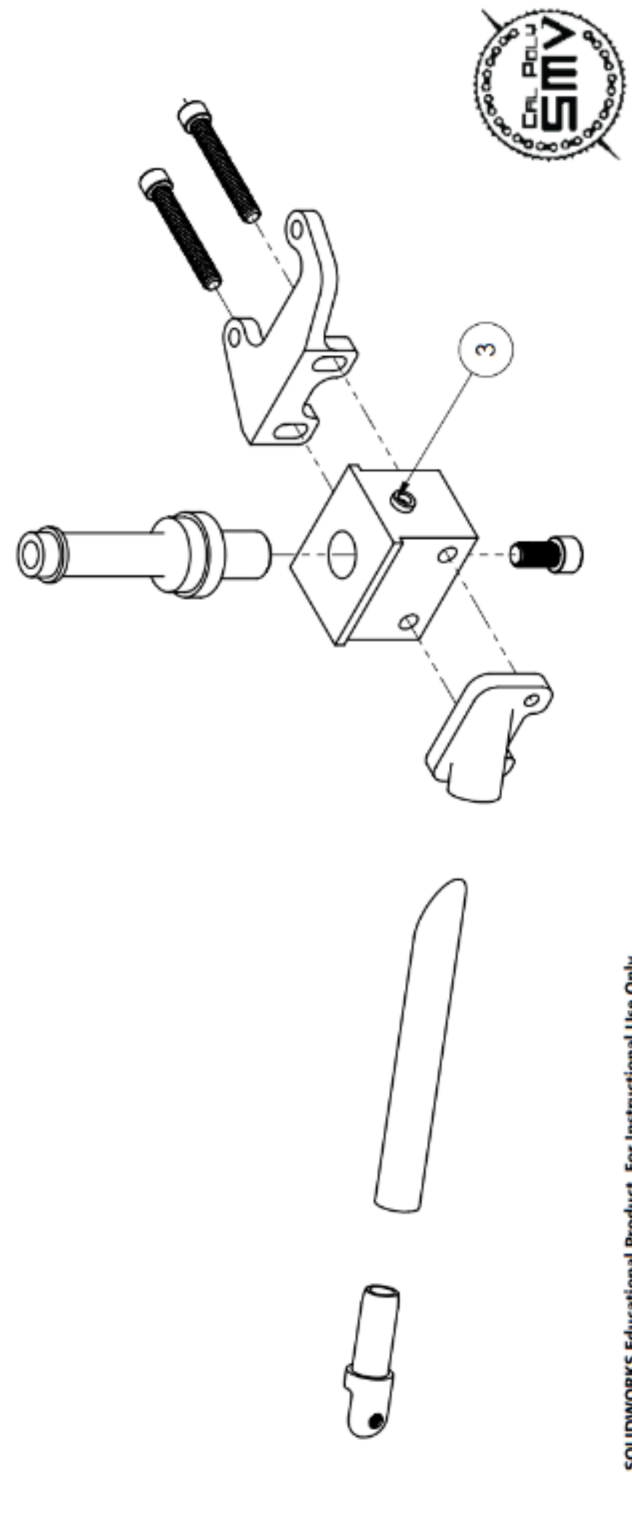


SOLIDWORKS Educational Product. For Instructional Use Only

PART NO: 103000	DESCRIPTION: AXLE ASSEMBLY RIGHT	SCALE: 1:2	REV	SIZE
DRAWN BY: L RYBARCZYK DATE: 2/10/2017	MATERIAL:	SHEET 1 OF 1	01	A

Part Number: 103001

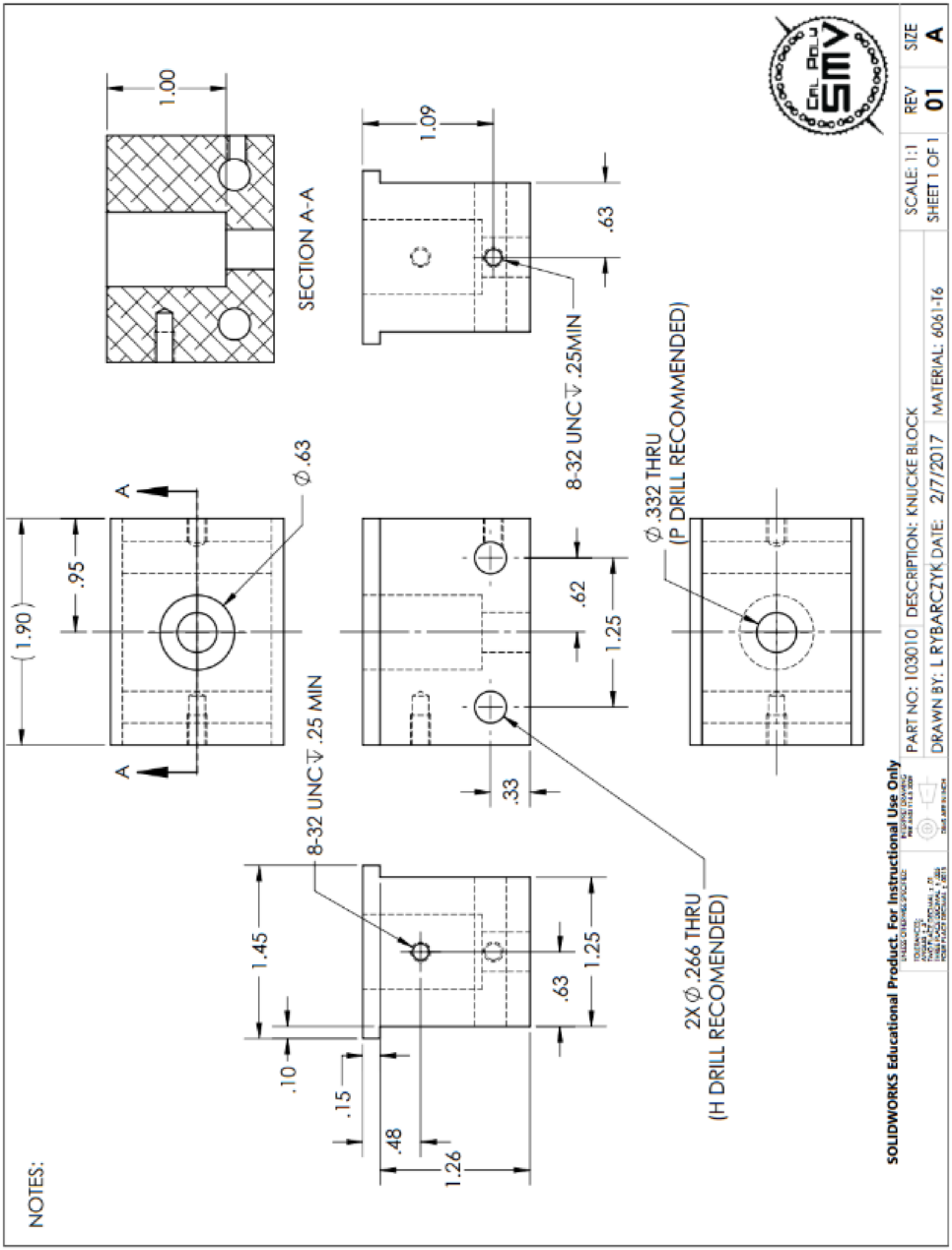
ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	103010	KNUCKE BLOCK	6061-T6	1
2	103020	MCMASTER 91251A380	BLACK OXIDE COATED STEEL	1
3	103030	MCMASTER 92320A462	18-8 STAINLESS	2
4	103040	MCMASTER 90044A124	ALLOY STEEL	2
5	103050	BRAKE BOSS	AL 6061-T6	1
6	103060	SPINDLE	AISI 4340 STEEL	1
7	103071	ACKERMAN BOSS LEFT	3D PRINTED STAINLESS	1
8	103080	CARBON ACKERMAN ARM	CARBON FIBER	1
9	103090	0.5" SINGLE SIDED THREADED CLEVIS INSERT	6061-T6	1



SOLIDWORKS Educational Product. For Instructional Use Only

PART NO: 103001	DESCRIPTION: KNUCKLE ASSEMBLY LEFT	SCALE: 1:2	REV 01
DRAWN BY: L RYBARCZYK	DATE: 2/10/2017	MATERIAL: N/A	SHEET 1 OF 1	SIZE A

Part Number: 103010



Part Number: 103030

Stainless Steel Unthreaded Spacer

5/16" OD, 1/4" Length, for Number 10 Screw Size

Each

ADD TO ORDER

In stock
1-9 Each $2.17
10 or more $1.84
92320A462

Material	18-8 Stainless Steel
OD	5/16"
OD Tolerance	-0.005" to 0.005"
Length	1/4"
For Screw Size	No. 10
ID	0.192"
ID Tolerance	0" to 0.01"
Length Tolerance	-0.005" to 0.005"
Shape	Round
Specifications Met	ASTM A582
Tensile Strength	80,000 psi
Hardness	Rockwell B60
RoHS	Compliant

These spacers are also known as clearance spacers.

18-8 stainless steel has excellent corrosion resistance. It is electrically conductive and nonmagnetic.

Part Number: 103040

Black-Oxide Alloy Steel Socket Head Screw

1/4"-20 Thread Size, 1-3/4" Long, Fully Threaded

Packs of 50

ADD TO ORDER

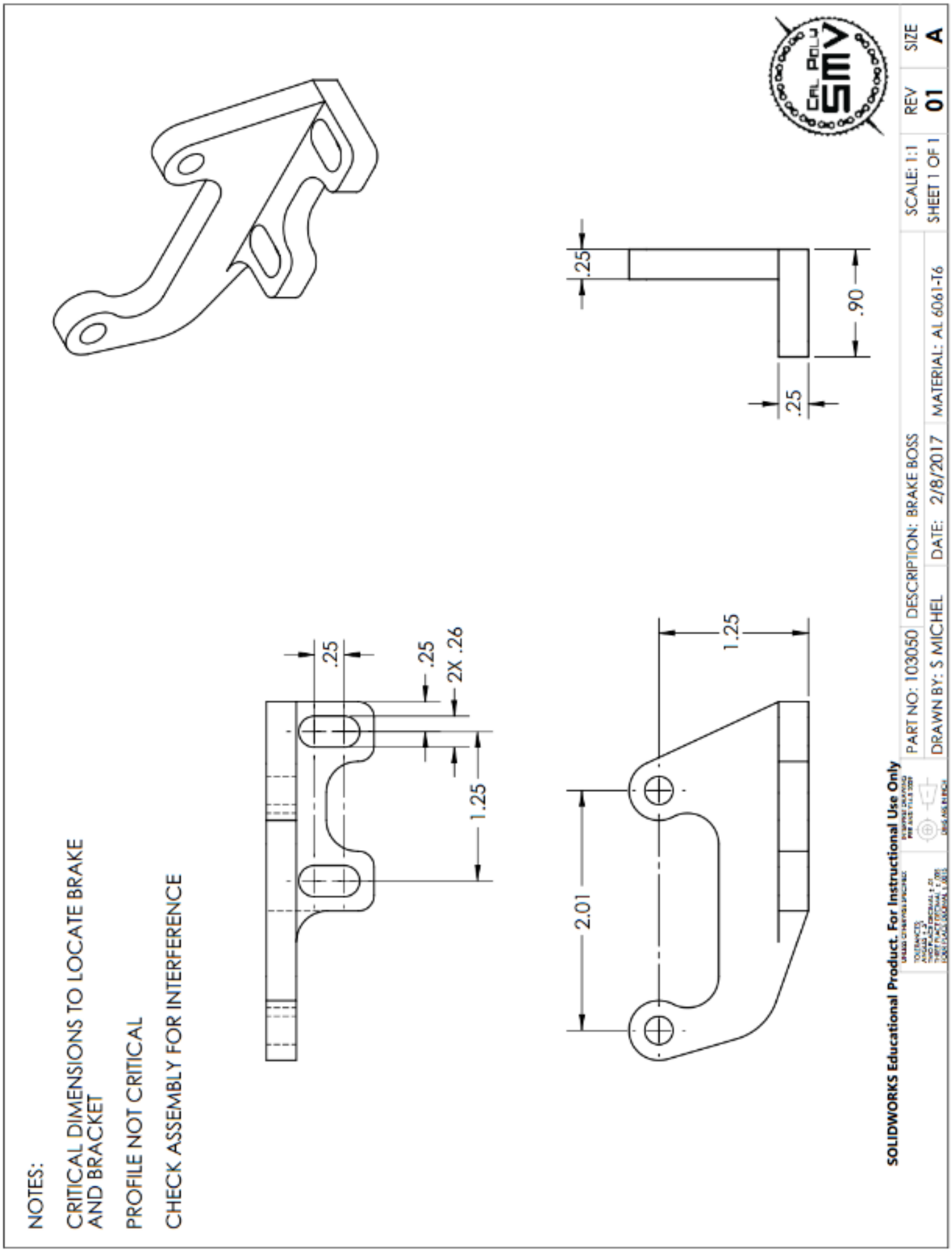
In stock
$9.34 per pack of 50
90044A124

Thread Size	1/4"-20
Length	1 3/4"
Threading	Fully Threaded
Head Diameter	0.375"
Head Height	0.25"
Drive Size	3/16"
Material	Black-Oxide Alloy Steel
Hardness	Rockwell C37
Tensile Strength	170,000 psi
Screw Size Decimal Equivalent	0.250"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 3A
Thread Direction	Right Hand
Head Type	Socket
Socket Head Profile	Standard
Drive Style	Hex
Specifications Met	ASTM A574
System of Measurement	Inch
RoHS	Compliant

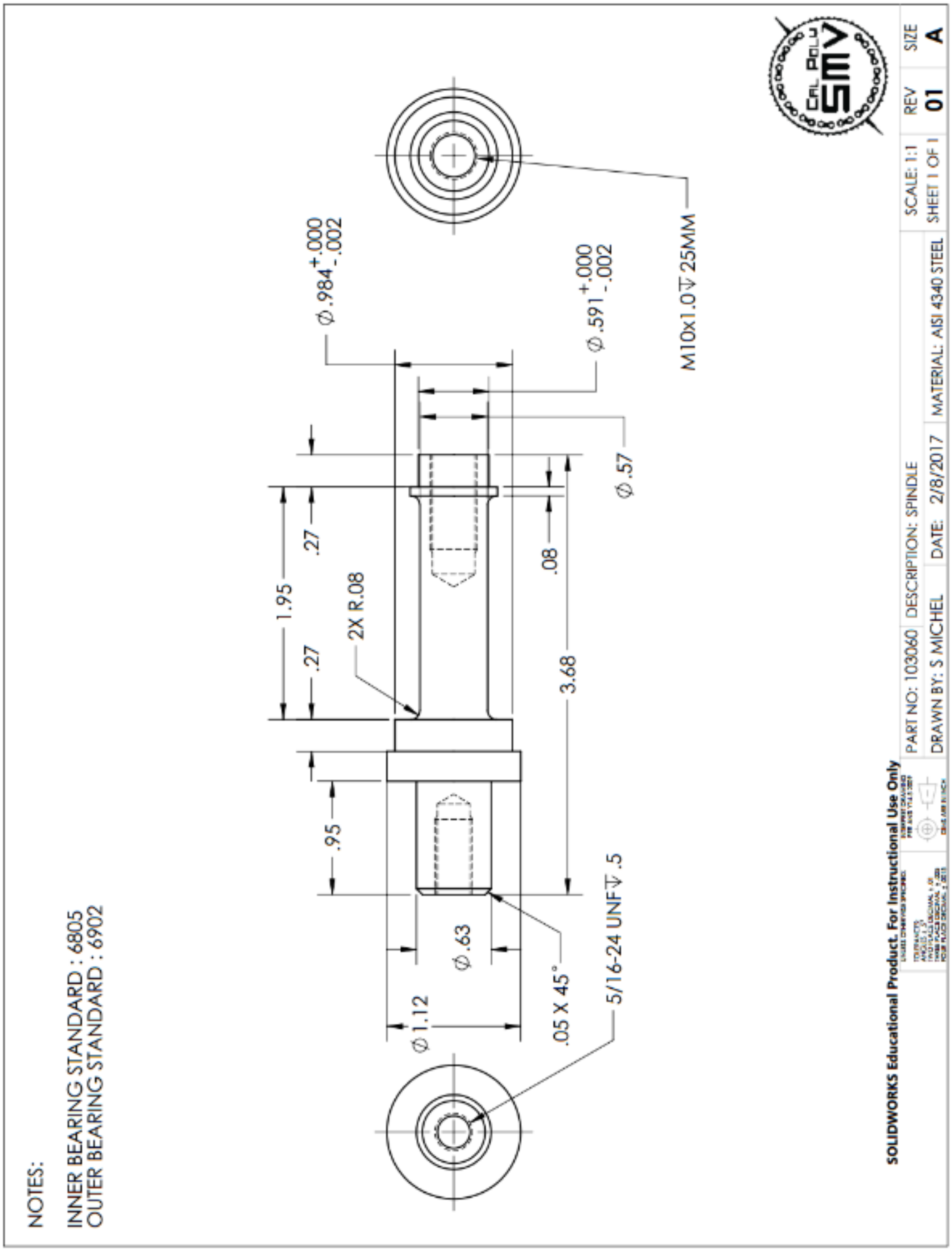
These screws are made from an alloy steel that's stronger than Grade 8 steel. Length is measured from under the head.

Black-oxide steel screws are mildly corrosion resistant in dry environments.

Part Number 103050



Part Number: 103060



Part Number: 103060

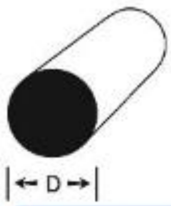
ALLOY STEEL ROUGH TURNED ROUND 4340 NORMALIZED

This material is Rough Turned and Normalized.

View our "Guide to Alloy Steel" for available grades, shapes and additional information.

Mill Test Reports are available on this item and can be selected during the checkout process.

Material Meets These Standard(s): AMS 6415



DIMENSIONS	Weight/Lineal Foot: 3.374 pounds
Dimension Name	Value
Diameter	1.125"

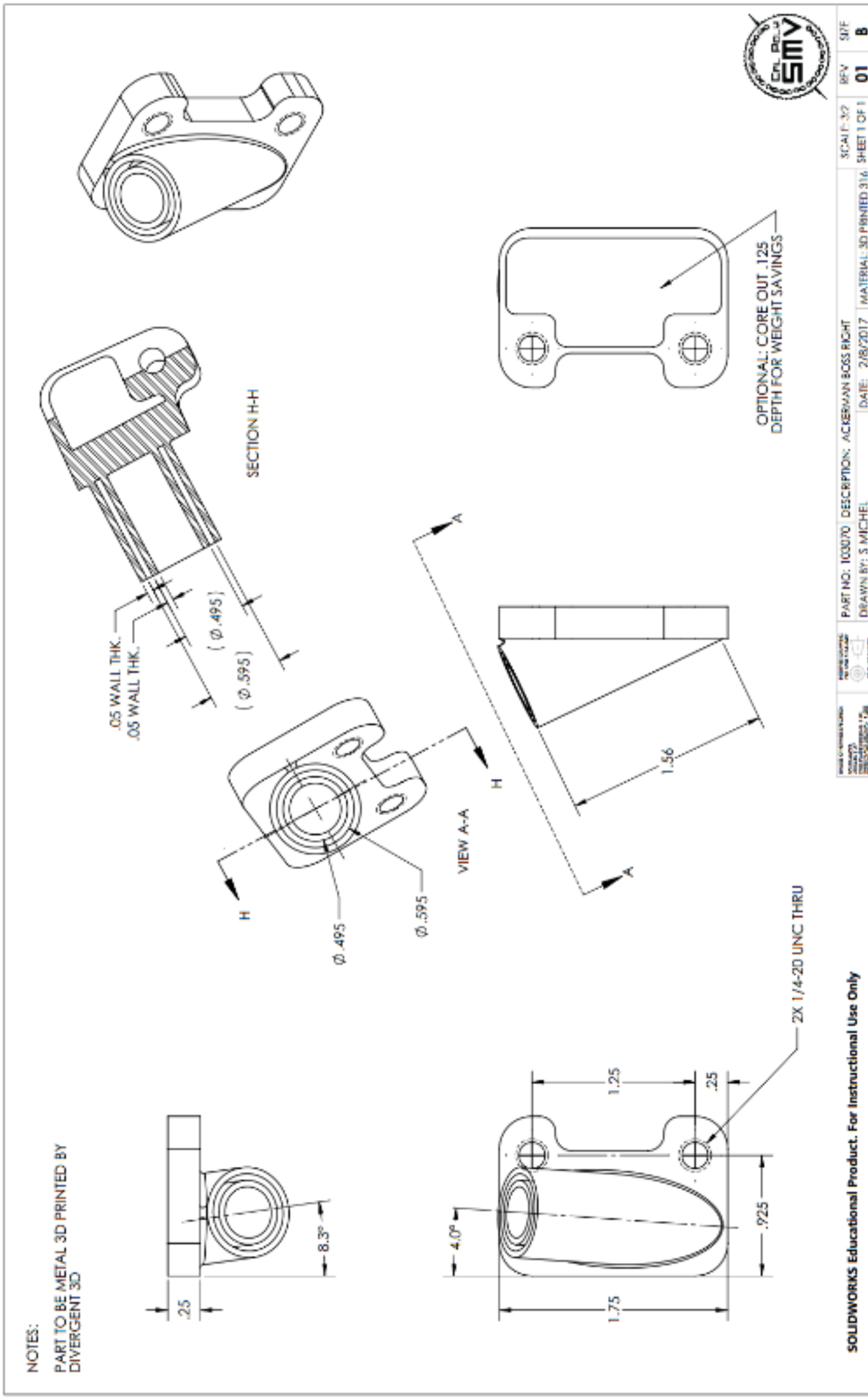
Available Sizes | Create a Custom Size | Technical Information

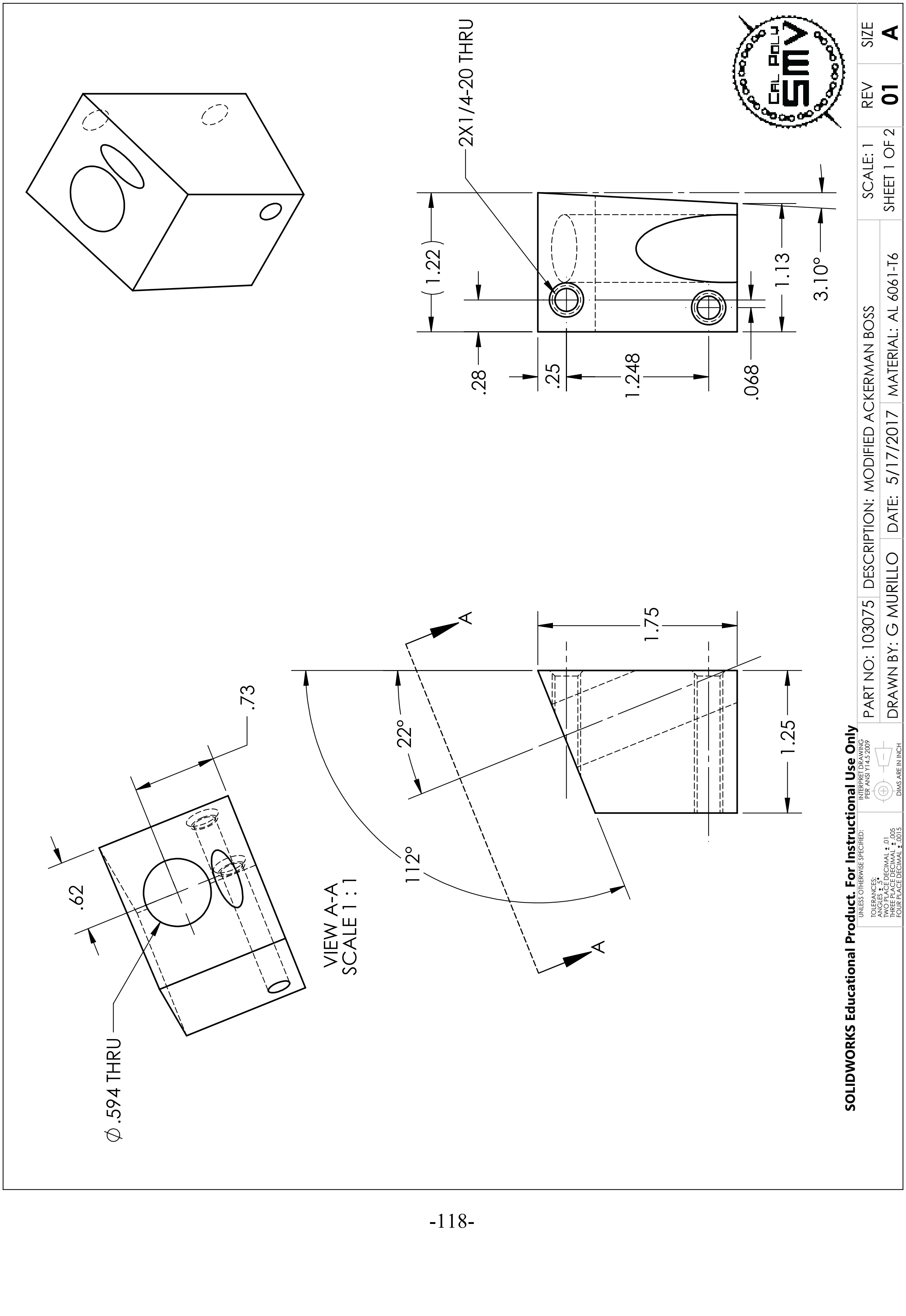
Weight/Lineal Foot
3.374 pounds
Material Specifications
This material meets the following specs: **AMS 6415**

Chemistry Information: 4340 Alloy Steel	
Element	**Percentage**
C	0.37 - 0.43
Cr	0.8
Fe	96
Mn	0.7
Ni	1.83
P	0.035 max
S	0.04 max
Si	0.23

Please note that this data is to be used ONLY FOR REFERENCE, NOT FOR DESIGN, and by using it, you agree that any decisions you make regarding materials for your project are at your own discretion.

Part Number: 103070




2X1/4-20 THRU
(1.22)
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1.248
.068
1.75
1.25
22°
112°
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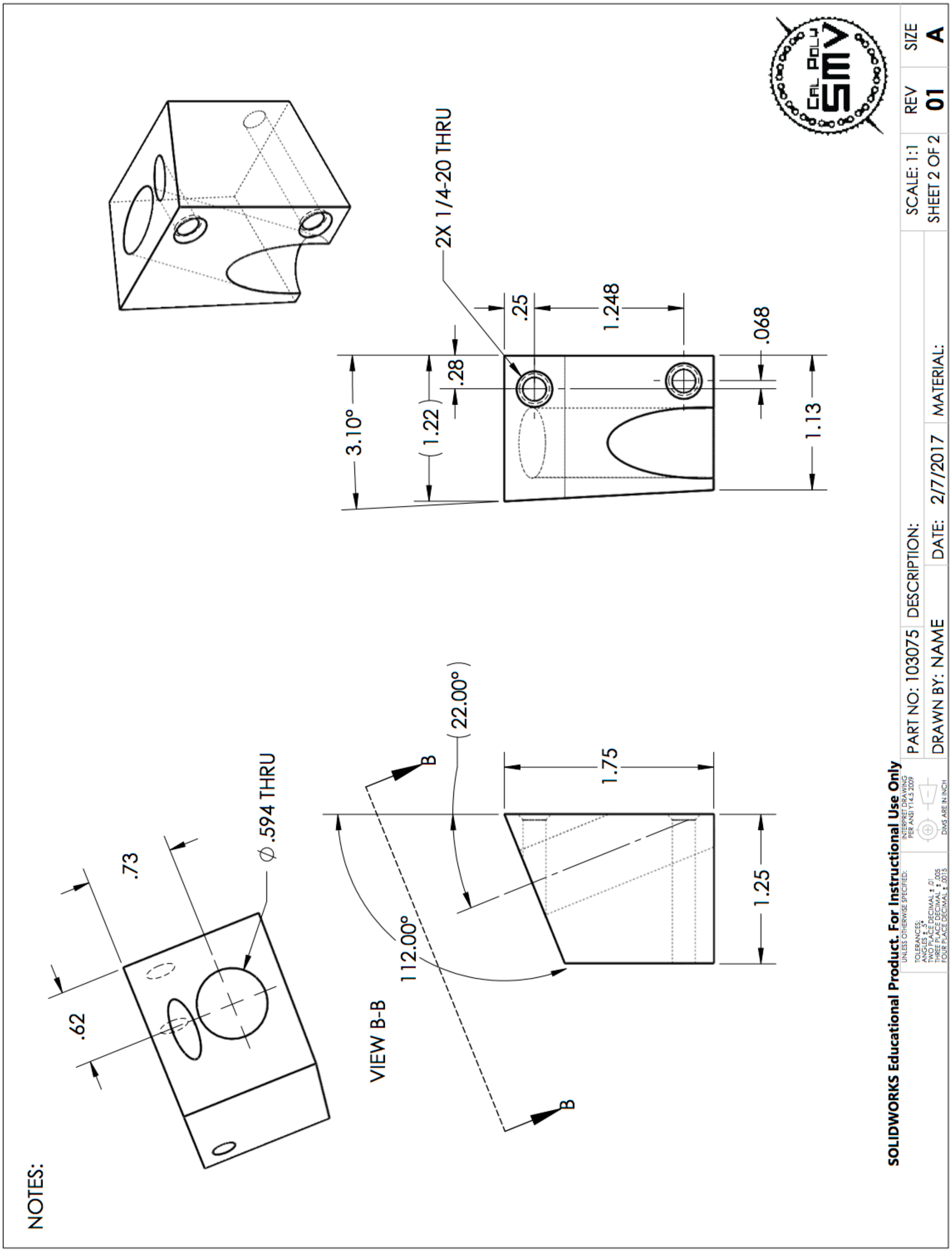
SCALE 1 : 1
Ø.594 THRU
SOLIDWORKS Educational Product. For Instructional Use Only
UNLESS OTHERWISE SPECIFIED:
TOLERANCES:
ANGLES ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
FOUR PLACE DECIMAL ± .0015
INTERPRET DRAWING PER ANSI Y14.5 2009
DIMS ARE IN INCH
PART NO: 103075
DESCRIPTION: MODIFIED ACKERMAN BOSS
DRAWN BY: G MURILLO
DATE: 5/17/2017
MATERIAL: AL 6061-T6
SCALE: 1
SHEET 1 OF 2
REV
01
SIZE
A
CAL POLY
SMV



NOTES:
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.068
1.13
SOLIDWORKS Educational Product. For Instructional Use Only
PART NO: 103075
DESCRIPTION:
DRAWN BY: NAME
DATE: 2/7/2017
MATERIAL:
SCALE: 1:1
SHEET 2 OF 2
REV
01
SIZE
A

Part Number: 103080, 104070, 104071

Products > Carbon Fiber Tubes > Roll Wrapped Carbon Fiber Tube > Roll Wrapped Unidirectional Tubes

Carbon Fiber Roll Wrapped Uni Tube ~ 0.5" ID x 48", Gloss Finish

Like

Pin it

$36.00 USD ADD TO CART

Product description:

This high strength to weight carbon fiber tubing is fabricated from unidirectional carbon fiber prepreg. The unidirectional layers are oriented to provide high bending stiffness and axial strength, as well as high hoop strength (resistance to crushing from a side load). This economical product is ideal for building lightweight frames and structures, tubular vessels, poles, column supports, and any other application where low weight and high stiffness are essential.

These tubes are made from standard modulus unidirectional prepreg, cello wrapped for a gloss finish.

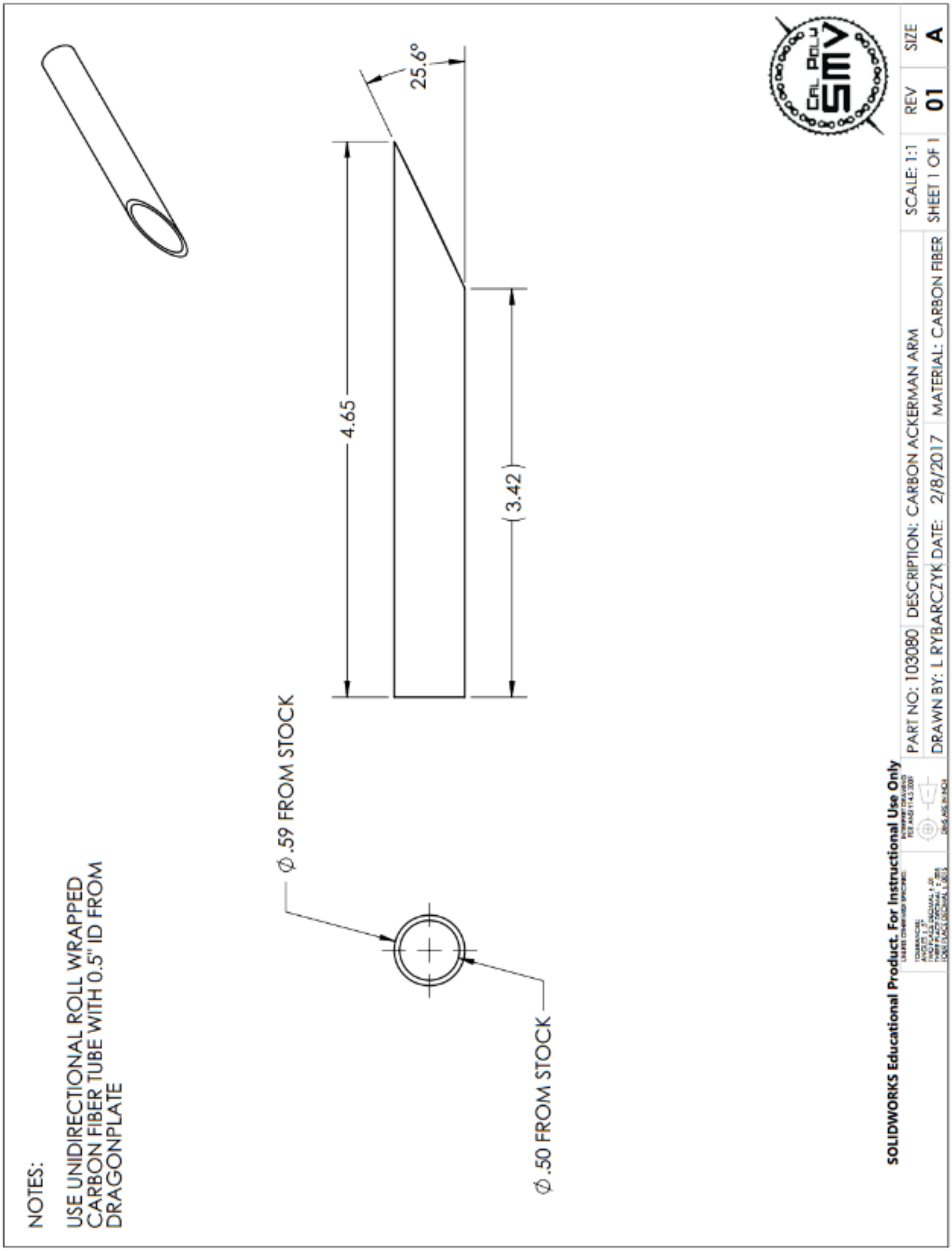
0.5" ID x 0.045" wall

SPECIFICATIONS

Fiber Modulus: 33 MSI
Fiber UTS: 700 KSI
Tg: 250° f

BACK TOP

Part Number: 103080



Part Number: 103090

Products > Tube Connector Systems > Modular Carbon Fiber Tube Connectors > 0.5" Modular Round Tube Connectors

0.5" Single Sided Clevis Threaded Connector

Like

Pin it

Product description:

DragonPlate tube connectors provide an easy and robust method for connecting our 0.5" carbon fiber tubes together to form lightweight rigid structures.

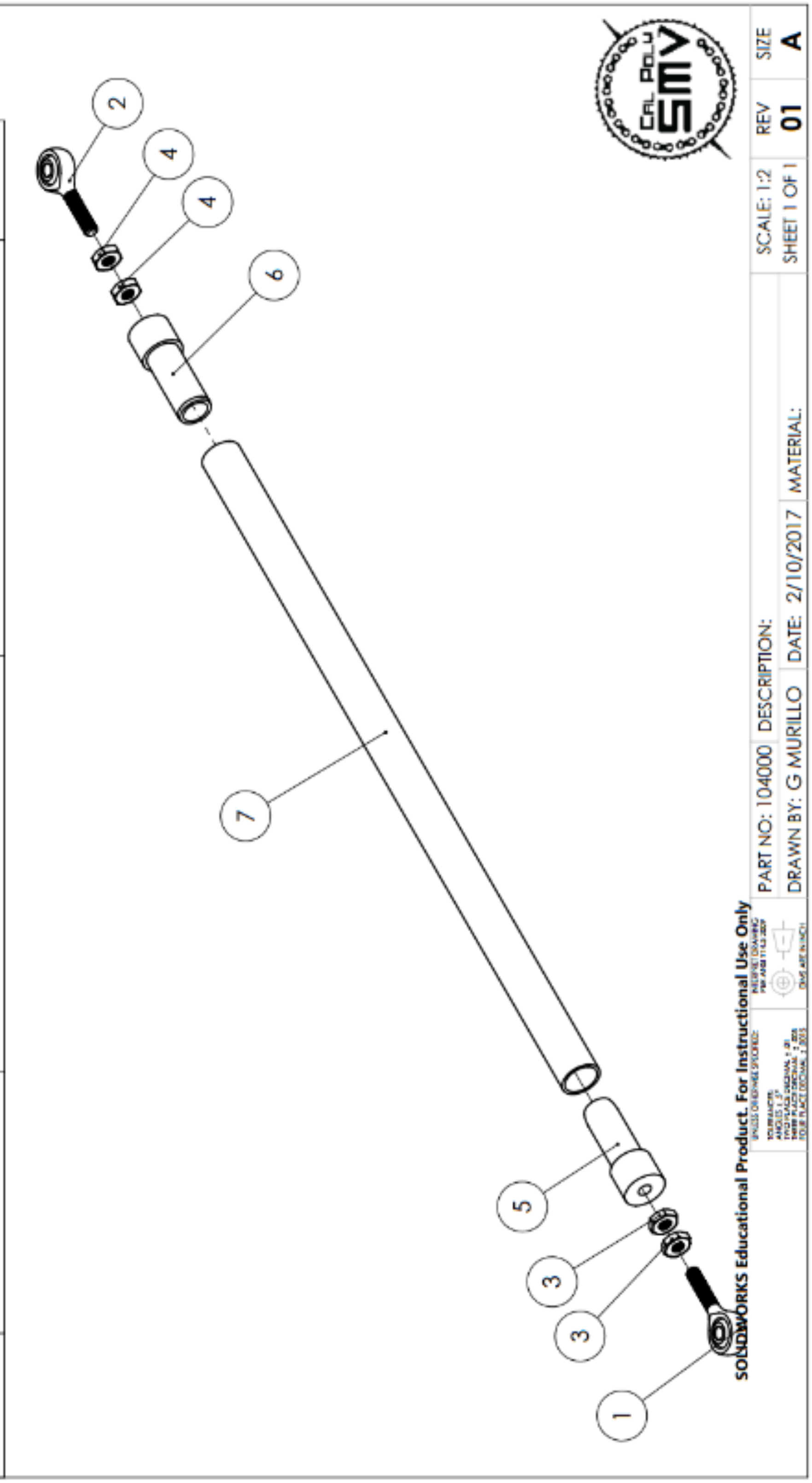
One of the primary concerns when bonding metal fittings into carbon fiber tubes is the fact that the metal component, when subjected to reductions in temperature, will shrink much more than the carbon fiber tube. To eliminate this problem, our patent pending connector incorporates a slotted tubular design, which has a two-fold effect. First, the slots allow the aluminum to contract circumferentially without as much change in the nominal diameter of the insert. Secondly, the slots provide compliance to the part, which further alleviate peel stresses by prohibiting the aluminum part from imparting as much peel force on the adhesive layer. In addition, this design includes a ridged outer surface. This further strengthens the bond inside the carbon fiber tube by placing more epoxy in shear (and most structural epoxies are about 100 times stronger in shear than in peel).

This combination of form, function, and resistance to thermal delaminations makes our DragonPlate tube connectors a versatile and robust option for many projects. For added performance, reliability and integrity this connector is fitted with a HeliCoil stainless threaded insert. Each connector also comes with a foam plug to contain adhesive and enough bond line control micro glass beads to ensure a proper bond fit.

BACK TOP

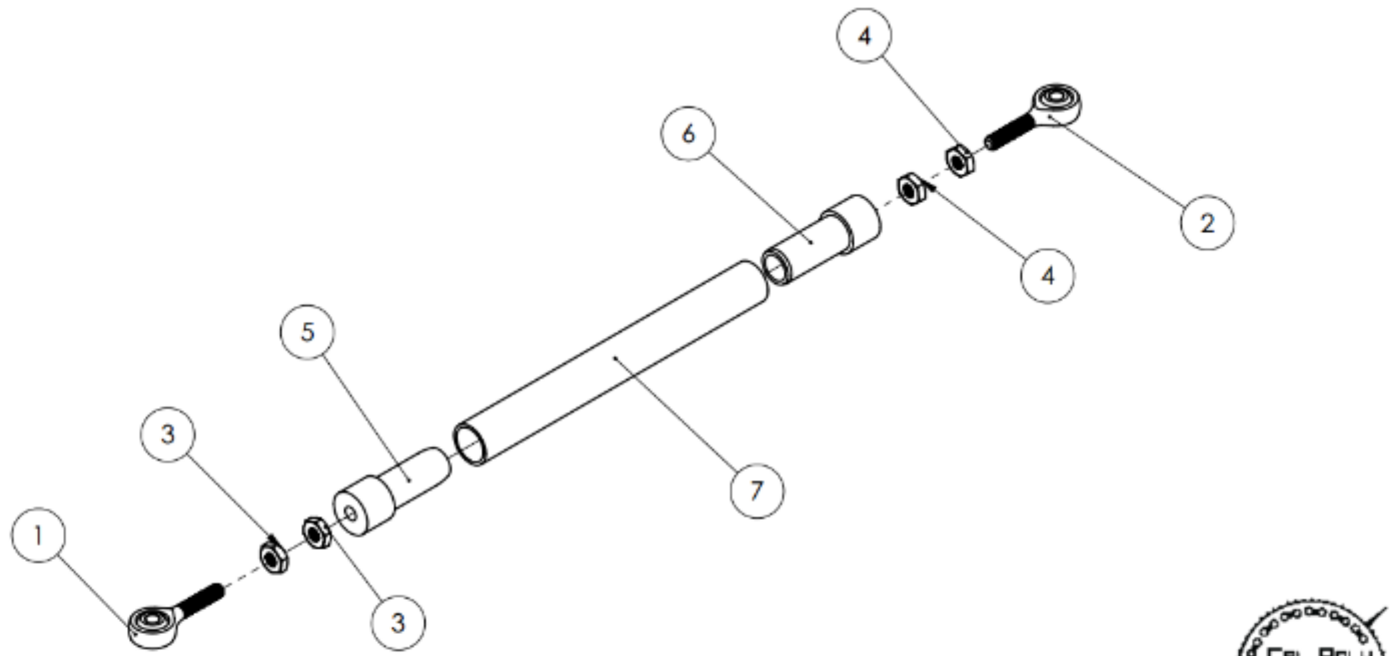
Part Number: 104000

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIALS	QTY.
1	104010	MCMASTER 60645K111	ALLOY STEEL	1
2	104020	MCMASTER 60645K112	ALLOY STEEL	1
3	104030	MCMASTER 90480A195	ALLOY STEEL	2
4	104040	MCMASTER 99961A520	ALLOY STEEL	2
5	104050	1/2" threaded end connector	ALLOY STEEL	1
6	104060	1/2" LH threaded end connector	ALLOY STEEL	1
7	104070	TIE ROD BODY LONG	CARBON FIBER	1



Part Number: 10401

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	Default/ QTY.
1	105010	MCMASTER 60645K111	ALLOY STEEL	1
2	105020	MCMASTER 60645K112	ALLOY STEEL	1
3	104030	MCMASTER 90480A195	ALLOY STEEL	2
4	104040	MCMASTER 99961A520	ALLOY STEEL	2
5	104050	1/2" threaded end connector	ALLOY STEEL	1
6	104060	1/2" LH threaded end connector	ALLOY STEEL	1
7	104071	TIE ROD BODY SHORT	CARBON FIBER	1



PART NO: 104001	DESCRIPTION:	SCALE: 1:2	REV	SIZE
DRAWN BY: S MICHEL	DATE: 2/10/2017 MATERIAL:	SHEET 1 OF 1	01	A

Part Number: 104010

Steel Ball Joint Rod End

10-32 RH Male Shank, 3/16" Ball ID, 3/4" Long Thread

Each

ADD TO ORDER

In stock
$3.53 Each
60645K111

Shank Thread Direction	Right-Hand Threads
Shank Type	Male-Threaded
Shank Thread Size	10-32
Ball ID (A)	3/16"
Maximum Ball Swivel	20°
Overall Width (B)	5/8"
Overall Thickness (C)	5/16"
(D)	1 1/4"
Thread Length (E)	3/4"
Static Radial Load Capacity	1,558 lbs.
Additional Specifications	Inch Sizes
RoHS	Compliant

Our general purpose rod ends will meet your basic connection needs.

Inch sizes have a zinc-plated steel housing and chrome-plated steel ball (unless noted).

Part Number: 104020

Steel Ball Joint Rod End

10-32 Left-Hand Male Shank, 3/16" Ball ID, 3/4" Long Thread

Each	In stock $3.53 Each 60645K112

ADD TO ORDER

Shank Thread Direction	Left-Hand Threads
Shank Type	Male-Threaded
Shank Thread Size	10-32
Ball ID (A)	3/16"
Maximum Ball Swivel	20°
Overall Width (B)	5/8"
Overall Thickness (C)	5/16"
(D)	1 1/4"
Thread Length (E)	3/4"
Static Radial Load Capacity	1,558 lbs.
Additional Specifications	Inch Sizes
RoHS	Compliant

Our general purpose rod ends will meet your basic connection needs.

Inch sizes have a zinc-plated steel housing and chrome-plated steel ball (unless noted).

Part Number: 104030

Low-Strength Steel Hex Nut

Zinc-Plated, 10-32 Thread Size

Packs of 100

ADD TO ORDER

In stock
$1.83 per pack of 100
90480A195

Material	Zinc-Plated Steel
Thread Size	10-32
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 2B
Thread Direction	Right Hand
Width	3/8"
Height	1/8"
Drive Style	External Hex
Nut Type	Hex
Hex Nut Profile	Standard
System of Measurement	Inch
RoHS	Compliant

About half the strength of medium-strength steel nuts, these nuts are for light duty fastening applications, such as securing access panels.

Zinc-plated steel nuts resist corrosion in wet environments.

Part Number: 104040

Left-Hand Threaded Low-Strength Steel Hex Nut

Grade 2, Zinc-Plated, 10-32 Thread Size

Packs of 25

ADD TO ORDER

In stock
$11.06 per pack of 25
99961A520

Material	Zinc-Plated Steel
Fastener Strength Grade/Class	Grade 2
Thread Size	10-32
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 2B
Thread Direction	Left Hand
Width	3/8"
Height	1/8"
Drive Style	External Hex
Nut Type	Hex
Hex Nut Profile	Standard
System of Measurement	Inch
RoHS	Compliant

These nuts tighten when turned to the left; once fastened, they resist loosening from counterclockwise motion. They're about half the strength of medium-strength steel nuts and used in light duty fastening applications, such as securing access panels.

Zinc-plated steel nuts resist corrosion in wet environments.

Part Number: 104050

Products > Tube Connector Systems > Modular Carbon Fiber Tube Connectors > 0.5" Modular Round Tube Connectors

0.5" Threaded End Connector

Like

Pin it

Options:

Select from the options available for this product. Required options are marked with a *. Option price adjustments will be reflected in final product price once added to cart.

Quantity Discount*

Select...

$7.60 USD

ADD TO CART

Product description:

DragonPlate tube connectors provide an easy and robust method for connecting our 0.5" carbon fiber tubes together to form lightweight rigid structures.

One of the primary concerns when bonding metal fittings into carbon fiber tubes is the fact that the metal component, when subjected to reductions in temperature, will shrink much more than the carbon fiber tube. To eliminate this problem, our patent pending connector incorporates a slotted tubular design, which has a two-fold effect. First, the slots allow the aluminum to contract circumferentially without as much change in the nominal diameter of the insert. Secondly, the slots provide compliance to the part, which further alleviate peel stresses by prohibiting the aluminum part from imparting as much peel force on the adhesive layer. In addition, this design includes a ridged outer surface. This further strengthens the bond inside the carbon fiber tube by placing more epoxy in shear (and most structural epoxies are about 100 times stronger in shear than in peel).

This combination of form, function, and resistance to thermal delaminations makes our DragonPlate tube connectors a versatile and robust option for many projects. Each connector also comes with a foam plug to contain adhesive and enough bond line control micro glass beads to ensure a proper bond fit. Accepts standard 10-32 thread.

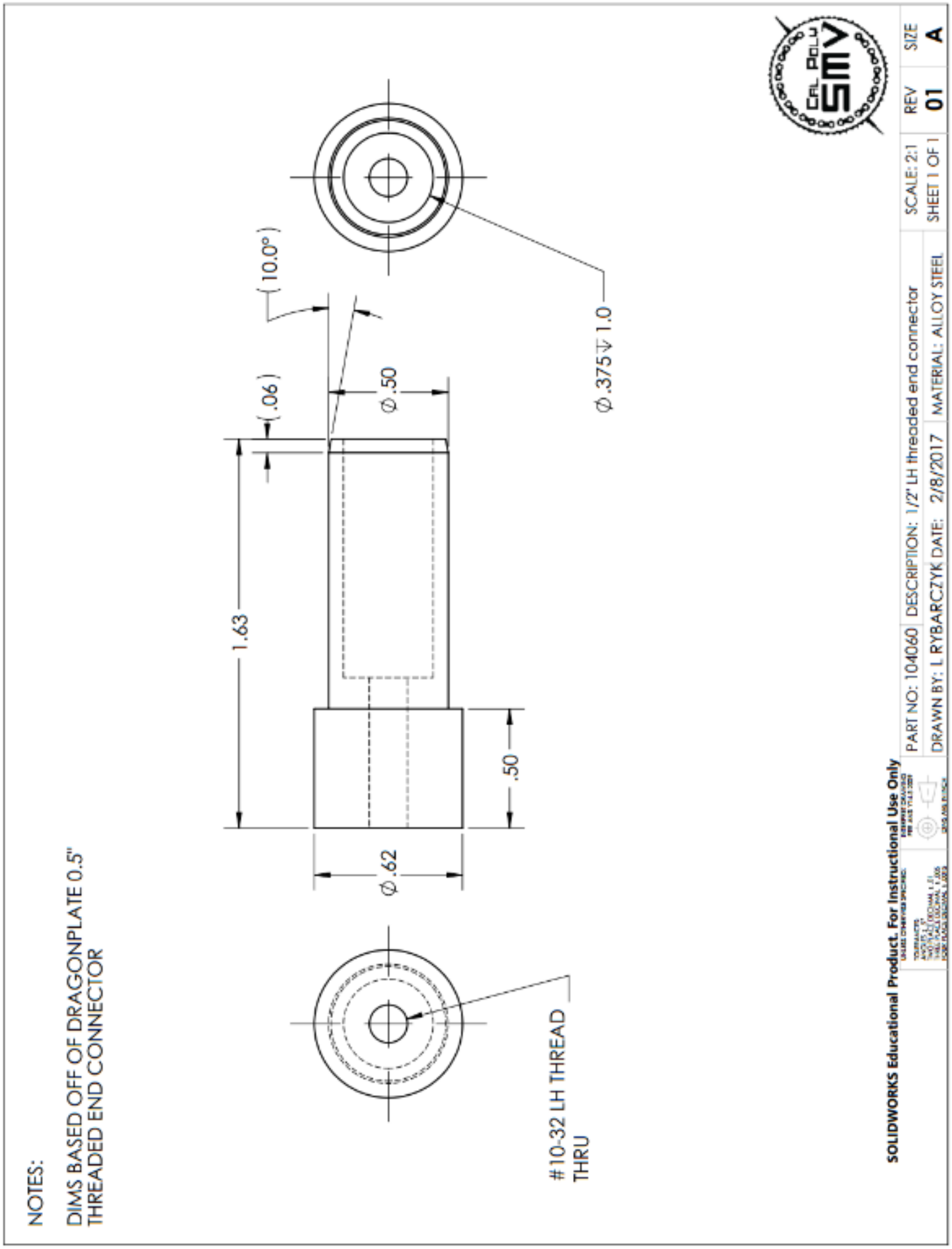
Part Number: 104060

Multipurpose 6061 Aluminum Rod

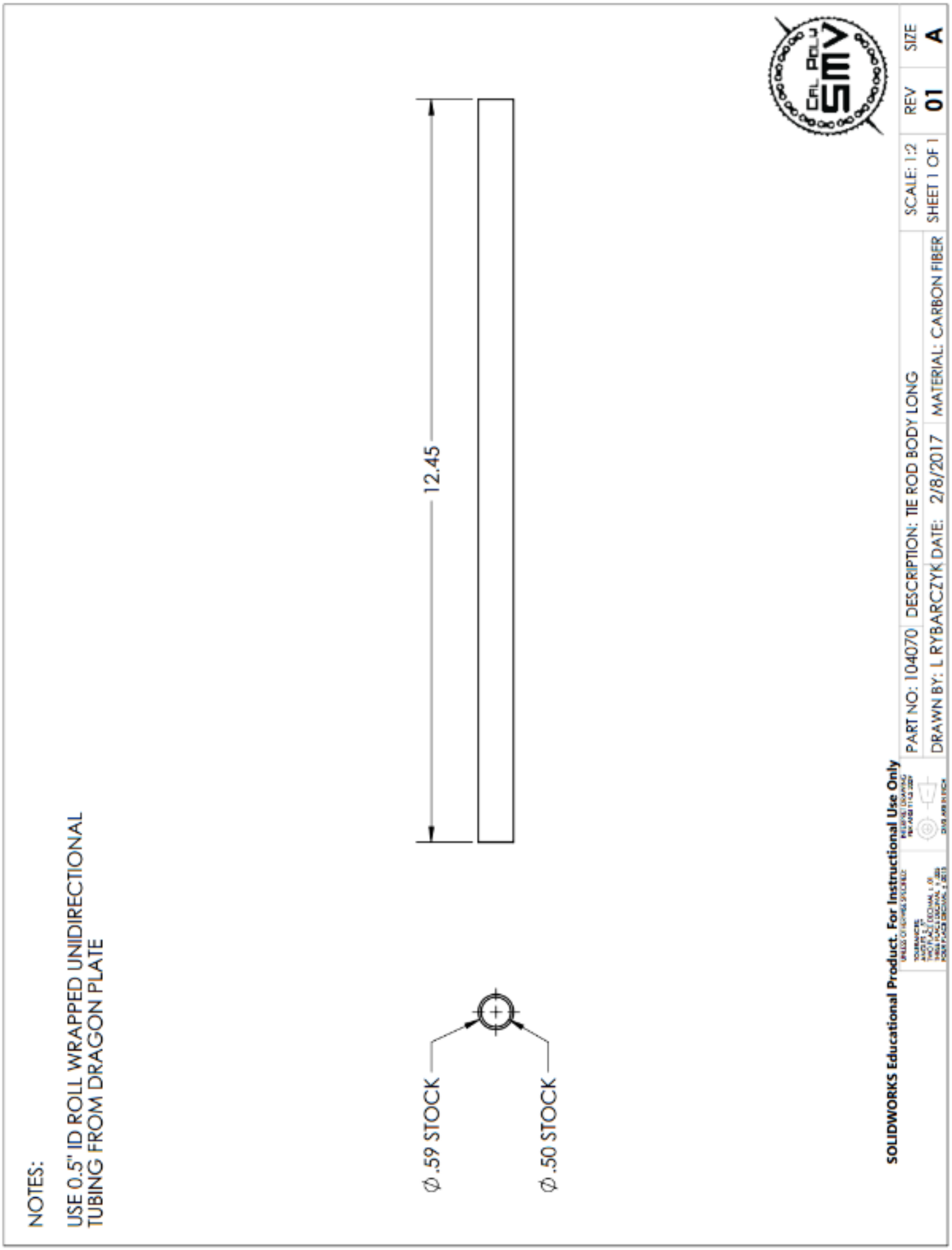
5/8" Diameter

Material	6061 Aluminum
Cross Section Shape	Round
Construction	Solid
Appearance	Plain
Diameter	5/8"
Diameter Tolerance	-0.006" to 0.006"
Tolerance Rating	Standard
Yield Strength	35,000 psi
Fabrication	Heat Treated
Temper	T6511 (Hardened)
Hardness	Brinell 95
Hardness Rating	Soft
Heat Treatable	Yes
Temperature Range	-320° to 300° F
Specifications Met	ASTM B221
Straightness Tolerance	Not Rated
Magnetic Properties	Nonmagnetic
Density	0.1 lbs./cu. in.
Surface Resistivity	25 Ohm-Cir Mil/ft
Melting Point Temperature	1080° F
Modulus of Elasticity	10.0 ksi × 10^3
Thermal Conductivity	1,160 Btu/hr. × in./sq. ft./°F @ 75° F
Elongation	12.5%
Material Composition	
Aluminum	95.1-98.2%
Chromium	0.4-0.8%
Copper	0.05-0.4%
Iron	0-0.7%
Magnesium	0.8-1.2%
Manganese	0-0.15%
Nickel	0-0.05%
Silicon	0.4-0.8%
Titanium	0-0.15%
Zinc	0-0.25%
Zirconium	0-0.25%
Other	0.15%

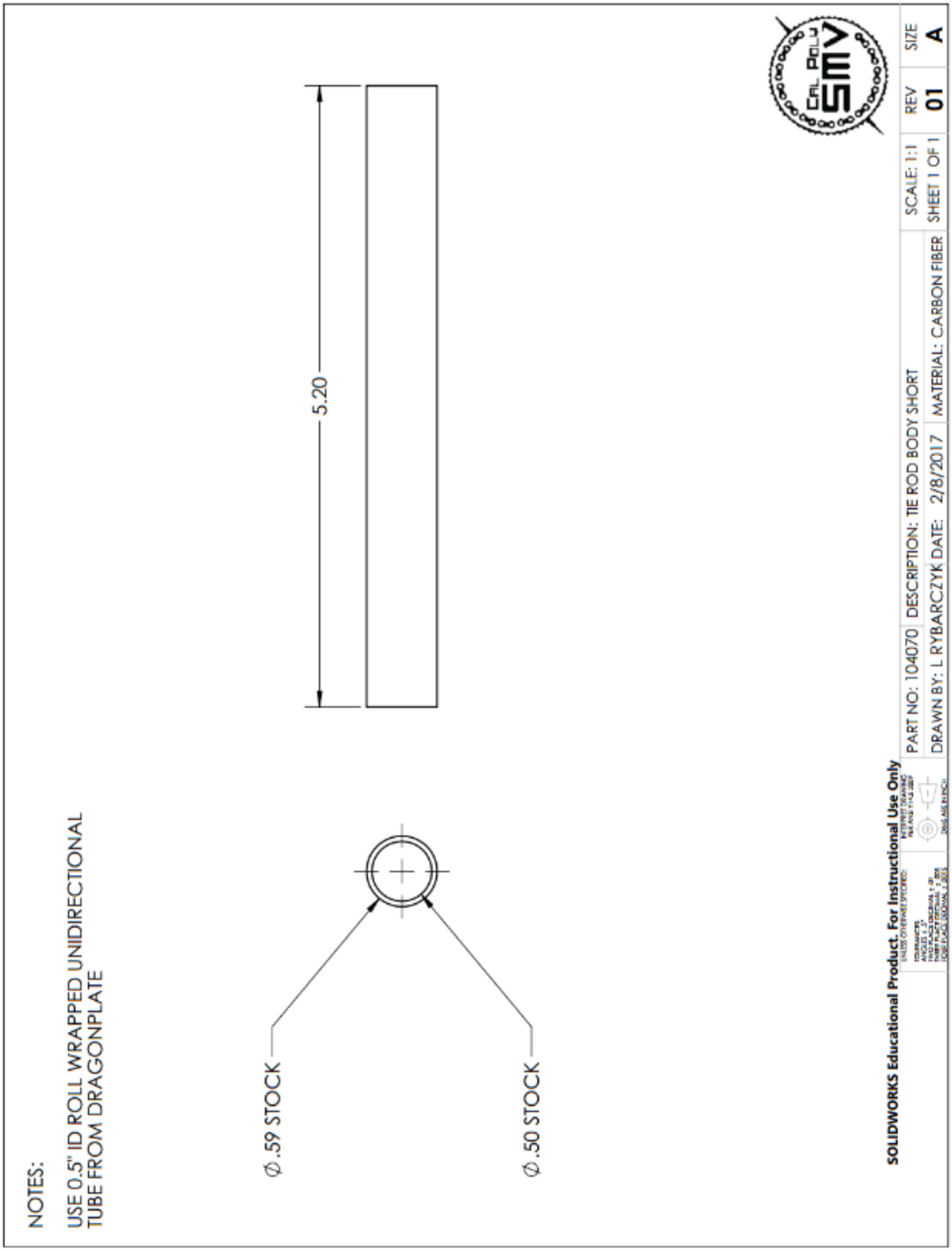
Part Number: 104060



Part Number: 104070



Part Number: 104071



Part Number: 104080

Zinc-Plated Alloy Steel Socket Head Screw

10-32 Thread Size, 5/8" Long

Packs of 50

ADD TO ORDER

In stock
$6.82 per pack of 50
90128A944

Thread Size	10-32
Length	5/8"
Threading	Fully Threaded
Head Diameter	0.312"
Head Height	0.19"
Drive Size	5/32"
Material	Zinc-Plated Alloy Steel
Hardness	Rockwell C37
Tensile Strength	170,000 psi
Screw Size Decimal Equivalent	0.190"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 3A
Thread Direction	Right Hand
Head Type	Socket
Socket Head Profile	Standard
Drive Style	Hex
Specifications Met	ASTM A574
System of Measurement	Inch
RoHS	Compliant

These screws are made from an alloy steel that's stronger than Grade 8 steel. Length is measured from under the head.

Zinc-plated steel screws are more corrosion resistant than black-oxide screws for use in wet environments.

Part Number: 104090

Zinc-Plated Alloy Steel Socket Head Screw

10-32 Thread Size, 1-1/4" Long

[|] Packs of 25

ADD TO ORDER

In stock
$4.55 per pack of 25
90128A948

Thread Size	10-32
Length	1 1/4"
Threading	Partially Threaded
Minimum Thread Length	3/4"
Head Diameter	0.312"
Head Height	0.19"
Drive Size	5/32"
Material	Zinc-Plated Alloy Steel
Hardness	Rockwell C37
Tensile Strength	170,000 psi
Screw Size Decimal Equivalent	0.190"
Thread Type	UNF
Thread Spacing	Fine
Thread Fit	Class 3A
Thread Direction	Right Hand
Head Type	Socket
Socket Head Profile	Standard
Drive Style	Hex
Specifications Met	ASTM A574
System of Measurement	Inch
RoHS	Compliant

These screws are made from an alloy steel that's stronger than Grade 8 steel. Length is measured from under the head.

Zinc-plated steel screws are more corrosion resistant than black-oxide screws for use in wet environments.

Appendix G – Spindle Material Selection Report

Cal Poly Supermileage Steering System – Spindle Materials Selection Report
Materials Engineering Student Society

February 5st, 2017
Joe DeCesaro
David Otsu

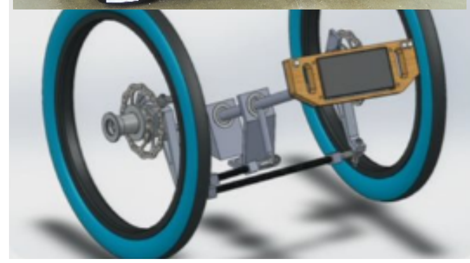
Supermileage Steering System – Spindle Materials Selection

Materials Engineering Student Society Consulting Branch | Jan-19, 2017

Project Background

Each year, the Cal Poly Supermileage team designs and builds light-weight, fuel-efficient vehicles to be entered in the annual SAE Supermileage competition. For this iteration, the team is revamping the steering system to reduce its weight, and increase its structural integrity. The system includes all components depicted in the image on the right.

Sponsor Presentation: https://goo.gl/RtoIYO @ *53:05*



Materials Engineering Problem Statement

A critical component in need of improvement is the steering system's spindles. In the past, Al 6061 and Al 7075 were used with little success - both alloys showed extensive surface wear during the vehicle's normal operation, greatly reducing the efficiency of their overall design. The team is looking for a hard, strong, and light-weight alternative that can be purchased at a relatively low cost, manufactured at Cal Poly, and integrated into the final system.

Explicit Tasks to Perform

Materials selection analysis for the steering system's spindle

Determine the appropriate mechanical property criteria and constraints

Down-select and research the top material candidates with manufacturability in mind

Identify suitable material forms, vendors, and pricing for the top material candidates

Deliverables and Deadline

Materials selection report for the steering system's spindle shall be submitted by Feb. 4th, 2017

Client Information

Sean Michel
skmichel@calpoly.edu
310-738-2452

Materials Selection Objectives and Constraints

The following objectives (properties to be minimized or maximized) and constraints (imposed minimum or maximum value limits) were identified for the Supermileage spindle material:

Constraint – Hardness/Yield Strength

Hardness is the measurement of the surface of a material's resistance to plastic deformation. Although hardness and yield strength are inter-related, hardness is generally more useful for evaluating material candidates in bearing and anti-abrasive operating conditions. A minimum hardness of 30HRC (~285 HV) constraint is set for this material selection effort.

Objective – Maximizing Resistance to Yielding

In addition to the minimum hardness constraint, the following material index was identified for optimizing resistance to yielding in blunt contact, sliding load applications:

$$M = \frac{H^3}{E^2}$$

where:
H = Hardness
E = Young's Modulus

Objective – Maximizing Resistance to Crack Propagation

Fracture toughness quantifies a material's resistance to crack propagation. It is analogous to a material's mechanical durability and brittleness. For blunt bearing applications with a sliding load, the applicable material index to maximize is as follows:

$$M = \frac{K_{1c}^3}{E^2(1-2v)^3}$$

where:
K_{1C} = Fracture Toughness
E = Young's Modulus
v = Poisson's Ratio

Objective - Minimizing Cost Vs Minimizing Density

The Supermileage spindle has two additional competing objectives: minimizing cost and minimizing density. For this selection initiative, cost is favored over mass reduction, as it correlates well with low lead times, stock form availability, and ease of procurement from a wide variety of vendors. Additionally, low cost candidates generally have well-understood manufacturing methods that are easy to identify and follow.

Analysis and Candidate Down-Selection

CES EduPack Level 3 Materials Database (3078 valid entries) was used to identify the general material candidate most appropriate for this application. 346 candidates remained after the implementing the hardness constraint. The following charts were generated for each of the identified objectives:

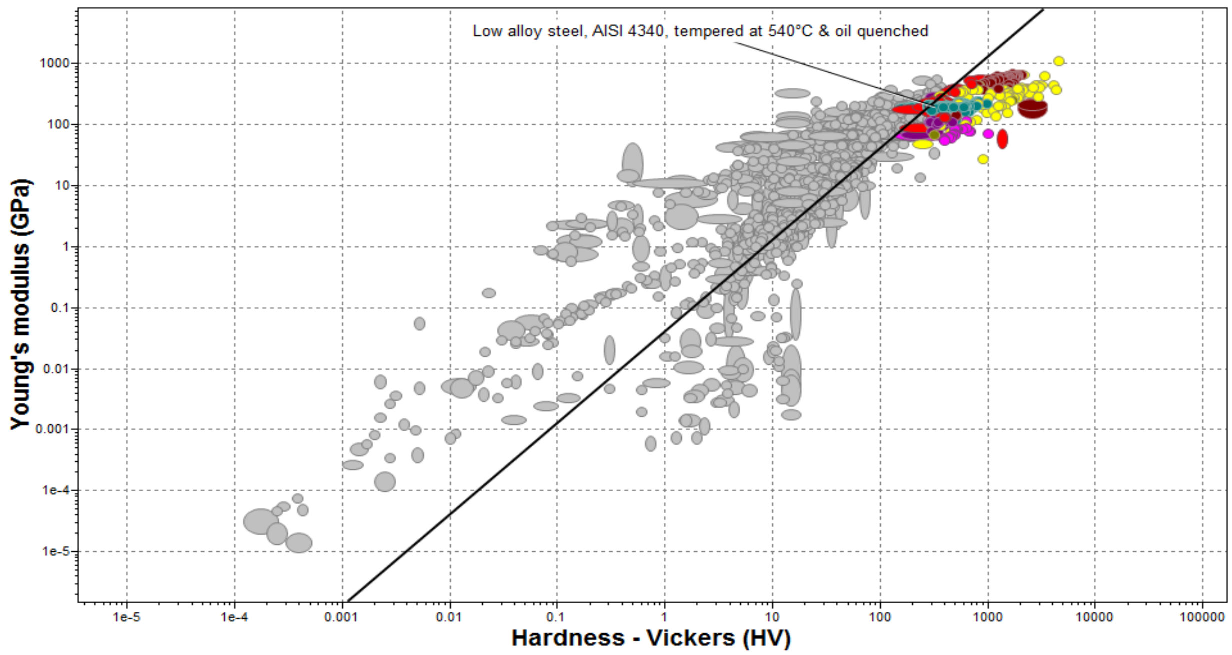


Figure 1. Graphical depiction of Hardness (HV) vs Young's Modulus (GPa). Material candidates that fall to the right of the line maximize the index M=H^3/E^2. Ferrous entries are teal, non-ferrous entries are red, ceramic entries are yellow, composite entries are dark red, and glasses are purple.

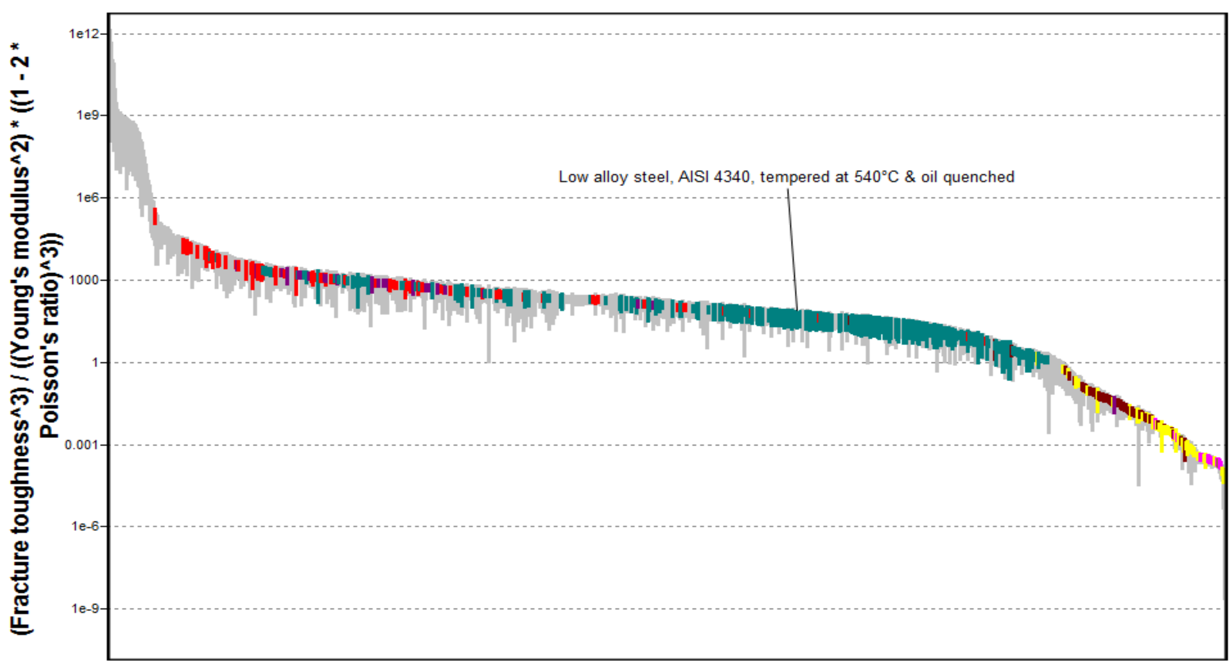


Figure 2. Graphical depiction of the fracture toughness material index. Note that most ceramic, glass, and composite entries perform quite poorly. Any candidate with an index value above 1 passed into the next evaluation stage.

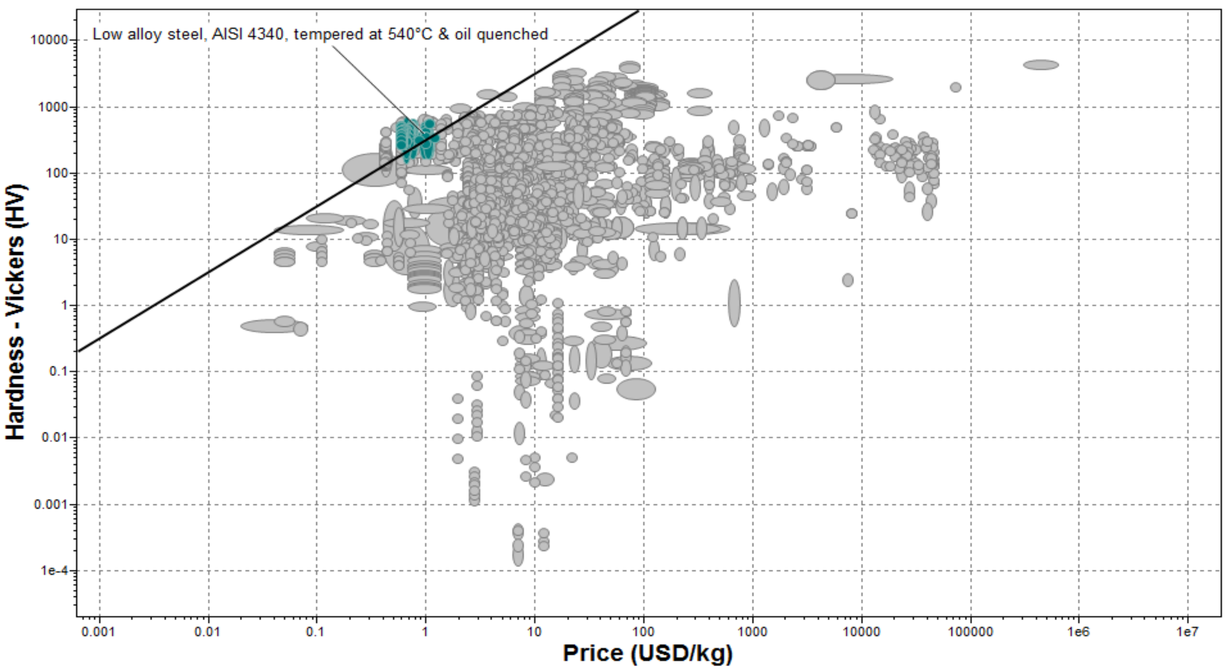


Figure 3. Graphical depiction of hardness (HV) vs price (USD/kg). Entries to the left of the line are considered optimal for minimum cost designs. What remains are low alloy and plain carbon steels.

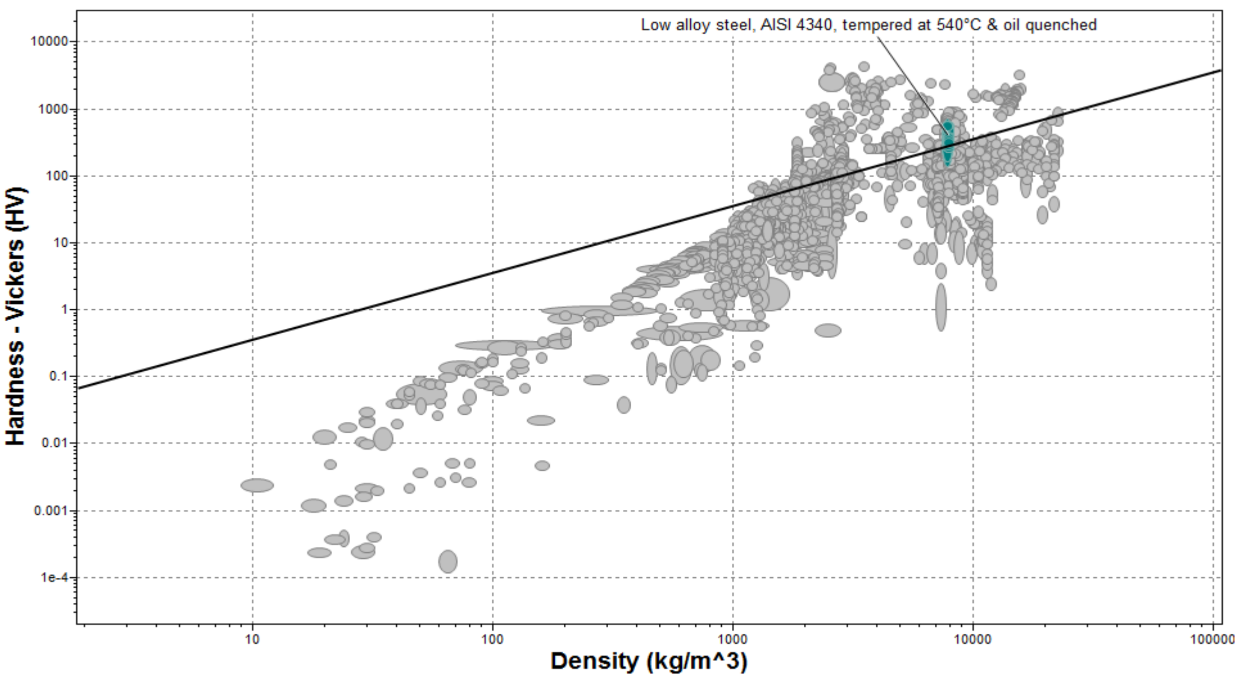


Figure 4. Graphical depiction of Hardness (HV) vs density (kg/m^3). Since low alloy and plain carbon steel entries do not differ considerably in density, the same entries pass this stage.

With 49 low alloy and plain carbon steel entries remaining, each candidate's manufacturability was evaluated. Two factors were considered: machinability (a relative measure of an alloy's ability to be machined using conventional subtractive methods) and hardenability (a relative measure of a heat treatable steel alloy's ability to be strengthened). From this analysis, one final candidate was selected: AISI 4340 steel.

Final Candidate Information

AISI 4340 is a nickel-chromium-molybdenum low alloy heat treatable steel. The following processing steps have been identified to produce the desired mechanical properties for this application. Approximate material property values corresponding to a slightly elevated tempering temperature may be found at the end of this report.

1. Procure 4340 stock

AISI 4340 is available from a variety of vendors. Stock should be procured in the annealed or normalize condition, both of which are considered readily machinable.

Example vendors:
https://www.mcmaster.com/#standard-steel-rods/=lki72m8wfiythwyw6 (annealed)
http://www.onlinemetals.com/merchant.cfm?id=255&step=2 (normalized)

2. Machine to specification

The stock should be machined to specification per best practice (ref. any machinist's handbook) **before** it is heat treated. Heat treating the steel will raise its strength significantly, increasing the difficulty of machining by a considerable amount.

3. Heat Treatment

The purpose of the heat treatment is to increase the strength (and hardness) of the steel. The following steps provide a general overview of the process. Should the Supermileage team decide to follow these procedures, it is highly recommended that a materials engineer consultant provide direct assistance and that a witness evaluation sample be processed alongside the actual component. Point of contact information is provided at the end of this report.

Preparation

The specimen must be free of all oil, grease, and cutting fluid prior to heat treatment. Additionally, any chips, dirt, or other contaminants must be removed from the surface.

If a standard atmosphere furnace is used to for heat treating, the steel must be protected from the oxygenated environment to mitigate detrimental decarburization effects. Two common methods exist: employing a protective ceramic coating or using a sealable heat treatment bag. The Materials Engineering department has access to both methods.

Austenization

The sample should be austenitized at 825 °C (1517 °F) for 20 minutes so long as component thickness does not exceed 1 inch.

Quenching

After 20 minutes, the component should be grabbed at its very edge (or at a location less critical to the application) and completely submerged in quenching oil for 1 minute. While in the oil the component should be constantly moved and stirred.

Tempering

The component should be tempered in a furnace at 500°C (932°F) for 2 hours. After two hours, remove the piece from the furnace and allow it to air cool for a minimum of 5 hours. The piece should then be tempered a second time at 500°C (932°F) for 2 hours. After two hours, remove the piece from the furnace and allow it to air cool for a minimum of 5 hours.

4. Descaling and Final Inspection

The final hardened part will have a thin layer of oxide on its surface. This can be removed using fine grit sand paper. The final part should be inspected for cracks and pores that may have formed during the heat treatment process. If a witness evaluation sample was heat treated alongside the component, verify its hardness to be around 35HRC.

Consultant Point of Contact

Processing at Cal Poly will require use of the Materials Engineering department's resources and facilities. The following point of contact has been designated to support the Supermileage team on any materials engineering-related tasks until the end of the academic year (Spring 2017):

Joe DeCesaro
jdecesar@calpoly.edu
jdecesaro@comcast.net
1-503-704-8776

Low alloy steel, AISI 4340, tempered at 540°C & oil quenched

General information

Designation

AISI 4340

Condition Tempered at 540°C & oil quenched

UNS number G43400

US name SAE E4340, SAE 4340, SAE E4340, SAE 4340H, SAE 4340, SAE 4330H, ASTM E4340, ASTM 4340, ASTM G43406, ASTM G43400, ASTM E4340H, ASTM E4340, ASTM 1B 1, ASTM B24V, ASTM B23, ASTM 4340H, ASTM 4340, ASTM 4 G, ASME E4340, ~SAE E4340H, ~ASTM B24

GB (Chinese) name ~ 40CrNiMoA

JIS (Japanese) name SNCM447RCH, SNCM 439, SNB24-5, SNB24-4, SNB24-3, SNB24-2, SNB23-1, ~ SNCM 439, ~SNCM439RCH, ~SNB24-1, ~SNB23-5, ~SNB23-4, ~SNB23-3, ~SNB23-2

Typical uses

High tensile applications; General engineering parts; Through-hardened gears; Connecting rods and bolts; Gun barrels;

Composition overview

Compositional summary

Fe95-96 / Ni1.6-2 / Cr0.7-0.9 / Mn0.6-0.8 / C0.38-0.43 / Mo0.2-0.3 / Si0.15-0.3 (impurities: S<0.04, P<0.035)

Material family Metal (ferrous)

Base material Fe (Iron)

Composition detail (metals, ceramics and glasses)

C (carbon)	0.38	-	0.43	%
Cr (chromium)	0.7	-	0.9	%
Fe (iron) *	95.2	-	96.3	%
Mn (manganese)	0.6	-	0.8	%
Mo (molybdenum)	0.2	-	0.3	%
Ni (nickel)	1.65	-	2	%
P (phosphorus)	0	-	0.035	%
S (sulfur)	0	-	0.04	%
Si (silicon)	0.15	-	0.3	%

Price

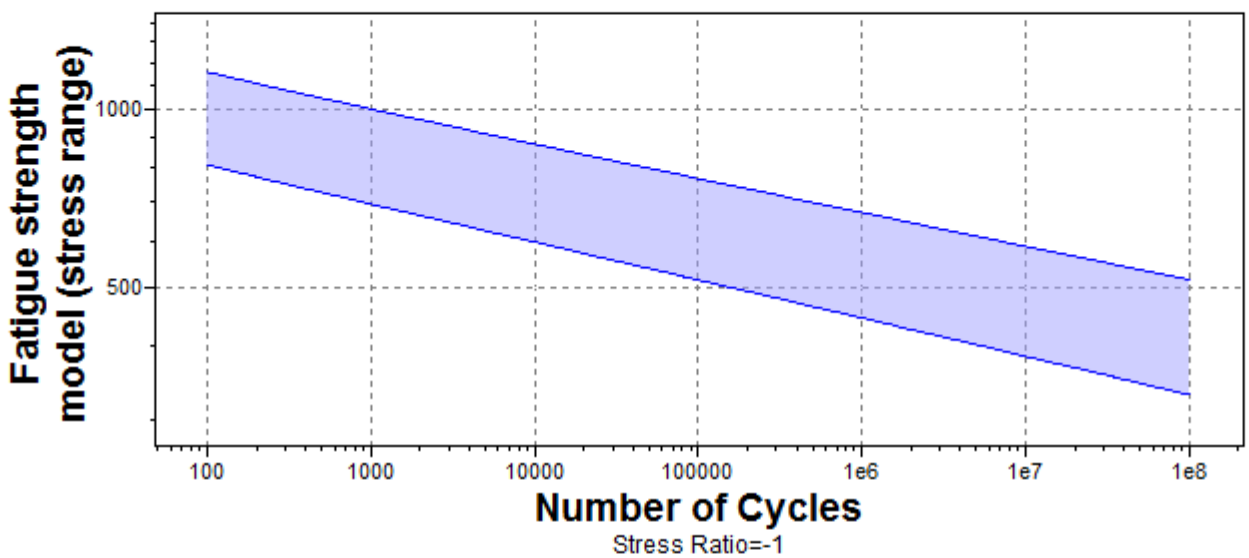
Price *	0.94	-	1.02	USD/kg

Physical properties

Density	7.8e3	-	7.9e3	kg/m^3

Mechanical properties

Young's modulus 205 - 213 GPa
Yield strength (elastic limit) 965 - 1.19e3 MPa
Tensile strength 1.05e3 - 1.3e3 MPa
Elongation 10 - 16 % strain
Compressive strength * 965 - 1.19e3 MPa
Flexural modulus * 205 - 213 GPa
Flexural strength (modulus of rupture) 965 - 1.19e3 MPa
Shear modulus 79 - 83 GPa
Bulk modulus 158 - 174 GPa
Poisson's ratio 0.285 - 0.295
Shape factor 23
Hardness - Vickers 325 - 400 HV
Fatigue strength at 10^7 cycles * 442 - 513 MPa
Fatigue strength model (stress range) * 385 - 589 MPa
Parameters: Stress Ratio = -1, Number of Cycles = 1e7cycles



Mechanical loss coefficient (tan delta) * 3.3e-4 - 4.2e-4

Impact & fracture properties

Fracture toughness * 37 - 64 MPa.m^0.5

Thermal properties

Melting point 1.43e3 - 1.51e3 °C
Maximum service temperature * 500 - 530 °C
Minimum service temperature * -63 - -38 °C
Thermal conductivity * 35 - 50 W/m.°C
Specific heat capacity * 440 - 520 J/kg.°C
Thermal expansion coefficient 11.5 - 13 µstrain/°C
Latent heat of fusion * 265 - 280 kJ/kg

Electrical properties

Electrical resistivity * 18 - 27 µohm.cm
Galvanic potential * -0.5 - -0.42 V

Magnetic properties

Magnetic type Magnetic

Optical properties
Transparency Opaque
Bio-data
Food contact Yes
Restricted substances risk indicators
RoHS (EU) compliant grades? False
Processing properties
Metal casting Unsuitable
Metal cold forming Excellent
Metal hot forming Excellent
Metal press forming Excellent
Metal deep drawing Limited use
Carbon equivalency 0.77 - 0.937
Durability
Water (fresh) Acceptable
Water (salt) Limited use
Weak acids Limited use
Strong acids Unacceptable
Weak alkalis Acceptable
Strong alkalis Limited use
Organic solvents Excellent
Oxidation at 500C Acceptable
UV radiation (sunlight) Excellent
Galling resistance (adhesive wear) Acceptable
Flammability Non-flammable
Primary production energy, CO2 and water
Embodied energy, primary production 30.8 - 33.9 MJ/kg
Sources
19.4 MJ/kg (Dhingra, Overly, Davis, 1999); 23 MJ/kg (Norgate, Jahanshahi, Rankin, 2007); 27.9 MJ/kg (Ecoinvent v2.2); 29.2 MJ/kg (Hammond and Jones, 2008); 32.8 MJ/kg (Hammond and Jones, 2008); 34.7 MJ/kg (Hammond and Jones, 2008); 35.4 MJ/kg (Hammond and Jones, 2008); 37.2 MJ/kg (Sullivan and Gaines, 2010); 38 MJ/kg (Hammond and Jones, 2008); 45.4 MJ/kg (Hammond and Jones, 2008)
CO2 footprint, primary production 2.26 - 2.49 kg/kg
Sources
0.396 kg/kg (Voet, van der and Oers, van, 2003); 1.75 kg/kg (Ecoinvent v2.2); 1.81 kg/kg (Voet, van der and Oers, van, 2003); 2.23 kg/kg (Voet, van der and Oers, van, 2003); 2.3 kg/kg (Norgate, Jahanshahi, Rankin, 2007); 2.74 kg/kg (Hammond and Jones, 2008); 2.77 kg/kg (Hammond and Jones, 2008); 2.87 kg/kg (Hammond and Jones, 2008); 2.89 kg/kg (Hammond and Jones, 2008); 3.03 kg/kg (Hammond and Jones, 2008); 3.27 kg/kg (Hammond and Jones, 2008)
NOx creation * 12.6 - 13.9 g/kg
SOx creation * 21.5 - 23.8 g/kg
Water usage * 50.8 - 56.1 l/kg

Processing energy, CO2 footprint & water

Casting energy	*	10.9	-	12	MJ/kg
Casting CO2	*	0.815	-	0.901	kg/kg
Casting water	*	20.6	-	30.9	l/kg
Rough rolling, forging energy	*	8.93	-	9.87	MJ/kg
Rough rolling, forging CO2	*	0.67	-	0.74	kg/kg
Rough rolling, forging water	*	5.37	-	8.05	l/kg
Extrusion, foil rolling energy	*	17.6	-	19.4	MJ/kg
Extrusion, foil rolling CO2	*	1.32	-	1.46	kg/kg
Extrusion, foil rolling water	*	9.06	-	13.6	l/kg
Wire drawing energy	*	65.1	-	72	MJ/kg
Wire drawing CO2	*	4.88	-	5.4	kg/kg
Wire drawing water	*	24.5	-	36.8	l/kg
Metal powder forming energy	*	37.8	-	41.7	MJ/kg
Metal powder forming CO2	*	3.02	-	3.34	kg/kg
Metal powder forming water	*	41.2	-	61.8	l/kg
Vaporization energy	*	1.09e4	-	1.2e4	MJ/kg
Vaporization CO2	*	815	-	901	kg/kg
Vaporization water	*	4.53e3	-	6.8e3	l/kg
Coarse machining energy (per unit wt. removed)	*	1.77	-	1.96	MJ/kg
Coarse machining CO2 (per unit wt. removed)	*	0.133	-	0.147	kg/kg
Fine machining energy (per unit wt. removed)	*	13.4	-	14.9	MJ/kg
Fine machining CO2 (per unit wt. removed)	*	1.01	-	1.11	kg/kg
Grinding energy (per unit wt. removed)	*	26.4	-	29.2	MJ/kg
Grinding CO2 (per unit wt. removed)	*	1.98	-	2.19	kg/kg
Non-conventional machining energy (per unit wt. removed)	*	109	-	120	MJ/kg
Non-conventional machining CO2 (per unit wt. removed)	*	8.15	-	9.01	kg/kg

Recycling and end of life

Recycle	False				
Embodied energy, recycling	*	8.1	-	8.96	MJ/kg
CO2 footprint, recycling	*	0.636	-	0.703	kg/kg
Recycle fraction in current supply		39.9	-	44	%
Downcycle	False				
Combust for energy recovery	Combust for energy recovery				
Landfill	False				
Biodegrade	Biodegrade				

Possible substitutes for principal component

Iron is the least expensive and most widely used metal. In most applications, iron and steel compete either with less expensive nonmetallic materials or with more expensive materials having a property advantage. Iron and steel compete with lighter materials, such as aluminum and plastics, in the motor vehicle industry; aluminum, concrete, and wood in construction; and aluminum, glass, paper, and plastics in containers.

Geo-economic data for principal component

Principal component Iron

Typical exploited ore grade 45.1 - 49.9 %

Minimum economic ore grade 25 - 70 %

Abundance in Earth's crust 4.1e4 - 6.3e4 ppm

Abundance in seawater 0.0025 - 0.003 ppm

Annual world production, principal component 2.3e9 tonne/yr.

Reserves, principal component 1.6e11 tonne

Main mining areas (metric tonnes per year)

Australia, 530e6
Brazil, 389e6
Canada, 40e6
China, 1.32e9
India, 150e3
Iran, 37e3
Kazakhstan, 25e6
Russia, 102e6
South Africa, 67e6
Sweden, 26e6
Ukraine, 80e6
United States of America, 52e6
Venezuela, 30e6
Other countries, 88e6

Eco-indicators for principal component

Eco-indicator 95 110 millipoints/kg

Eco-indicator 99 198 millipoints/kg

Notes

Other notes

A very popular, versatile steel. It can be heat-treated to produce a wide range of tensile strengths in moderate sections.

Keywords

A-1270, AFORA (Aceros Afora S.A.) (SPAIN); A-1272, AFORA (Aceros Afora S.A.) (SPAIN);

Standards with similar compositions

The following information is taken from ASM AlloyFinder 3 - see link to References table for further information.

IAS IRAM 4340 (Argentina)
EN 10083/1(91)A1(96) 1.6582 (Europe)
EN 10083/1(91)A1(96) 1.7037 (Europe)
EN 10083/1(91)A1(96) 34CrNiMo6 (Europe)
EN 10083/1(91)A1(96) 34CrS4 (Europe)
BDS 6354 40ChN2M (Bulgaria)
BDS 6354(74) 35Ch2N2M (Bulgaria)
GB 3077(88) 40CrNiMoA (China)
GB 8162(87) 40CrNiMoA (China)
GB/T 3078(94) 40CrNiMoA (China)
GB/T 3079(93) 40CrNiMoA (China)
CSN 416341 16341 (Czech Republic)
AFNOR NFA35551(75) 35NCD6 (France)
DIN 40NiCrMo6 (Germany)
DIN 40NiCrMo8-4 (Germany)
DIN WNr 1.6562 (Germany)

DIN WNr 1.6565 (Germany)
MSZ 61(85) NCMo5 (Hungary)
IS 1570 40Ni2Cr1Mo28 (India)
IS 1570 40NiCr1Mo15 (India)
UNI 5332(64) 40NiCrMo7 (Italy)
UNI 6926(71) 40NiCrMo7 (Italy)
UNI 7356(74) 40NiCrMo7KB (Italy)
UNI 7845(78) 40NiCrMo7 (Italy)
UNI 7874(79) 40NiCrMo7 (Italy)
JIS G4103(79) SNCM439 (Japan)
JIS G4103(79) SNCM8 (Japan)
JIS G4108(94) SNB24-1 (Japan)
JIS G4108(94) SNB24-2 (Japan)
JIS G4108(94) SNB24-3 (Japan)
JIS G4108(94) SNB24-4 (Japan)
JIS G4108(94) SNB24-5 (Japan)
DGN B-203 4340 (Mexico)
DGN B-297 4340 (Mexico)
NMX-B-300(91) 4340 (Mexico)
AS 1444(96) 4340 (NSW Australia)
PNH84030/04 36HNM (Poland)
PNH84030/04 40HNMA (Poland)
GOST 4543 40Ch2N2MA (Russian Federation)
GOST 4543(61) 38ChNWA (Russian Federation)
GOST 4543(71) 36Ch2N2MFA (Russian Federation)
GOST 4543(71) 38Ch2N2MA (Russian Federation)
GOST 4543(71) 40Ch2N2MA (Russian Federation)
UNE 36012(75) 35NiCrMo4 (Spain)
UNE 36012(75) 40NiCrMo4 (Spain)
UNE 36012(75) 40NiCrMo7 (Spain)
UNE 36012(75) F.1272 (Spain)
ISO 683-8 4 (International)
ISO 683-8 4A (International)
ISO 683-8 4b (International)
ISO R683-8 4A (International)
ISO R683-8 4b (International)
BS 4670 818M40 (United Kingdom)
BS 970/3(91) 817M40 (United Kingdom)
AMS 6359 (USA)
AMS 6409 (USA)
AMS 6414 (USA)
AMS 6415 (USA)
AMS 6454 (USA)
ASTM A29/A29M(93) 4340 (USA)
ASTM A322(96) 4340 (USA)
ASTM A331(95) 4340 (USA)
ASTM A372 Type VII (USA)
ASTM A506(93) 4340 (USA)
ASTM A519(96) 4340 (USA)

ASTM A646(95) Grade 7 (USA)
ASTM A752(93) 4340 (USA)
ASTM A829/A829M(95) 4340 (USA)
DoD-F-24669/1(86) 4340 (USA)
FED QQ-S-626C(91) 4340 (USA)
MIL-S-16974E(86) 4340 (USA)
MIL-S-19434B(SH)(90) Class 2 (USA)
MIL-S-24093A(SH)(91) Type I Class A (USA)
MIL-S-24093A(SH)(91) Type I Class B (USA)
MIL-S-24093A(SH)(91) Type I Class C (USA)
MIL-S-46059 G43400 (USA)
MIL-S-5000E(82) 4340 (USA)
MIL-S-83135USAF3(95) 4340M (USA)
MIL-S-8844D(90) 4340 (USA)
SAE 770(84) 4340 (USA)
SAE J404(94) 4340 (USA)
AISI 4340 (USA)
COPANT 334 4340 (Venezuela)
COPANT 514 4340 (Venezuela)
C.5431 (Yugoslavia)

Appendix H – Bill of Materials

Indented Bill of Material (BOM)

2018 Supermileage Steering System

Part Number	Description	MFG Notes	Vendor	Part #	Qty Needed	Cost	Line Cost	Notes	Matl	Weight [lb]	Line Wt
	Lvl0 Lvl1 Lvl2										
100000	Full Assembly										
101000	Subframe Assembly										
101010	#10-32 RH Female Thrust Rated Rod End (3/16" Ball, 9/16" thread)		McMaster Carr	8405K291	2	$ 6.84	$ 13.68		Alloy Steel	0.0300	0.0600
101020	#10-32 RH Female Steel Ball Joint Rod End (3/16" ball, 1/2" thread)		McMaster Carr	60645K311	2	$ 3.32	$ 6.64		Alloy Steel	0.0300	0.0600
101030	Upright - Left (2.25" X 1.25")	CNC'd from aluminum stock	McMaster Carr	8975K955	1	$ 22.52	$ 22.52	1 ft stock	Al 6061-T6	0.2792	0.2792
101040	Upright - Right (2.25" X 1.25")	CNC'd from aluminum stock	McMaster Carr	8975K955	1	-----	-----	purchased above	Al 6061-T6	0.2792	0.2792
101050	3/16"x3/8" Shoulder Screw		McMaster Carr	93985A204	4	$ 2.97	$ 11.88		416 Stainless	0.0070	0.0280
101060	1/4"x5/32" Shoulder Screw		McMaster Carr	94035A176	2	$ 2.47	$ 4.94		18-8 Stainless	0.0044	0.0088
101070	Carbon Frame Cross Bar (1.01X1.13 - 2.00X2.13)	Cut to length and mitered	Rockwest	25507-36	1	$ 163.99	$ 163.99	36" length tube	carbon fiber	0.0310	0.0310
101071	Carbon frame Top Piece (1.01X1.13 - 2.00X2.13)	Cut to length and mitered	Rockwest	25507-36	2	-----	-----	Purchased above	carbon fiber	0.0056	0.0112
101072	Carbon frame Bottom Piece (1.01X1.13 - 2.00X2.13)	Cut to length	Rockwest	25507-36	2	-----	-----	Purchased above	carbon fiber	0.0081	0.0162
101080	1/4"x7/8" Shoulder Screw		McMaster Carr	92012A597	2	$ 7.62	$ 15.24		Alloy Steel	0.0190	0.0380
101090	1/4" Washer		McMaster Carr	92141A029	4	$ 3.37	$ 3.37	Pack of 100	18-8 Stainless	0.0039	0.0156
101100	Base bracket	CNC'd from aluminum stock	McMaster Carr	8975K39	2	$ 20.79	$ 20.79	1ft stock	Al 6061-T6	0.1400	0.2800
101120	5/16-18X0.5" SHCS		McMaster Carr	91251A378	8	$ 11.12	$ 11.12	Pack of 50	Alloy Steel	0.0208	0.1664
101130	Corner Lugs (1.5"x1.5" Stock)	Machined from aluminum	Online Metals	Link to Stock	2	$ 14.31	$ 14.31	1ft stock	Al 6061-T6	0.1420	0.2840
102000	Steering Column Assembly										
102010	1/2" Clamping Two-Piece Shaft Collar		McMaster Carr	6436K71	2	$ 5.15	$ 10.30		Al 2024	0.0116	0.0232
102020	1/2" Flanged sleeve bearings		McMaster Carr	6294K448	2	$ 2.05	$ 4.10		MDS-filled nylon	0.0046	0.0093
102030	1/2" Steering shaft (ID=0.260", t=0.120")		McMaster Carr	1968T23	1	$ 14.33	$ 14.33	1 ft stock	Al 2024-T3	0.0845	0.0845
102050	Steerer (3/4" stock)	CNC machined	McMaster Carr	9008K12	1	$ 3.00	$ 3.00	1/2 ft stock	Al 6061-T7	0.0353	0.0353
102060	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	$ 6.13	Package of 25	black oxide alloy steel	0.0044	0.0044
103000	Knuckle Assembly Right										
103010	Knuckle body (1.25"X1.25" stock)	CNC'd from 6061 stock	McMaster Carr	9008K46	1	$ 14.56	$ 14.56	1 ft stock	Al 6061-T6	0.2630	0.2630
103020	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	-----	Purchased above	black oxide alloy steel	0.0044	0.0044
103030	Stainless Steel Unthreaded Spacer	Length machined to length	McMaster Carr	92320A462	2	$ 2.17	$ 4.34		Stainless Steel	0.0030	0.0060
103040	1/4"-20 x 1-3/4" SHCS		McMaster Carr	90044A124	2	-----	$ 9.34	Package of 50	black oxide alloy steel	0.0020	0.0040
103050	Brake Boss	From current vehicle	-----	-----	1	-----	-----		Al 6061-T6	0.0756	0.0756
103060	Spindle (1.125" round stock)	CNC'd from 4340 steel stock	Online Metals	Link to Stock	1	$ 41.34	$ 41.34	2ft stock	4340 normal. Rough turned	0.3340	0.3340
103070	Ackerman Boss Right	Metal 3D printed	Divergent	Website	1				316 Stainless	0.1251	0.1251
103080	Ackerman arm (ID=0.5", OD=0.59")	Cut to length and Mitered	DragonPlate	Link to Part	1	$ 36.00	$ 36.00	48" long rod	Uni carbon fiber	0.0016	0.0016
103090	0.5" Single Sided Threaded Clevis Insert		DragonPlate	Link to Part	1	$ 7.60	$ 7.60		aluminum alloy (TBD)	0.0200	0.0200
103001	Knuckle Assembly Left										
103010	Knuckle body (1.25"X1.25" stock)	CNC'd from 6061 stock	McMaster Carr	9008K46	1	-----	-----	Purchased above	Al 6061-T6	0.2630	0.2630
103020	5/16"-24 X 1" SHCS		McMaster Carr	91251A383	1	-----	-----	Purchased above	black oxide alloy steel	0.0044	0.0044
103030	Stainless Steel Unthreaded Spacer	Length machined to length	McMaster Carr	92320A462	2	$ 2.17	$ 4.34		Stainless Steel	0.0030	0.0060
103040	1/4"-20 x 1-3/4" SHCS		McMaster Carr	90044A124	2	-----	-----	Purchased above	black oxide alloy steel	0.0020	0.0040
103050	Brake Boss	From current vehicle	-----	-----	1				Al 6061-T6	0.0756	0.0756
103060	Spindle (1.125" round stock)	CNC'd from 4340 steel stock	Online Metals	Link to Stock	1	-----	-----	Purchased above	4340 normal. Rough turned	0.3340	0.3340
103071	Ackerman Boss Left	Metal 3D printed	Divergent	Website	1				316 Stainless	0.1251	0.1251
103080	Ackerman arm (ID=0.5", OD=0.59")	Cut to length and Mitered	DragonPlate	Link to Part	1	-----	-----	Purchased above	Uni carbon fiber	0.0016	0.0016
103090	0.5" Single Sided Threaded Clevis Insert		DragonPlate	Link to Part	1	$ 7.60	$ 7.60		aluminum alloy (TBD)	0.0200	0.0200
104000	Tie Rod Assembly Long										
104010	10-32 RH Male threaded shank (3/16" ball)		McMaster Carr	60645K111	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104020	10-32 LH Male threaded shank (3/16" ball)		McMaster Carr	60645K112	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104030	10-32 RH hex nut		McMaster Carr	90480A195	2	-----	$ 1.83	Package of 100	zinc-plated steel	0.0004	0.0008
104040	10-32 LH hex nut		McMaster Carr	99961A520	2	-----	$ 11.06	Package of 25	zinc-plated steel	0.0004	0.0008
104050	1/2" RH threaded end connector		Dragon Plate	Link to Part	1	$ 7.60	$ 7.60		aluminum	0.0350	0.0350
104060	1/2" LH threaded end connector (5/8" stock)	Machined in house	McMaster Carr	8974K48	1	$ 2.41	$ 2.41	1/2 ft stock	6061-T6	0.0240	0.0240
104070	Tie Rod Body Long (ID=0.5", OD=0.59")	Cut to length	Dragon Plate	Link to Part	1	$ 36.00	$ 36.00	48" long rod	carbon fiber	0.0061	0.0061
104080	10-32 X 5/8" SHCS		McMaster Carr	90128A944	1	-----	$ 6.82	Box of 25		0.0072	0.0072
104001	Tie Rod Assembly Short										
104010	10-32 RH Male threaded shank (3/16" ball)		McMaster Carr	60645K111	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104020	10-32 LH Male threaded shank (3/16" ball)		McMaster Carr	60645K112	1	$ 3.53	$ 3.53		alloy steel	0.0032	0.0032
104030	10-32 RH hex nut		McMaster Carr	90480A195	2	-----	-----	Purchased above	zinc-plated steel	0.0004	0.0008
104040	10-32 LH hex nut		McMaster Carr	99961A520	2	-----	-----	Purchased above	zinc-plated steel	0.0004	0.0008
104050	1/2" RH threaded end connector		Dragon Plate	Link to Part	1	$ 7.60	$ 7.60		aluminum	0.0350	0.0350
104060	1/2" LH threaded end connector (5/8" stock)	Machined in house	McMaster Carr	8974K48	1	-----	-----	Purchased above	6061-T6	0.0240	0.0240
104071	Tie Rod Body Short (ID=0.5", OD=0.59")	Cut to length	Dragon Plate	Link to Part	1	-----	-----	Purchased above	carbon fiber	0.0026	0.0026
104080	10-32 X 5/8" SHCS		McMaster Carr	90128A944	1	-----	-----	Purchased above	black oxide alloy steel	0.0072	0.0072
104090	10-32 X 1-1/4" SHCS		McMaster Carr	90128A948	1	-----	$ 4.55	Box of 25	black oxide alloy steel	0.0124	0.0124
					Total part cost		$ 543.45			Total weight	3.5513

Appendix I – Design Hazard Checklist

ME 428/429/430 Senior Design Project 2016-2017

DESIGN HAZARD CHECKLIST

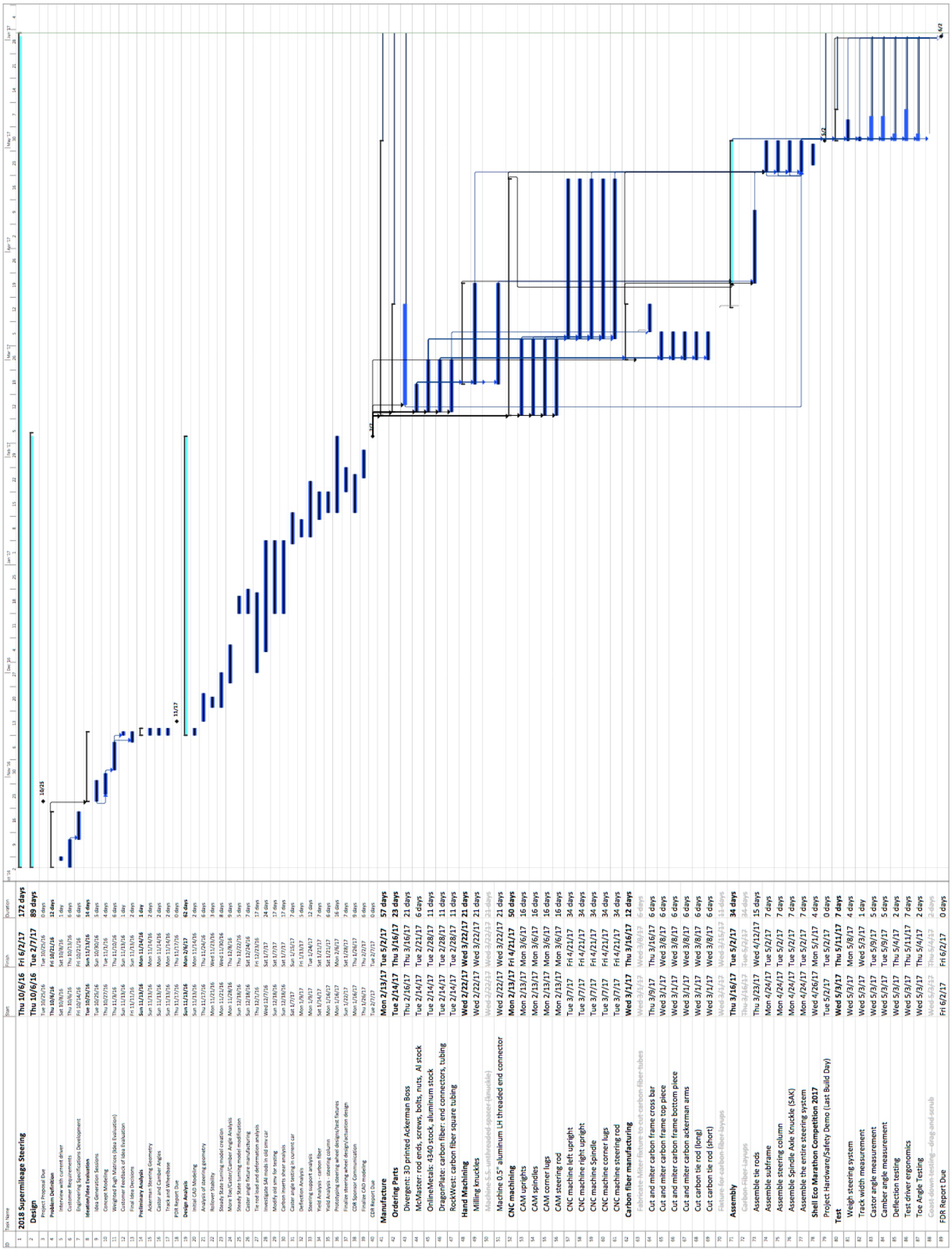
Team: 52 - Supermileage Steering Advisor: Sarah Harding

Y	N	
☐	☒	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?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☐	☒	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☐	☒	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☒	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☒	☐	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Can the system generate high levels of noise?
☐	☒	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐	☒	16. Is it possible for the system to be used in an unsafe manner?
☐	☒	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

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.

During the fabrication of the steering system, chemicals that are known to be hazardous to humans will be used. These chemicals include but are not limited to various solvents, resins, releasing agents, and carbon fiber. The team acknowledges the dangers in using these materials. They will keep SDSs on file for each of these materials and wear appropriate PPE to minimize the risk of exposure

Appendix J – Gantt Chart



Appendix K – Design Verification Plan and Test Procedures

Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Minimal deflection under laod	Load car up to 250lbs and measure deflection of supports using digital level	Supports do not deflect more than 1°	Gio	Complete	1	C	6/8/17	6/8/17	Pass	1	0	No measurable angle change.
2	Pass drop test	Securely load car with 250 lbs of weight and drop from a height of 6 inches (max curb height)	No delamination or cracking of carbon. Metal components do not deform or shear	Lucas	PV, Complete	2	C	5/30/17	6/8/17	Pass	1	1	Steering system subframe failed when loaded up with 250 pounds. Not able to subject it to the entire 250 pounds in the drop test, it failed the test with 75 pounds. Restested with bolted subframe with full load and passed.
3	Weight	Weigh steering subsystem without tires or brakes on scale accurate to at least ±0.1 pounds	Weighs less than 6 pounds	Sean	PV, Complete	1	C	5/30/17	5/30/17	5.849 pounds	1	0	Passed test, but will likely gain weight when fixes are implemeted to ensure structural integrity
4	Driver steering force	Load car with driver, use linear scale to turn car when not moving. Take car to test track and use a linear scale to measure the turning force while moving.	<12 pounds while static and <7 pounds while moving	Gio	Not Complete								Not able to be tested due to failure when loading cart
~~5~~	~~No excessive play~~	~~Rotate steering wheel through slop and record angle change using a digital level~~	~~<0.5° of play~~	~~Gio~~	~~Not Complete~~								Dropped from scope as steering wheel attachment can add play
6	Track width	Measure between the center of the tires when final build is complete	Meets competition rules of >50cm and Height/Track Width<1.25	Gio	PV, Complete	1	C	5/30/17	5/30/17	54 cm	1	0	Meets competition specifications
7	Minimum Turning radius	Take car to area outside hangar door. Mark the ground by the outside edge of the inside front wheel closest to the center of rotation and measure out to a centerpoint of 8 meters. Travel 90° CCW at max turning angle and mark the ground at the same wheel location. Measure from center of rotation to the mark. Repeat test for CW turn.	Turning radius CW and CCW are both <8 meters	Gio	PV, Complete	6	C	5/30/17	5/30/17	7.6 meters left, 7.6 meters right	2	4	Manufacturing defects were found in the knuckles when turning radius was tested. Ajustments to Ackerman bosses allowed the team to finally make turning radius.
~~8~~	~~Reflexive button placement~~	~~Instruct 5 people in 30 seconds how top use steering wheel. Wait 10 minutes and test 5 people on each of the button functions.~~	~~75% or better from each person~~	~~Sean~~	~~Not Complete~~								Steering wheel out of scope
9	Cycling capabilities	Roll car forward slowly (<5mph) and cycle from max right to max left 300x. Total load 250lbf	<0.5° of change in steering geometry, no components come loose or get damaged	Sean	Not Complete								Not able to be tested due to failure when loading cart
10	Size and inteference	Overall packaging fits inside vehicle (if chassis not built use CAD) and around driver. Test will entail all potential drivers sitting in steering system and measure clearances and assesing window coverage.	>0.5 inches of space from driver legs to steering system, no contact of wheels with chassis when at max steer, steering system covers less than 25% of window space	Sean	PV, Complete	1	C	6/3/17	6/3/17	Pass, Pass, 0%	1	0	Confirmed in CAD, no wheels touching new chassis and no window coverage by new steering system
11	Disassembly time	Completely install system into one of the current chassis. Begin timer and have team of two members remove and completely disassemble the steering system	Takes less than 10 minutes to remove and disassemble	Lucas	PV, Complete	1	C	5/30/17	5/30/17	08:07.0	1	0	System was disassembled completely to ensure a conservative measurement of disassembly timing
12	Caster Testing	Test various caster angles in the steering setup whith various drivers to find ideal caster angle for most drivers	Find ideal caster angle for all future Supermileage vehichles	Lucas	Not Complete								Testing for caster did not fit into normal Supermileage timeframe
~~13~~	~~Scrubbing around corners~~	~~TBD~~	~~TBD~~		~~Not Complete~~								Difficult to quanitfy, was dropped from scope

Test Procedure

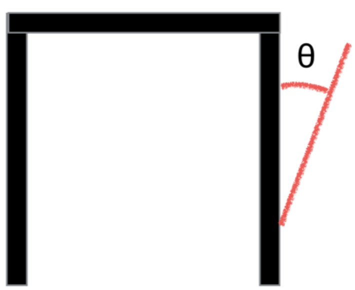
Item 1: Minimum deflection under load

Description of Test:
Load car up to 250lbs and measure deflection of supports using digital level.

Acceptance Criteria:
- Supports do not deflect more than 1°.

Required Materials:
- 250lb load (cart and driver)
- Test Cart
- Digital inclinometer
- Flat ground

Testing Protocol:
1. Place test cart on flat ground, and lock the rear wheel so the test cart cannot roll away.
2. Measure initial inclination angle of the supports shown in the figure on both sides.



3. Load the cart with 250lb of mass (driver + ballast).
4. Measure angles of both supports.
5. Data:

	Before Angle	After Angle
Right		
Left		

PASS/FAIL

Test Procedure

Item 2: Drop test

Description of Test:
Securely load car with 250lbs of weight and drop from a height of 6 inches (max curb height).

Acceptance Criteria:
- No delamination or cracking of carbon. Metal components do not deform or shear.

Required Materials:
- 250lb load (cart and driver)
- Test Cart
- Ruler/tape measure
- Flat ground

Testing Protocol:
1. Place test cart on flat ground, and lock the rear wheel so the test cart cannot roll away.
2. Load the cart with 250lb of mass (driver + ballast).
3. Lift front end up 6in.
4. Drop
5. Assess Damage

Data:
Observations:

PASS/FAIL

Test Procedure

Item 3: Weight

Description of Test:
Weigh steering subsystem without tires or brakes on scale accurate to at least ±0.1 pounds

Acceptance Criteria:
- Weighs less than 6lb

Required Materials:
- Scale

Testing Protocol:
1. Weight steering system using scale. Split into individual sub systems if necessary.

Data:

Total Weight (lbs)

Observations:

PASS/FAIL

Test Procedure

Item 4: Driver steering force

Description of Test:
Load car with driver, use linear scale to turn car when not moving. Take car to test track and use a linear scale to measure the turning force while moving.

Acceptance Criteria:
- <12 pounds while static and <7 pounds while moving.

Required Materials:
- 250lb load (cart and driver)
- Test Cart
- Linear spring force gauge
- Flat ground

Testing Protocol:
1. Place Test cart on ground and load with driver + ballast.
2. Use spring gauge to hook onto outside of steering wheel and pull. Record force.
3. Then, slowly roll vehicle forward and repeat test.

Data:

	Force (lb)
Stationary	
Rolling	

PASS/FAIL

Test Procedure

Item 6: Track width

Description of Test:
Measure between the center of the tires when final build is complete.

Acceptance Criteria:

- Meets competition rules of >50cm.

Required Materials:

- Tape measure

Testing Protocol:

1. Lock wheels in straight forward orientation.
2. Measure distance of center of contact patches.

Data:

Track Width (cm)

PASS/FAIL

Test Procedure

Item 7: Minimum turning radius

Description of Test:
Take car to area outside hangar door. Mark the ground by the outside edge of the inside front wheel closest to the center of rotation and measure out to a centerpoint of 8 meters. Travel 90° CCW at max turning angle and mark the ground at the same wheel location. Measure from center of rotation to the mark. Repeat test for CW turn.

Acceptance Criteria:
- Turning radius CW and CCW are both <8 meters

Required Materials:
- Test cart
- Tape measure
- Chalk/cones to mark arc

Testing Protocol:
1. Use tape measure and markers to mark out a 8m quarter circle.
2. Align cart’s outside wheel with the arc.
3. Turn steering wheel into the arc and roll car forward.
4. Make sure that vehicle stayed within the arc.
5. Turn vehicle around and test other side.

Data:
Observations:

PASS/FAIL

Test Procedure

Item 9: Cycling capabilities

Description of Test:
Roll car forward slowly (<5mph) and cycle from max right to max left 300x. Total load 250lbf.

Acceptance Criteria:
- <0.5° of change in steering geometry, no components come loose or get damaged.

Required Materials:
- 250lb load (Driver)
- Test Cart
- Digital inclinometer
- Flat ground

Testing Protocol:
1. Load test cart with weight
2. Measure caster and camber of knuckle/wheel.
3. Roll car forward slowly and cycle steering.
4. Turning the steering wheel all the way left then all the way right is “1 cycle”. Repeat 300 times.

Data:

	Angle Before Testing	Angle After Testing
Caster		
Camber		

Observations**:**

PASS/FAIL

Test Procedure

Item 10: Size and interference

Description of Test:
Driver enters vehicle in complete racing attire and remains perfectly still. Measure distance from drives legs to steering system structure. Then CAD is used to measure clearance from chassis to the steering system and window area coverage

Acceptance Criteria:

- >0.5 inch of space from driver legs to steering system.
- >0.5 inch from steering system to chassis
- <25% coverage of windshield

Required Materials:

- Test cart
- Driver with full racing attire
- Measuring tape/ruler
- CAD

Testing Protocol:
Driver clearance

1. Place test cart on flat ground, and lock the rear wheel so the test cart cannot roll away.
2. Have driver assume driver position
3. Measure clearance with measuring tape/ruler.

Chassis Clearance

1. Update CAD model
2. Place steering assembly in current chassis design
3. Measure minimum distance from steering system to chassis. This will most likely be the wheels.

Window Coverage

1. Update CAD model
2. Place steering assembly in current chassis design
3. Observe view from point of view of driver

Data:

PASS/FAIL

Test Procedure

Item 11: Disassembly Time

Description of Test:
Measure time needed to disassemble steering system.

Acceptance Criteria:
Less than ten minutes
Required Materials:
Assembled steering system
Test cart

Testing Protocol:

1. Begin timer and have team of two members remove and completely disassemble the steering system
2. Stop timer when complete

Data:

Total Weight (lbs)

Observations:

PASS/FAIL

Test Procedure

Item 12: Caster Testing

Description of Test:
Test various caster angles in the steering setup with various drivers to find ideal caster angle for most drivers.
Find ideal caster angle for all future Supermileage vehicles.

Acceptance Criteria:
None; mainly for research

Required Materials:
- Old Supermileage vehicle with engine
- Digital inclinometer
- Drivers
- Full test track
- Adjustable caster steering system

Testing Protocol:
1. Caster will first be set to 0 degrees and verified with digital inclinometer
2. Drivers will complete several laps around test track
3. After the run, the driver will complete a short survey rating their opinion of the steering system feedback
4. The caster will then be adjusted to 12 degrees and test will be repeated.
5. Once the two extremes are done, data will be taken for 2, 4, 6, 8, and 10 degrees of caster.

Data:
Observations:

PASS/FAIL

Appendix L – User Manual

2018 Steering System User Manual

For the safe and effective operation and maintenance of your steering system

This steering system has been designed specifically for the 2018 Supermileage vehicle in mind. It has been designed to be as lightweight as possible but provide an efficient steering system for competition. This manual will detail the installation, maintenance, and operation of the new steering system.

Safety

Safety is an important part of this steering system. Before working on any of the components, it is highly recommended that proper personal protective equipment (PPE) is used. Safety glasses should be worn when working on any component of the steering system. When working with epoxy, make sure to also wear nitrile gloves to avoid direct contact with skin.

Installation

Once the 2018 Supermileage chassis is complete, the subframe must be bonded into the vehicle. To do this, proper alignment and bonding technique must be used.

To achieve proper alignment, align one inch 8020 extruded aluminum with the front alignment holes in the chassis mold. These holes are located where the steering system should be along the length of the vehicle. Then, use a 1:1 print out of the pattern from Attachment A to properly cut out the curvature to match the bottom tubes of the subframe onto the chassis. For proper adhesion of the epoxy in the next step, scuff the carbon tube and chassis with 220 grit sand paper and clean the surface with a solvent such as acetone or high concentration isopropyl alcohol.

Hysol E-20HP

Next, mix Hysol E-20HP high strength epoxy (as seen in Figure 1) with chopped carbon fiber to create an epoxy slurry to bond the steering system to the chassis. Carbon fiber strands should be approximately 1/4" long and mixed into the epoxy in approximately a 1:1 ratio by volume while lofted. Apply liberally to all areas where the subframe contacts the chassis. Then, perform a layup using at least 2-3 plies of 6k fabric with West Systems 105 epoxy with 209 hardener, making sure to overlap the subframe tubes and the chassis.

Assembly Tools

Assembling the steering system has been made relatively simple. The tools required are as follows:

- Standard and Metric Allen wrench (hex key) set
- 3/8 inch and 7/16 inch crescent wrenches
- An adjustable crescent wrench can be used
- Tape measure

Assembly Instructions

First, assemble the entire Axle Assembly for both the left and right side. Look at Figure 1 for the exploded view drawing of the Axle subsystem to help with assembling it. First, insert the spindle into the axle and screw it in place with the 5/16”-24 by 1 inch hex bolt and hand tighten. Next, thread the 1/4-20 by 1.75 inch bolt through the brake boss and knuckle and thread it into the Ackerman boss and tighten using Allen wrench. Repeat the process for both the left and the right hand Axle Assemblies.

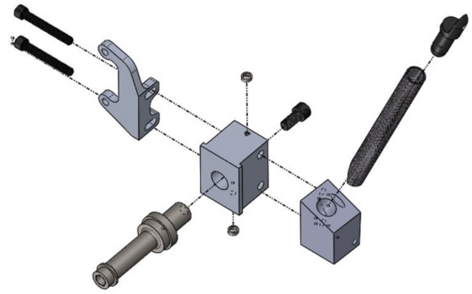


Figure 1

Next, install the mounting hardware onto both the left and right uprights. Look at Figure 2 for the exploded view drawing of the upright for help with assembling it. Install the top and bottom #10-32 female rod ends using the appropriate length shoulder bolts. Use #10 washers on both sides of the aluminum upright on the shoulder bolts and use the smaller sized #10 washers for the bottom female rod end.

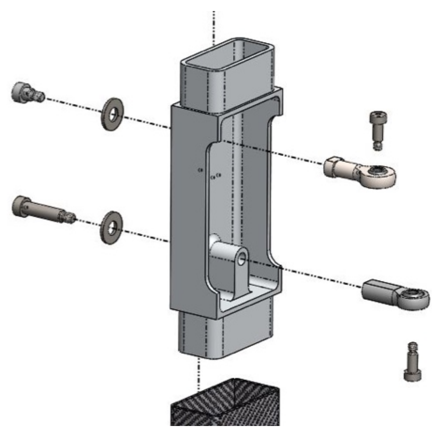


Figure 2

Next, install the Axle Assembly into the Upright. Using #10-32 by 5/8 inch hex bolts, install the axle assembly through the top and bottom female rod ends. Make sure to use the small, 0.098 inch thick spacers between the knuckle and rod end when installing it. BE CAREFUL TO NOT LOSE THE SPACERS. If spacers are lost, make sure at least four extra spacers are available at all times. It is recommended to superglue the washer directly around the hole for ease of use.

Next, install the steering column as per these instructions assuming the 1/2 inch steering column is still used. Secure the steering column in place using the shaft collars once a proper steering wheel location has been decided on. Install the steerer arm on the end of the column using the backing bolt or set screws, whichever is decided on.

Finally, install the tie rods to onto the Ackerman arms and steerer arm. The longer tie rod should be used to attach the two Ackerman arms together. Use the #10-32 by 1-1/4 inch hex bolts to bolt through the tie rods male rod ends and secure the bolts with two #10-32 nuts to ensure that the bolt will not unthread itself. The shorter tie rod uses the shorter #10-32 by 5/8 inch bolt to attach to the steerer arm and should be secured with two #10-32 nuts as well. If everything is done correctly, the steering system will resemble as seen in the full assembly exploded view in Figure 3

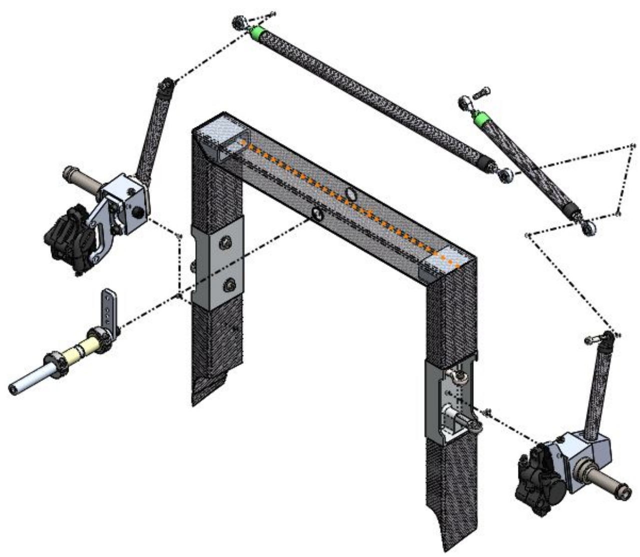


Figure 3

Attachment A – Patterns to contour bottom carbon tubes.