Chassis Torsional Stiffness Jig
Final Design Report

by

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ABSTRACT

Torsional stiffness plays a major role in any road vehicle. To understand torsional stiffness of a vehicle and make future iterations and improvements, a proper torsional stiffness jig is required to prove accurate and useful data. This report encompasses the new and improved testing jig and potential improvement ideas for more accurate results. With real data result relating to FEA calculations, designers can be confident in the FEA changes to torsional stiffness is accurate and will yield the probably results they desired. This report shows the methodology, manufacturing process and testing procedure to use on any Baja or SAE vehicle in years to come.

INTRODUCTION

We are in the Senior Project Spring 2018, Fall 2018, and Winter 2019. Our team consists of Reiley Schraeger, Cameron Kao, Raymond Deng, and Omar Roman.

Cal Poly Racing's Formula SAE team is one of the few teams in the world to build both a combustion and electric vehicle on the same platform. Taking advantage of the similar rules for the Formula SAE combustion and electric competitions, our team efficiently designs and manufactures two vehicles that share as many components as possible; i.e. platforming the chassis, suspension, brakes, ergonomics, and aerodynamics subsystems. Cal Poly Formula SAE regularly participates in the Lincoln competition at the end of June every year and occasionally in the Michigan competition in May.

In addition, Cal Poly Racing has a Baja SAE team that builds a Baja off road-style car for the Baja SAE competitions, Baja has two domestic competitions every year that Cal Poly goes to. In their history at Cal Poly the team has never tested or validated their torsional stiffness goals from design but would like to start doing so in coming years. This can help them do better in design judging and score better overall as a team at competitions. This is where our project can come in and help.

The goal of this project is to understand car & chassis stiffness in order to design and build a jig that can be used to test both Formula and Baja SAE cars. With accurate real life validation, it can help correlate FEA models to real world, thereby giving the team the ability to have more confidence in the FEA model and moving forward in future designs.

Understanding chassis torsional stiffness plays a major role in designing for the way a car handles. To improve the design of each new SAE vehicle each season, as well as validate the design, proper torsional stiffness testing is required. This includes understanding how suspension compliance, applied loads, and jig compliance all affect real life torsional test data. Previous FSAE chassis have been designed with stiffness goals, but with unreliable validation data to understand if the previous season met the stiffness goal specified.

The project required detailed analysis and proper testing methods to ensure that the results would yield helpful information for all CPFSAE and CP Baja teams currently and in the future years to come.

BACKGROUND RESEARCH

Importance of Torsional Stiffness

Torsional stiffness is regarded as one of the most important factors in determining chassis and vehicle performance. One reason is that a stiff chassis feels more responsive in transient cornering, while a compliant chassis feels laggy. It is important that what the driver inputs into the car "happens" immediately in order to improve car feel and driver confidence. In addition, a stiff chassis allows for the suspension to be tuned more effectively. If a chassis is too compliant, changes in spring stiffness do not result in predictable changes in overall car feel. To show this, a car can be modeled - on a very basic level - as springs in series (Figure 1). The equation that governs the total stiffness of this system is

$$k_{eq} = \frac{k_1 k_2}{k_1 + k_2}$$

where k_1 and k_2 represent the stiffnesses of the suspension and chassis, respectively. According to this equation, if k_2 is too small, changes in k_1 will have little effect on total stiffness since the numerator will be small. In addition, suspension is modeled assuming the chassis is infinitely stiff. If it is not, then suspension will not perform as expected.

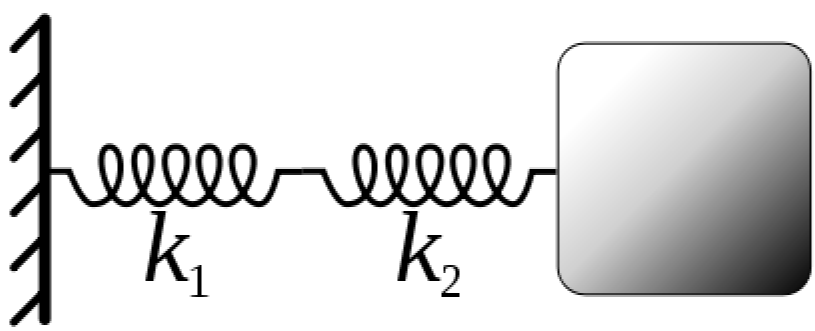


Figure 1. Springs in Series

The importance of chassis stiffness can even be seen in production cars. Many car owners invest significant time and money into increasing chassis stiffness with such modifications as strut bars, which connect between strut towers to reduce chassis flex (Figure 1), in order to improve vehicle performance.

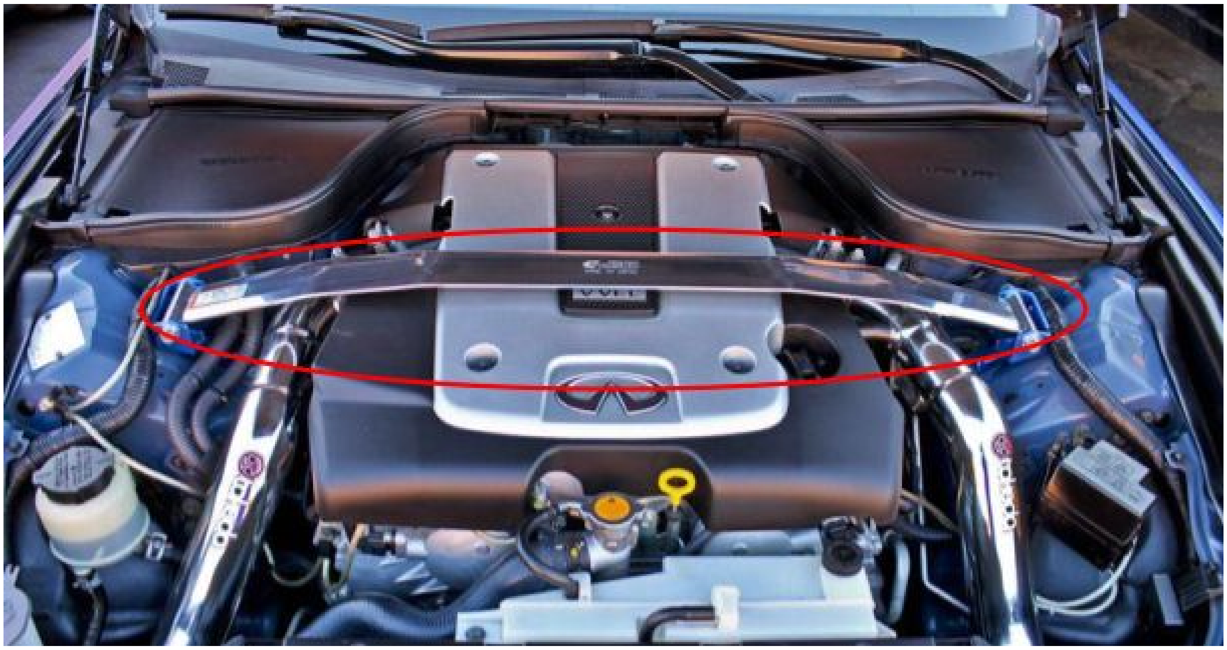


Figure 2. Strut Bars [6]

The importance of chassis stiffness is also evident due to how it is one of the driving factors of the chassis design for many FSAE cars. The torsional rigidity in turn influences chassis geometry, material choice, and quantity of material needed. Specifically, on the Cal Poly FSAE cars, the number of carbon fiber plies is chosen in part to fulfill chassis torsional stiffness requirements.

Choosing a torsional stiffness requirement is a difficult task, since the relationship between chassis stiffness and car performance is complicated to model. The basic trade off is that torsional stiffness - or any stiffness for that matter - is directly related to how much material used. Therefore, a stiffer car will also be heavier, which is negative for car performance. One prevailing theory is that chassis stiffness should be a certain magnitude above suspension stiffness in order for changes in suspension stiffness to be noticeable. A general rule of thumb is to make the chassis 10 times as stiff as the suspension. Another approach is to run vehicle simulations with varying chassis stiffness to determine the optimal stiffness.

Improvements From Previous Year Ideation

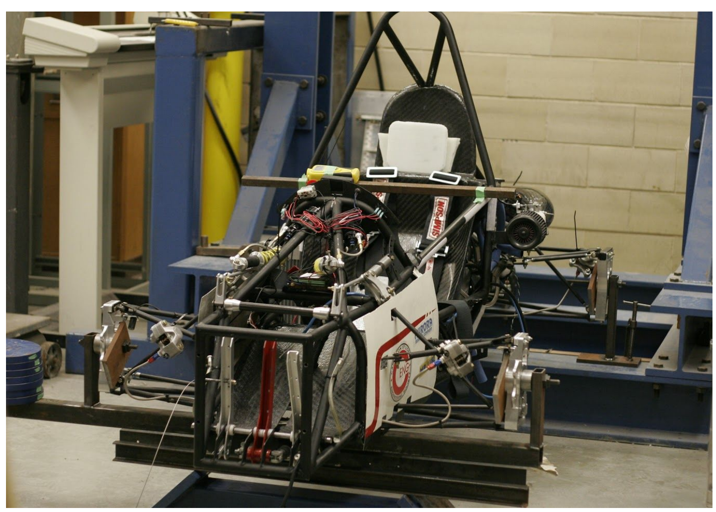
One of the main goals of this project is to improve upon the previous chassis torsional stiffness jig design, which has been used since 2015. This jig can be improved in several regards:

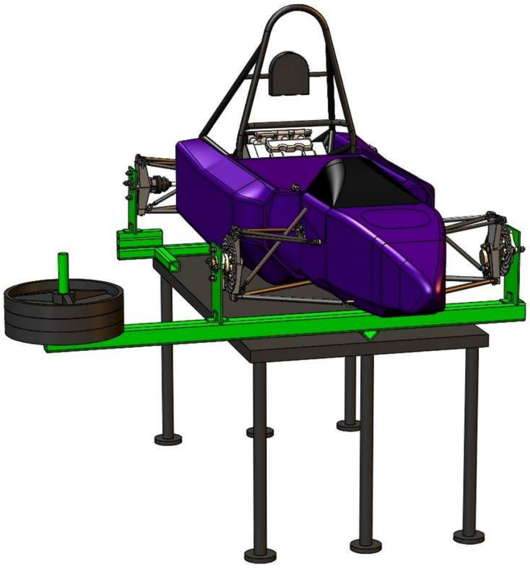
1. It is difficult to accurately measure compliance resulting from slop using the current jig. Slop is the compliance that occurs when shifting load direction from one side of the car to the other. This can manifest itself in a variety of components, the main perpetrators being bearings and bolted connections. Slop is not measured in the current torsional jig. However, it is important because this contributes to compliance the car feels when actually driving. By neglecting it during testing, a valuable piece of information is lost.
2. The current jig only measures at one point, giving the hub to hub stiffness. This has been sufficient because it is the only information the team needs to evaluate whether or not the team achieved its initial torsional stiffness goal. However, it would be more useful if the team had more detailed data by taking measurements of multiple points along the chassis/suspension. For example, one of the goals of running these tests is to validate FEA. If a certain model/method is determined to be accurate, then future chassis designers can utilize a similar one to effectively predict torsional stiffness. By testing and comparing multiple points rather than a single point, it can be ensured with a higher degree of certainty that the model is accurate, thus making it more useful for the team moving forward.
3. A final consideration is that the current jig's usability. Currently, it takes several people and at least an entire work night to set up the jig, run the test, and break down. During manufacturing season, time spent working on the car is invaluable. By reducing the amount of time it takes to set up the test, we could save the team time, as well as allow them to run multiple tests throughout the season. Multiple tests could be used for testing variations in bolted connections, for example. Or testing the effects of removing material in the chassis to save weight.

Existing Designs

It is important to consider existing designs from both other FSAE teams as well as production vehicles. Table 1 shows some of the existing designs we found and some notable features of each.

Table 1. Existing designs

Creator	Description/Notable Characteristics
Formula SAE Cal Poly (Current torsion jig)	- Used in previous years on Formula SAE Cal Poly team - Fulcrum point is at the hub - Needs to be set up on a table in order to be constrained - Only measures deflection at single point  Figure 3. Current CPFSAE Torsion Test Setup
Carleton University Ravens Racing	- Uses spaceframe - Inserts into the uprights rather than attaching to hub - Fulcrum point neither centered or on opposite hub. Instead, it is placed at arbitrary location.  Figure 4. Carleton Torsion Test Rig

Birkin	- Utilizes multiple dial indicators along chassis in order to get stiffness gradient, which is more useful than stiffness measured at only a single point - Uses spaceframe - Test performed on full size car, rather than smaller formula car.  Figure 5. Example of dial indicators along side of chassis
Pelican Parts	- Bolts to hub - Uses monocoque - Fulcrum is at the centerline of the car  Figure 6. Pelican Parts Torsion Test Setup

PRELIMINARY DESIGN REQUIREMENTS AND SPECIFICATIONS

Table 2 lists the specifications that our project should meet. This table includes the parameter and its tolerance, risk, compliance, and a more detailed explanation of the parameter. To recap what was mentioned earlier, the current jig requires lifting the car on top of a 4 feet tall table. Although it may not weigh much, therefore making it easy to move, it is not adaptable to all of Cal Poly Racing's cars. With this the current jig is not adjustable and takes quite the effort to set up. Finally, the current jig only measure deflection at the unconstrained axle and we would like to measure more data points along the chassis.

Table 2. Planned specifications for this project

Spec	Parameter	Comments and explanation of parameter	Requirement	Tolerance	Risk	Compliance
1	Weight	Maximum of 300 lbs. Needs to be liftable without machine	300lb	MAX	M	T,A,S
2	Production Cost	Limit the cost of raw materials and machining time	$850	MAX	H	A
3	Mobility	How difficult is it to move the jig without fully disassembling the jig? Relates to weight - want to qualitatively find how easy it is to move based on two people.	Less than 150 lbs per person	±10 lbs	M	T,I
4	Overall lifting height of car	Car should not be lifted more than 1 foot off the jig when setting up a test	1 ft.	Max	M	T,I
5A	Assembly and disassembly time	Allow set up and car be ready to apply first weight within this timeframe	30 min.	Max	H	T,I
6	Take more than one measured point of deflection	Have the ability to measure more than just the current upright deflection and one corner of the car	3 points	Min	M	T,A,I
7A	Adjustment in central bolting faces	Hub Pattern	Yes	∞ patterns	H	T
7B	Adjustability in y-axis	Track Width Adjustment	Yes	46-54 inches	H	T
7C	Adjustability in z- axis	Height of Jig Arms	Yes	Moment arm not greater than 12 in	M	T
7D	Adjustability in x-axis	Wheelbase Adjustment	Yes	∞	L	T
8	Percent error of measured torsional stiffness with model	Correlate a relationship between FEA to our jig to ensure we are getting meaningful results	<5%	Max	H	T,S

We will measure the success or failure of each parameter with this list. Each number corresponds to the spec number.

1. When front and rear jig components are assembled, each assembly should be able to be lifted by no more than 2 persons.
2. We as a team do not want to exceed $750. This is because our project is sponsored by CPFSAE. We do not want to use an excessive amount of resources and money, since it could benefit the team elsewhere.
3. This goal goes along with weight. We want the jig to be easy for any normal college student to move around and assemble.
4. If the jig requires the car to be lifted higher than one foot from the top of the I-Beam, then we have failed this goal. We wanted to avoid having to lift the car over a table to perform the test.
5. This goal is set so that we don't have to use a lot of time to run this test. We do not want to inhibit progress of the team as they finish up building and begin testing the car.
6. Our jig should be able to measure deflection at multiple points of the chassis during the test, if the chassis analysis team desires this information.
7. Adjustability for this project is huge because we want the past, present, and future CP Formula and Baja SAE teams to use this. Car parameters such as wheelbase, track width, car height, and hub pattern change for every car; and our jig has to be adjustable in at least those four categories.
    a. Hub patterns can change from year to year, so our jig has to be able to incorporate a way to adapt to hub patterns.
    b. Track width (distance between the center of the left front or rear wheel to the respective right wheel) changes per vehicle dynamics requirements, so the jig has to have width adjustability.
    c. Height of the jig arms needs to ensure both the bottom of the Baja SAE and Formula SAE chassis do not contact the ground in the Z-direction since the distance from to the hub mounting point varies.
    d. Wheelbase (length of the car) changes per team and car.
8. Jig will accurately measure the deflection of the chassis and help the Cal Poly racing close the loop on their design intentions. Previous studies have reflected a 10% correlation at best.

DESIGN DEVELOPMENT

Design Detail PDR

Our project has a big focus on adjustability. One of the main goals of our jig is to design and manufacture it such that both Cal Poly Baja and Formula SAE can test their cars on it. This includes both teams' past and present cars, and since car parameters such as hub patterns, track width, car height, wheelbase, weight, etc. all vary from year to year and per team, adjustability is of the utmost importance when designing and hashing out the details of this project. Since our project is not particularly a question of the overall "form" and more of how exactly we're going to accomplish the adjustability aspect, many Pugh matrices were made for each aspect of the jig. For example, Figure 7 shows an example of a Pugh matrix done for track width adjustment. The rest of the Pugh matrices done are in Appendix C.

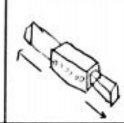
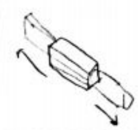
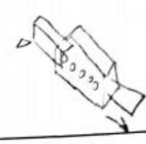
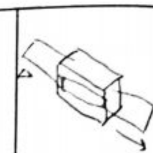
Concept / Criteria	N/A DATUM	 1 (Both sides sliding in/out with holes to lock in)	 2 (Both sides sliding in/out with slot to "lock in" track width)	 3 (One side fixed, holes to lock in)	 4 (One side fixed, slot to lock in)
Manufacturing Difficulty	S	-	+	-	+
Design Challenge	S	-	+	S	S
Adjustability	S	+	+	+	+
Ease of Use	S	+	-	+	+
Retainment	S	+	-	+	+
Presumed Accuracy	?	-	+	-	+
Σ+	0	3	4	3	5
Σ-	0	3	2	2	0
ΣS	5	0	0	1	1

Figure 7. Pugh Matrix made for track width-specific component

The question of "how stiff is stiff enough" was asked frequently during the development of this project thus far. The question was first asked about the chassis and car itself, but after reaching out to CPFSAE alumni for their insight on our project and its scope, we decided to narrow the scope a bit more to only focusing on the design of the jig instead of the chassis. There are enough improvements in the jig itself to get reliable results. However, with this narrowed scope, we will still be in contact with the 2018-2019 FSAE and Baja SAE teams so that we can help them achieve their goals for that year and validate their design choices. Further stiffness discussion is included later in this section.

Four main designs were drawn up in the preliminary process as seen in Figure 8 below. Design 1/Datum included three individual supports with hanging a weight off the hub. Design 2/3/4 all had the supports front and rear linked together. The difference is mainly the method for applying the load with a jack and scale and with single weight or weights on both sides, respectively. A weighted decision matrix can be seen in Table 3 below which shows our reasoning and design moving forward. The result of the matrix showed that option 2 is the best option to move forward with. This option allowed for the car to rotate around the central axis. Option 2, 3 and 4 all use the central axis rotation; therefore this eliminated Option 1. Yet, between these options, option 2 allowed for the most appropriate incremental adjustments as there is a set bottle jack to increase the force. The other options rely on weights added by the user, and without proper weight adjustment it can not be increased as precisely.

All three designs use the same I-Beam to attach their arm supports but the loading cases of each is the reason we went with Design 2.

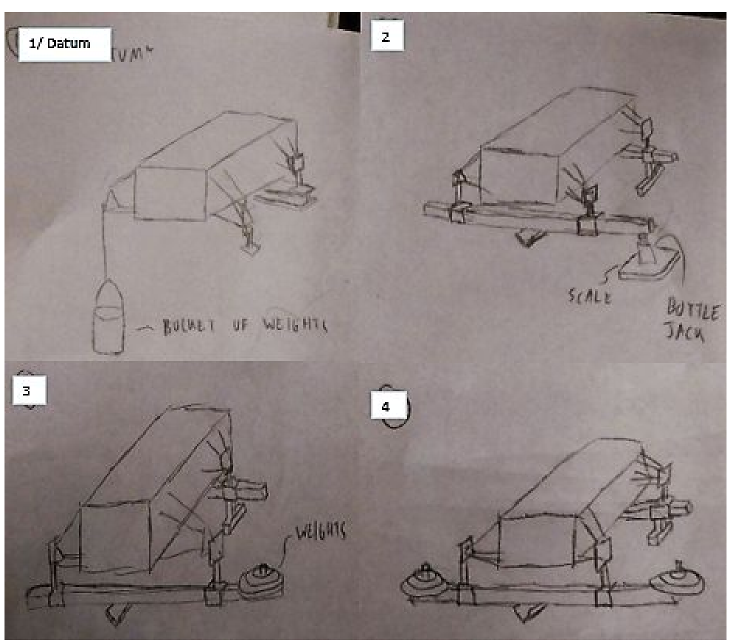


Figure 8. Sketches of possible designs

Table 3. Weighted decision matrix

Concept / Criteria	*Weights(1-5)*	1 (DATUM)	2	3	4
Manufacturing Time	*3*	5	3	2	1
Manufacturing Difficulty (CNC/ Welding/Other)	*3*	3	3	3	3
Assembly Time (To set up)	*2*	5	3	3	2
Mobility- Move without disassembly	*1*	5	3	3	2
Mobility - Individual components cannot be too heavy to be lifted	*1*	5	2	2	2
Does not put car in danger of being damaged with set up	*4*	3	5	5	5
Adjustability - Hub pattern	*4*	1	4	4	4
Adjustability - Track-width adjustment	*4*	3	3	3	3
Adjustability - Height of jig Arms	*4*	2	3	3	3
Presumed Test Accuracy	*5*	1	4	4	5
Ability to measure multiple data points	*4*	1	4	4	4
Cost	*3*	4	3	3	2
Weighted Sum	-	101	134	131	127

Front Hub Support Arms

Parameter Adjustability & Background

Track Width

A design element that varies from year to year on both teams is the track width of the car. This change is usually dictated by vehicle dynamics, so our jig needs to adapt to a variety of options. Therefore, we must adapt to whatever choices the Formula and Baja SAE teams make for their cars. Figure 9 shows a simple drawing of how track width is measured on a car. Track width may vary from front to rear (for vehicle dynamics purposes). For example, the CP18C was designed to have a 49.5 and 48.5 inch front and rear track-with, respectively. Even if a car's track width is designed to be the same as the year previous, manufacturing mishaps and tolerance stack ups can happen which would lead to a slightly different track width.

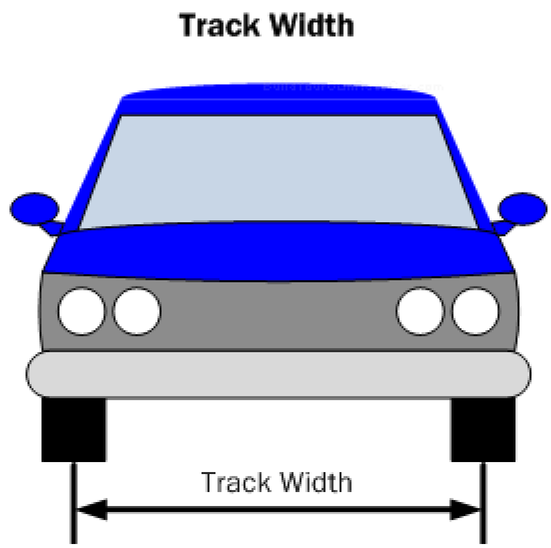


Figure 9. Track width measurement on a car [1]

In order to quantify the amount of adjustment needed, analysis of track width for all the teams that competed at the 2017 Formula SAE Lincoln/Electric [2] and 2017 Formula SAE Michigan [3] competitions was reviewed. This was used to determine the average, maximum, and minimum track widths that competitive teams run. The results are displayed in Table 4**.** This gives us a good estimate of how much adjustability our jig needs to have. In searching for the same numbers for Baja SAE, we were unable to find track width numbers from any Baja SAE competition. We turned next to the 2018 Collegiate Design Series Baja SAE Rules and found under B.1.6 [4] that the maximum width of vehicle from any point is 64 inches. However, in talking with Will Antes, the Technical Director for the 2017-2018 Baja team, we learned that the track width for CP Baja SAE has been the same for multiple years at around 52 inches and he does not anticipate the team ever going above 55 inches for the front track.

Table 4. Track width measurements in inches at stateside 2017 FSAE competitions

Competition	Avg Front	Avg Rear	Max Front	Max Rear	Min Front	Min Rear
Michigan	47.79	46.65	50.98	49.49	43.70	42.13
Lincoln	48.95	47.79	52.01	52.01	45	45

The minimum value for front and rear track width seen at the 2017 competitions was 43.7 inches and 42.13, respectively. These values are drastically lower than what track widths Cal Poly FSAE has ran in the past few years. From 2014-2017, the front/rear track width was 47"/46", respectively; and currently in 2018 is 49.5"/48.5". Since the upper limit is mostly set by Baja's wide track width as mentioned above, the lower limit will be set for Formula. Our chosen range for track width adjustability will be from 46 inches up to 54 inches. This will allow for future teams to use this jig, even if Formula decides to lower their track width (which we don't expect them to) or if Baja decides to goes up a little more.

The front and rear parts of the jig will both have the same amount of adjustability. While it is true that the front and rear track widths can be a square or staggered setup, it would be much easier to make identical front and rear parts of the jig. Therefore to account for the adjustability, the I Beam that the jig arm supports attach too will be modified. Our preliminary design is shown in Figure 10, which had one side of the jig that has the support 'arm' fixed (Figure 10), while the other side will have slots to allow for the adjustment. Figure 10 shows the slotted side on the right and the fixed side on the left. We will use 4 bolts on each support to lock the supports into place and 'fixing' it to the I-Beam. Since we are relying on a bolted connection, the holes in the I-Beam will need to have a tight positional tolerance to ensure there is no slop in the four bolted connections.

Because of the feedback we got from our PDR, we switched away from the "knife-edge" balancing point and decided to had a fulcrum pivot point assembly using bearings. Since the I-Beam has the fulcrum point assembly at the center rigidly attached, there needs to be adjustment for the arm supports to vary the different track widths across the Formula and Baja cars. Because of this, we decided to change the track width adjustability method to utilize slots on both sides of the I-Beam to adjust the arms as needed as seen in Figure 10.

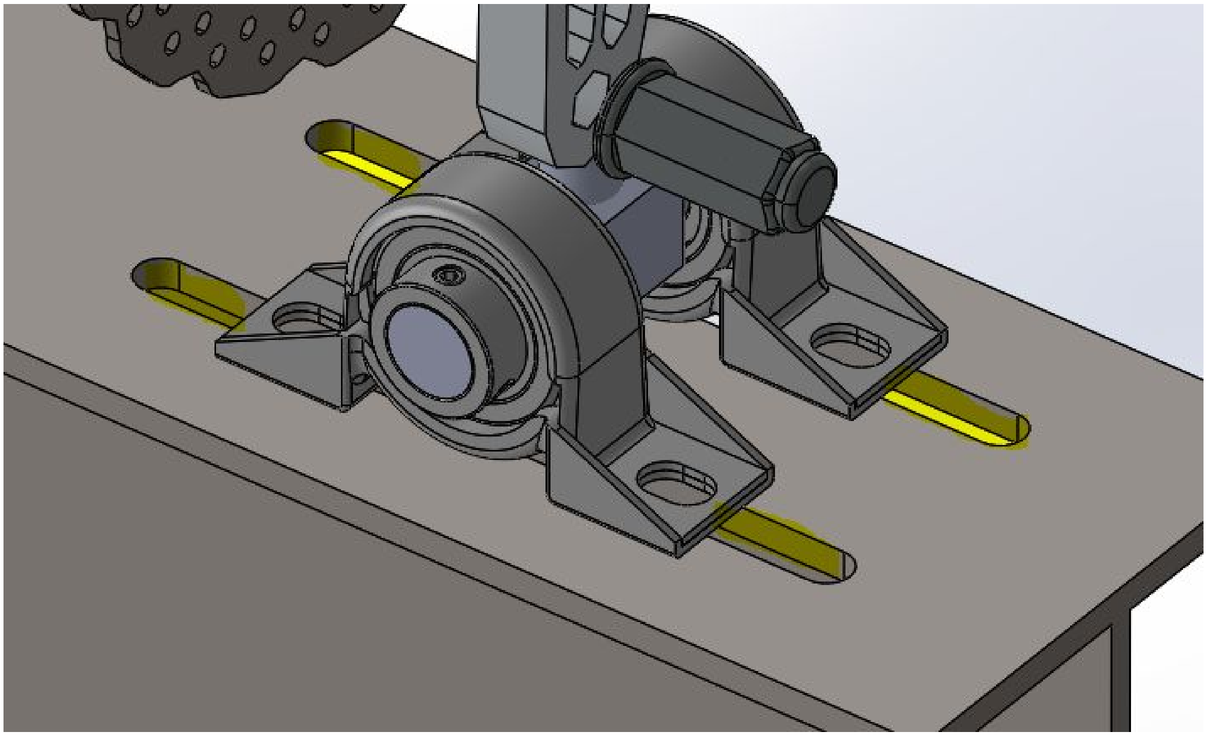


Figure 10. CDR track width adjustment method

In order to dial in the correct track widths per car, there will be set datums points so that we can slide the arm and lock it into place before tightening it once the car is place on the assembly. The center line will be scribed as the location of the fulcrum point and then different track width distances will be measured to different locations within the slot width. Figure 11 shows the graduated increments that allow for the user to preset the track width.

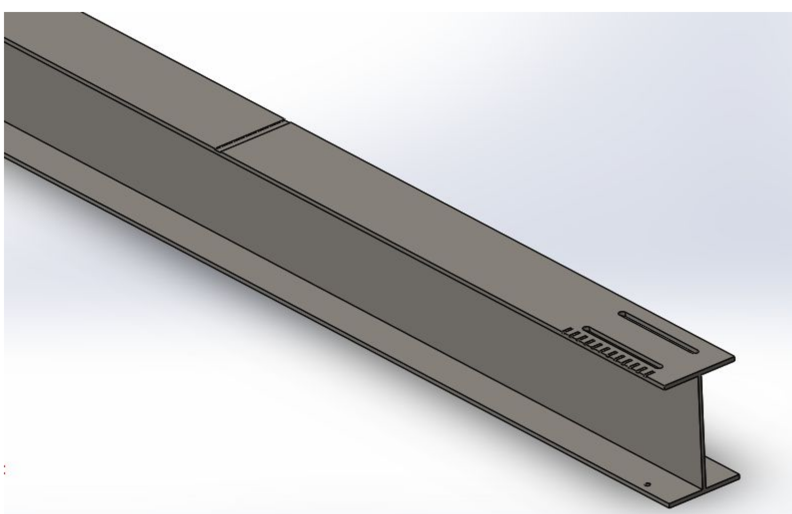


Figure 11. Different graduated increments to have pre-set track widths.

After CDR, we realized the impracticality of machining the partially square and partially round shaft, as well as the amount of compliance points with the pillow block bearings. The design was changed once more for track width adjustment and the final design is shown later on in this section.

Toe and Camber

A concern we had with the front hub arm supports was that toe and camber of the wheels would cause the support plates to be misaligned with the hubs as shown in Figure 12. Since the camber and toe differ between the Baja and Formula SAE cars, adjustment is needed for these suspension parameter changes. This could result in an inability to form a solid connection between the plates and hubs. This was not an issue in the previous design, as the front left hub was constrained through a simple support, and the right front hub was unconstrained. This allowed the hubs to be at any angle, since they were not fixed rotationally to anything. However, with the newest design, both hubs are fixed to the base, meaning we have to account for any camber or toe. One proposed design was to replace each of the vertical bars with links, as shown in Figure 13. This would avoid over constraining the car by constraining translational motion in one direction (r-direction in spherical coordinates) and not constraining rotational motion in any direction.

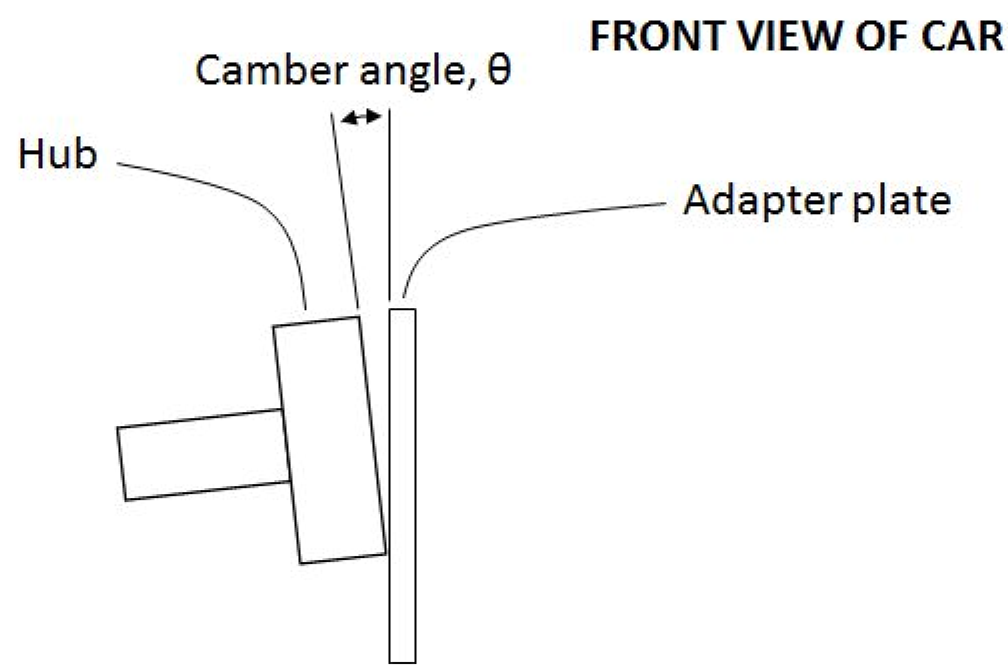


Figure 12. Possible hub perpendicularity misalignment

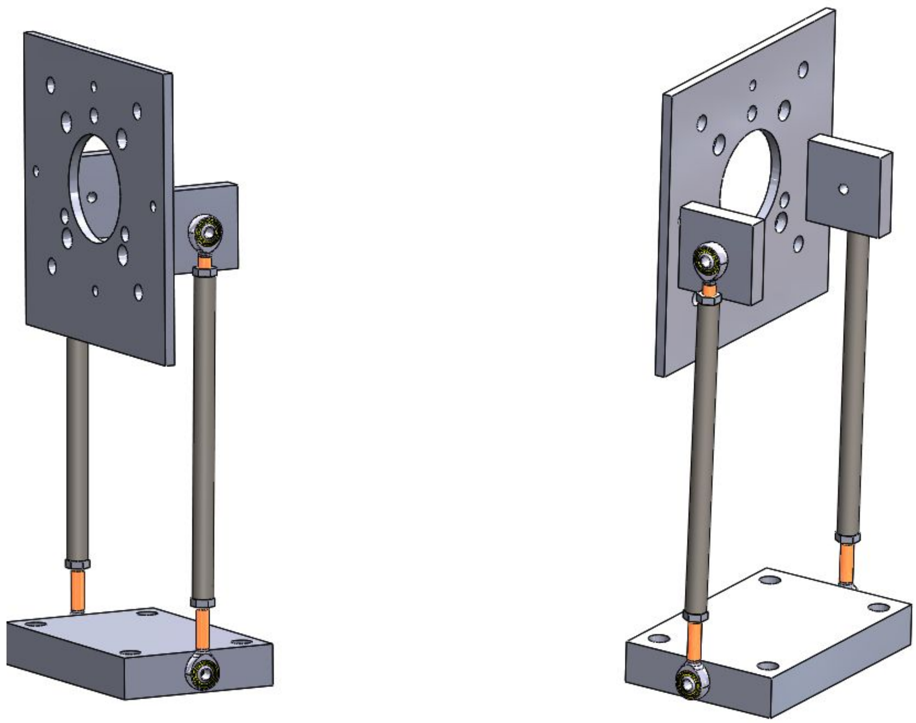


Figure 13. PDR solution to account for suspension parameters by adjusting tie rods.

With this new design, the front hub supports will be able to rotate about the x-axis. This decision was made so that the vertical jacking load will be transmitted up through the arm and into the hub directly affecting the twist of the chassis rather than the jig itself. Figures 14 and 15 show how the front arm support rotates with respect to the entire I-Beam rotating.

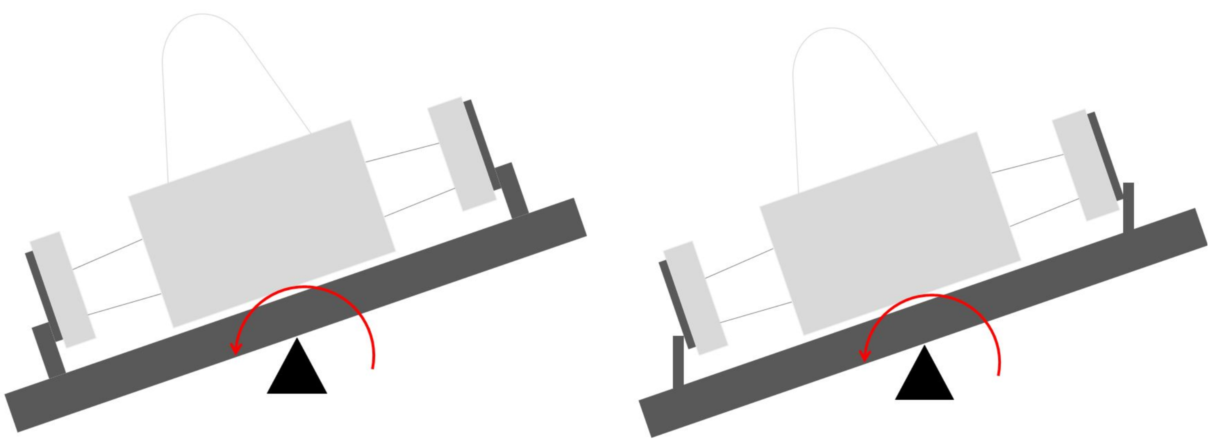


Figure 14. Previous arm design, where arms are solid structures (left). Updated arm design, where bearings are used at each end to allow them to rotate (right)

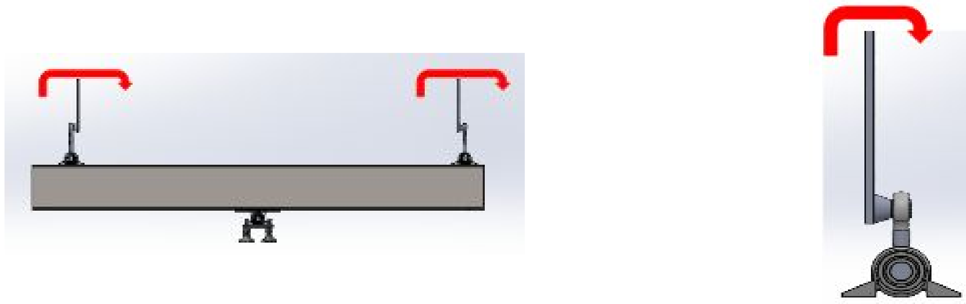


Figure 15. Hub arm support rotation shown

In addition to having the entire arm support initially on bearings, the adapter plates themselves will have 3 DOF to move and ensure that the plate is flush with the hub. To do this, the hub support arms will also have a threaded end for a rod end at the top. The rod end specified is a 5/16-24 thread (Figure 16). This will be threaded into a ½ inch rod. By having the adapter plates swivel, it will allow for the mounting plates to adjust to the camber and toe settings on the axles of the vehicles. Since this will be on both the front left and front right hubs, once the hubs are mounted, the car will be fully constrained. The rotation of the whole arm as mentioned earlier will allow for the car to be loaded properly.

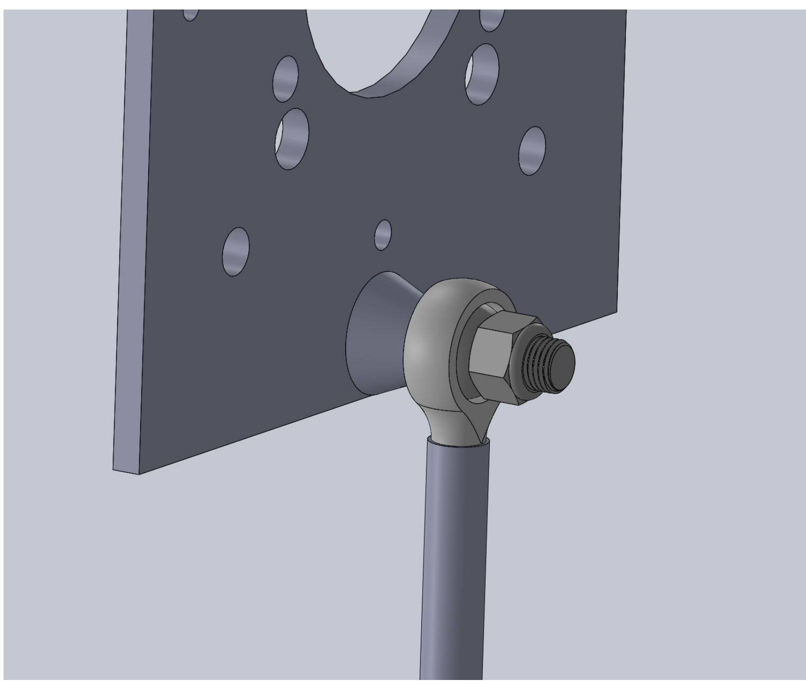


Figure 16. Spherical bearing on mounting plate and ½ inch OD Support Rod

The rod of OD 1/2 inch was calculated for buckling failure. The given SF was 4.6 with an over conservative load. These calculations can be seen in Table 5 to ensure there is no buckling failure.

Table 5. Calculated SF for buckling of hub arm support

Initial Hub Arm Support Calculations		
c factor	1	
E	29,000,000	psi
length (l)	4	inches
diameter of rod we currently have in CAD	0.500	inches
area of rod	0.196	$inches^2$
area of threaded portion	0.120	$inches^2$
second moment of inertia	0.00307	$inches^4$
radius of gyration (k)	0.125	inches
Yield Stress ASI 1018 Low Carbon Steel	63100	psi
l/k	32.0	n/a
l/k, crit	95.2	n/a
load applied	119	lb
d-max	0.108	inches
SF- buckling	4.63	
axial stress	995	psi
SF- compression	**63.4**	

Final Hub Arm Support Design Front

The design of the front hub arm supports changed quite a bit throughout our design cycle. We started with one fixed side and one adjustable side, to mounting the adapter plates via pillow block bearings pressed onto a shaft, to our final design with an aluminum base. An isometric view in CAD is shown in Figure 17, and a better description of the final method follows.

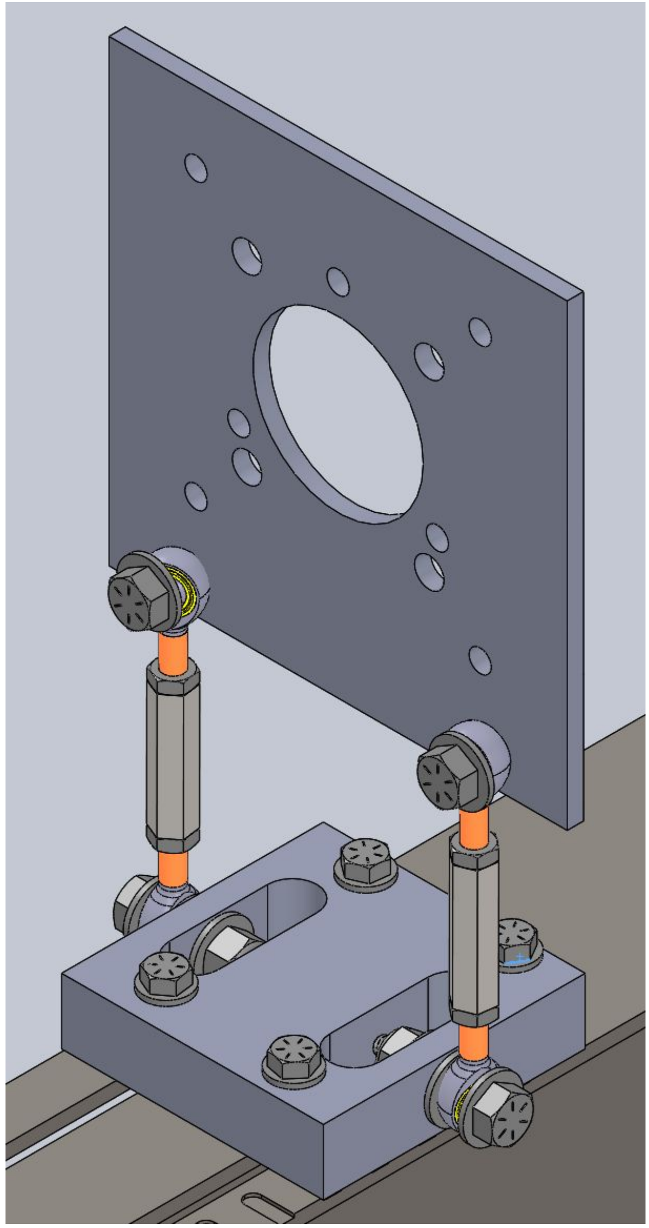


Figure 17. CAD isometric view of final hub arm design

The final design of the front hub arm supports includes adapter plates mounted via rod ends on links that bolt into a slotted aluminum base. Instead of having just one mounting point on the adapter plates as we did in PDR, on the final manufactured part we now have two. Some pictures of the manufactured front hub arm supports taken during testing are shown below in Figure 18.

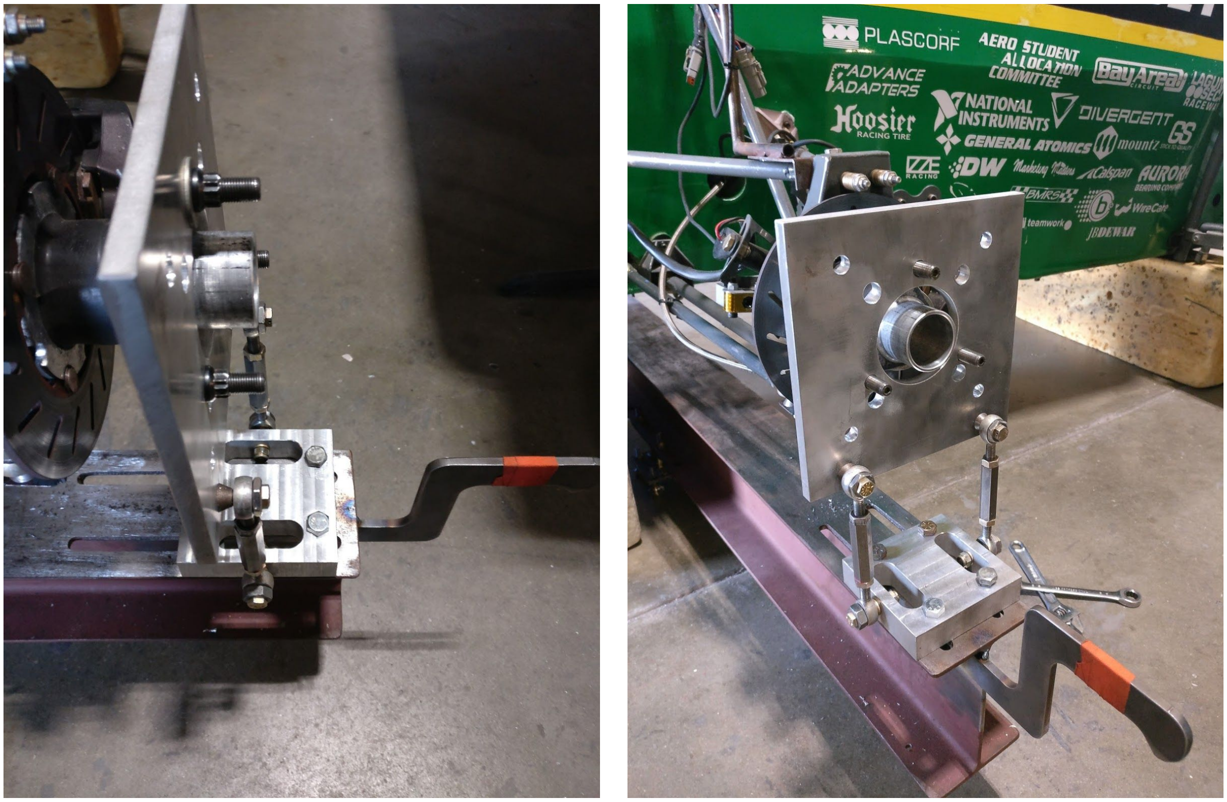


Figure 18. Front hub arm supports during testing

It can be seen that the rod end links are mounted in single shear. This is not ideal, but the bolt stresses are low enough where this does not matter. If we could redo it, we should have considered mounting the rod ends in double shear. The preliminary calculations were done with the rod ends mounted in single shear so we were confident that mounting them in single shear for our new design would work just fine.

Final Hub Arm Support Design Rear

One minor hiccup that was overlooked in the design was the adjustment in the rear. The thought process was that is a car had wildly radical rear camber or toe, it could be set to 0 degrees all around so that the rears could mate up to the arm supports properly and with little gap. While this would be an inconvenience on setup, it would allow us to keep a stiff support. We were heavily worried of the car toppling over if the rear was not a fixed support. Figure 19 shows the design of the rears.

Figure 19. Design in the Rear

While this might not have been the most elegant design solution, and something that should not have been overlooked, a quick technique we used on the fly was to add shim stock when we had discovered our error during testing. The shims were placed between the hub and the mating arm support face to allow for any changes in toe or camber and a proper ‘perpendicular’ mating surface. Figure 20 shows the location of shim stock to allow for proper mating surfaces.

Figure 20. Shim stock applied for rear adjustments.

Hub Adjustability & Adapter Plates

In PDR, we presented the idea of using a universal plate design that would allow for Formula and Baja to mount their hubs to. We had previously said that we would be bolting a plate with a certain hub's bolt pattern to a universal plate, but have decided to go with a single plate that has all the bolt patterns that Formula and Baja uses. Figure 21 shows the hubs both teams currently use or have used. The holes in the plate will be waterjet then the holes will be post machined to be a close fit with the hubs. The fiual adapter plate design is shown in Figure 22.

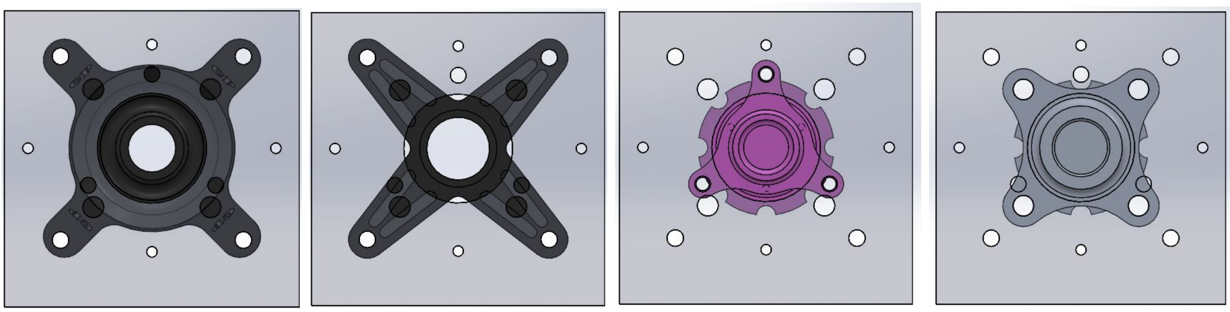


Figure 21. Baja and Formula hubs laid over adapter plates

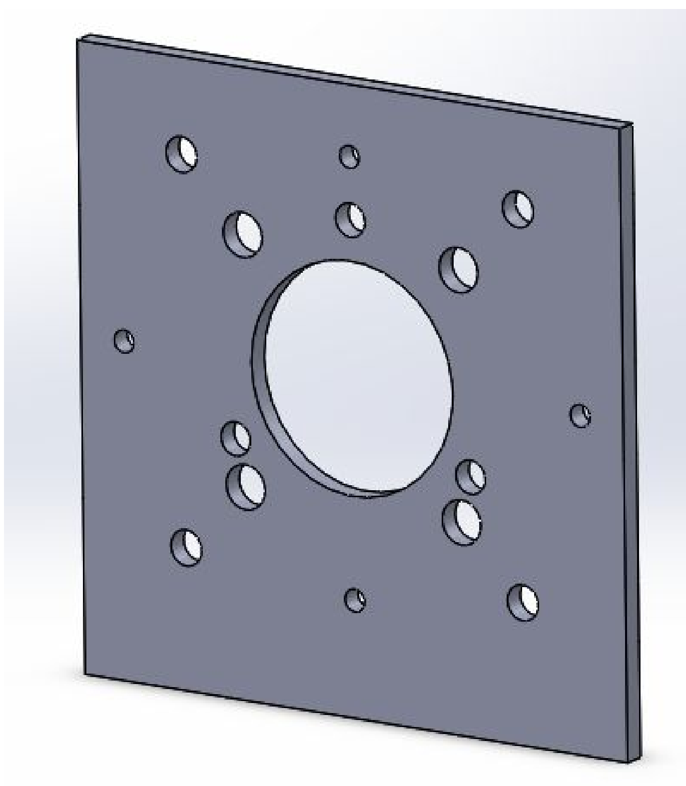


Figure 22. Adapter Plate Design

Calculations were done to ensure that the bolt attaching the adapter plate to the hub arms supports would be sufficient. Figure 23 shows the entire assembly from CDR and Table 6 shows the calculation for the final decision to go with Grade 8, 5/8-18 bolt on each arm support.

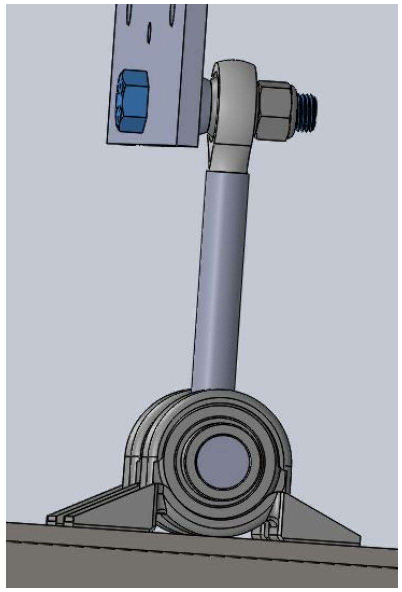


Figure 23. Bolt designed to attach arm support to adapter plate

Table 6. Calculations for chosen bolt and SF

Bolt Calculations		
	Value	Unit
Car Mass	476	lbs
Weight Distribution (F)	0.500	%
Carr Mass Front	238	lbs
Shank Length	1.50	in
Shear Limit	120,000	psi
pi/4	0.785	n/a
Area	0.307	in^2
Radius	0.312	in
Diameter	0.625	in
Bending Stress	14895	psi
Shear Stress	775.7	psi
Total	7457	psi
SF	16.0914	

Final Adapter Plate Design

With change in our design for how the front adapter plates were to mate to the front support arms, it required adjustment of the adapter plates. Since the change on the front involved two links, this required two mounting holes in the adapter plates. Figure 24 shows this design change and Figure 25 shows the changes within the adapter plate with two mounting locations.

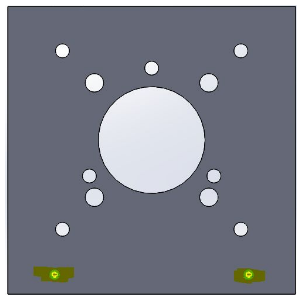


Figure 24. Updated adapter plates to match mating changes

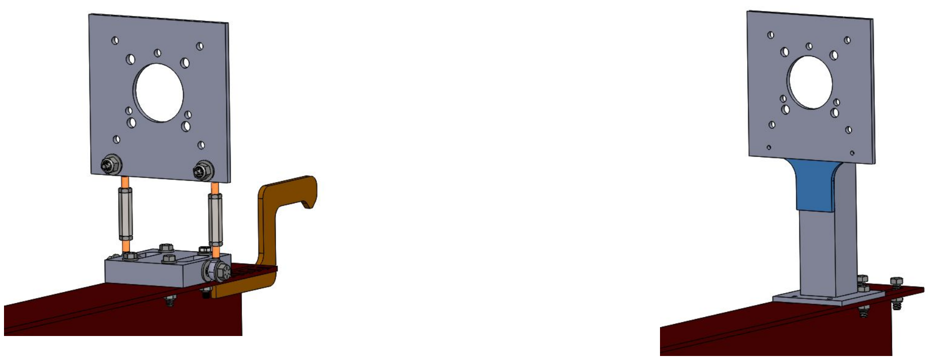


Figure 25. Adapter plate two hole mounting change. Front arms (left) and rear arms (right)

A new waterjet piece was used on the rear support which had the same dimensions as the adapter mating holes. This allowed the adapter plates to be universal front to rear. Figure 26 shows the waterjet piece.

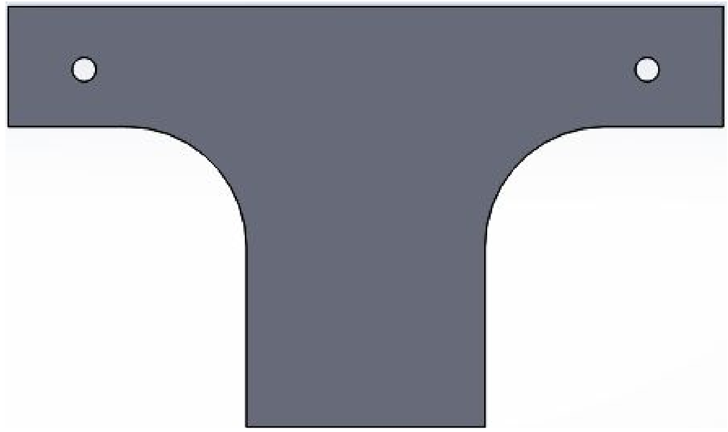


Figure 26. Waterjet piece for rear supports

With the switch and extremely high safety factor on the single 5/8th in bolt, we decided t two ¼ in bolts would still yield a safe safety factor and be a plausible solution. Table 7 shows the calculations with the two bolt design.

Table 7. Calculations for chosen bolts and SF

Bolt Calculations		
	Value	Unit
Car Mass	476	lbs
Weight Distribution (F)	0.500	%
Carr Mass Front	238	lbs
Shank Length	0.50	in
Shear Limit	120,000	psi
pi/4	0.785	n/a
Area	0.307	in^2
Radius	0.125	in
Diameter	0..25	in
Bending Stress	14895	psi
Shear Stress	775.7	psi
Total	38863	psi
Total w/ 2 bolts	19431	psi
SF	**6.175**	

The final check for the adapter plates was to ensure that there would not be any bearing failures. We wanted to ensure that a quarter inch of material was sufficient. The mounting hole bearing failure calculations were complete (Table 8) to ensure that the holes would not elongate as load was applied to these adapter plates.

Table 8 Adapter plate bearing failure checked

Mounting Hole Bearing Failure Calculation		
	Value	Unit
Moment	300	in-lb
I	0.0025	in^4
c	0.250	in
Shear Stress	1018	psi
Bending Stress	29723	psi
Combined Stress	29740	psi
Bearing Failure SF	**1.22**	
Biggest Baja Hub Hole Size Bearing Failure Calculation		
	Value	Unit
Shear Stress	1178	psi
Combined Stress	29746	psi
Bearing Failure SF	**1.22**	
Biggest Formula Hub Hole Size Bearing Failure Calculation		
	Value	Unit
Shear Stress	1094	psi
Combined Stress	30817	psi
Bearing Failure SF	**1.177**	

Wheelbase Adjustability

To compensate for wheel base adjustability (Figure 27), the design includes separate front and rear parts of the jig. Therefore the two front and rear jig pieces can be placed at any distance apart as they are not rigidly connected to one another. This allows for this goal to easily be adapted to a variety of changes.

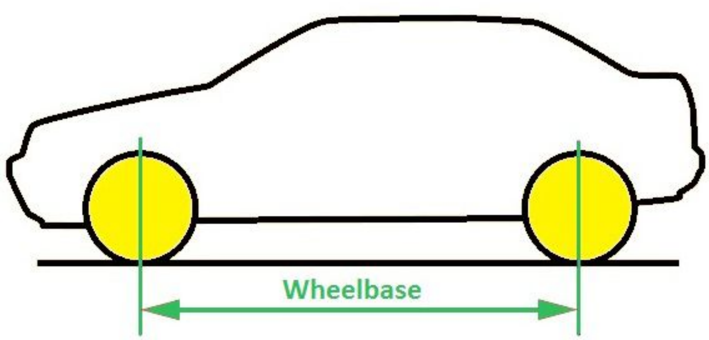


Figure 27. Wheelbase measurements on a car [5]

Leveling Adjustability

During PDR, concern arose that the bottom of the jig and the ground would not be mated perfectly, which could cause the entire jig to “shift” or otherwise deflect when loaded, which would in turn alter dial indicator measurements. Our initial design inadvertently made the assumption that the floor was perfectly flat, but after some consideration, this is clearly untrue. The solution was to add leveling feet to the I-Beam in order to keep the cars level front to rear and side to side.

Calculations for the specifying leveling feet are shown below in Tables 9 and 10. The criterion were for shearing the threads and also overloading the feet themselves.

Table 9. Force that a single leveling feet can handle

Leveling Feet Calculations		
Parameter	Value	Unit
Tensile Strength	70000	lbf/in^2
Major Diameter	0.25	in
Pitch / 2	0.025	in
Area (Shear)	0.0177	in^2
Pitch Diameter	0.225	in
Load on first thread	420.6	lbf
SF - Thread Shear	4.0	
Cross-Sectional Area	0.0491	in^2
Axial Stress	5093.0	psi
SF - Compression	13.744	

Table 10. Failure point for internal and external threads

Failure Mode	**Failure Point**
Bolt is stronger than the nut	Major diameter of internal threads
Nut is stronger than the nut	Minor diameter of external threads
Both bolt and nut are made of same material	Pitch line

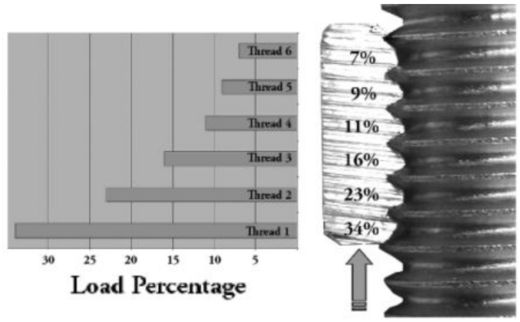


Figure 28. Load percent decrement on threads

For the leveling feet that we chose, both bolt nut are made of same material. The first thread is the one that experience the most load, 34%, as shown in Figure 28 above. If the load exceeds what the first thread can handle, the other threads will fail successively. Therefore, shear stress was calculated for the first thread, and using the pitch diameter to find the area of shear of the first thread.

The lower fulcrum point was placed on the microflat to ensure that the leveling feet were accurate to one another. Time was spent adjusting the feet so that the angle between all 4 corners was not more than ½ of a degree from left to right. This allowed us to keep the idea as the ground being flat and that the font jig was leveled accurately. Figure 29 shows the angle finder on different corners of the assembly to ensure it was correctly balanced.

Figure 29. Front fulcrum assembly placed in the microflat

Since the rear I beam could not fit on the microflat, it was determined to place the beam on the ground and slide pre-set shim measurements underneath each foot until there was not more than 0.005’ that could fit under any foot. Again this assumption assumed the floor was flat.

All fine tooth adjustments were made before any car was loaded onto the jig but if there needed to be adjustment one could always change the height with level feet while the jig held a car. By ensuring that the jig is balanced, it will allow us to ensure we are not preloading the car at all, and also allows the test to be performed as accurately as possible to what was calculated.

Fulcrum Point Design Development

In the preliminary design review, we originally planned to use a knife-edge fulcrum point to have the front I-beam rotate about. It would have been a triangular structure that would in theory be tangent to the I-beam. The hardest part was accurately locating this knife-edge assembly to the center of the I-beam every time. During the PDR, it was proposed to lift the whole jig up and place the knife edge in the center, there would be potential for significant error. The initial idea is shown in CAD screenshots in Figure 30.

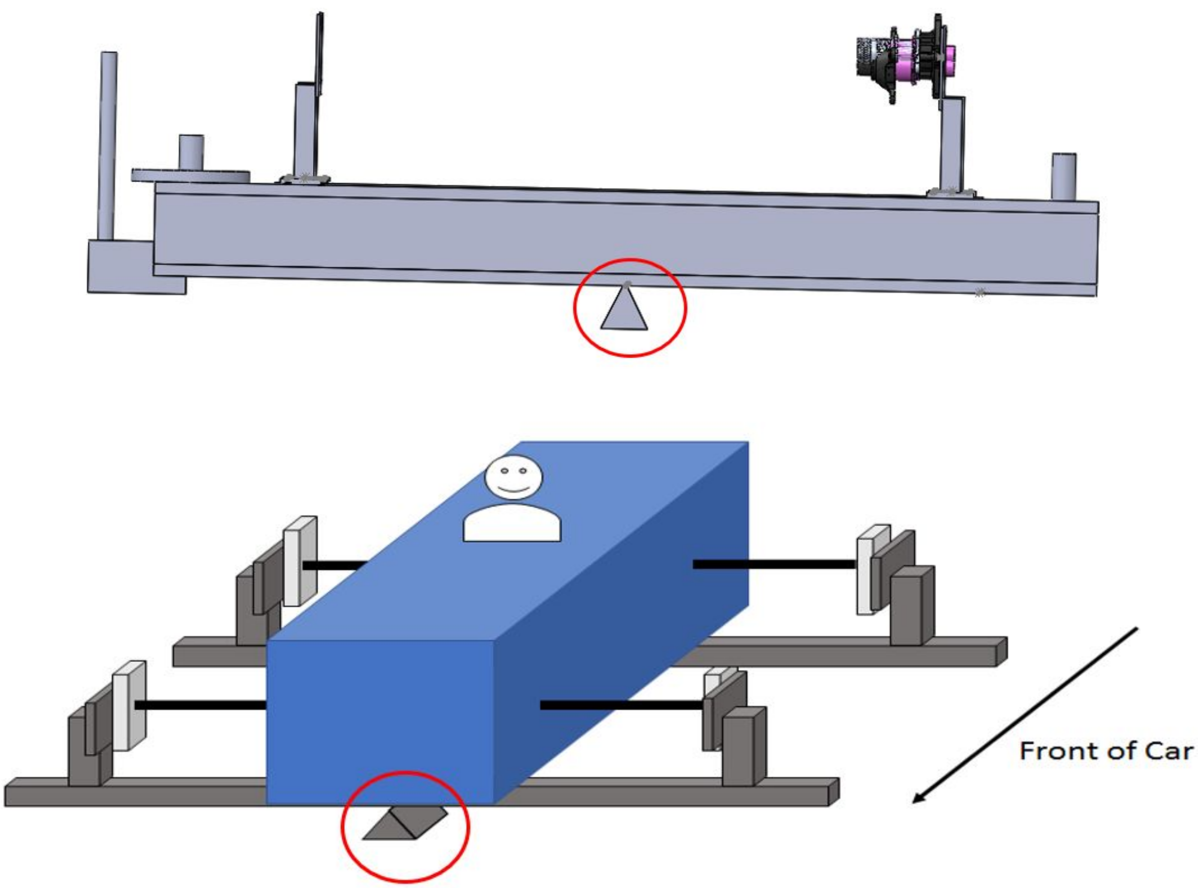


Figure 30. Initial knife-edge idea

The manufacturing plan for the initial knife edge plan would have been to waterjet three sides of the triangle and weld them together, and cut out part of a tube to weld to the top. So, in theory, the bottom of the I-beam would be tangent to the half-circle (or so). However, this method would have been impossible to implement since locating the center of the I beam with a car already on it would have been very hard to do. The original idea also would have had one side of the front suspension bolted to the I-beam, with the other side free to adjust per varying track widths. However, this was changed to a fulcrum point design using pillow block bearings for rotation, which should ensure the center point is always in the middle of the I beam and always perpendicular to the hub axis. The proposed solution is to have an assembly that is fixed to the I-Beam. Four 5/16-24 bolts will secure the bracket to the I-Beam. Figure 31 shows a detailed view of the Central Fulcrum Point assembly.

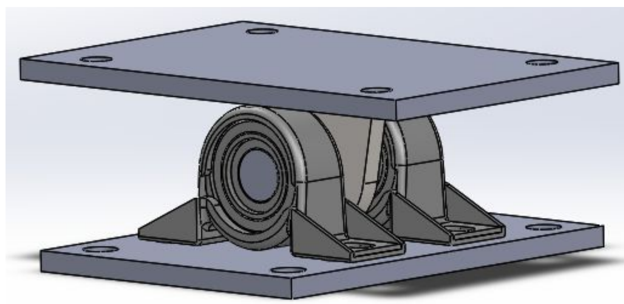


Figure 31. Central fulcrum point assembly unit

On this assembly, there are also two bearings. By allowing the I-Beam to rotate around the bearing support, it allows for the the central point to be fixed while still giving the rotational twist in the chassis. With the bearing being the rotational point for the jig to pivot, it ensures a consistent twist in the jig support.

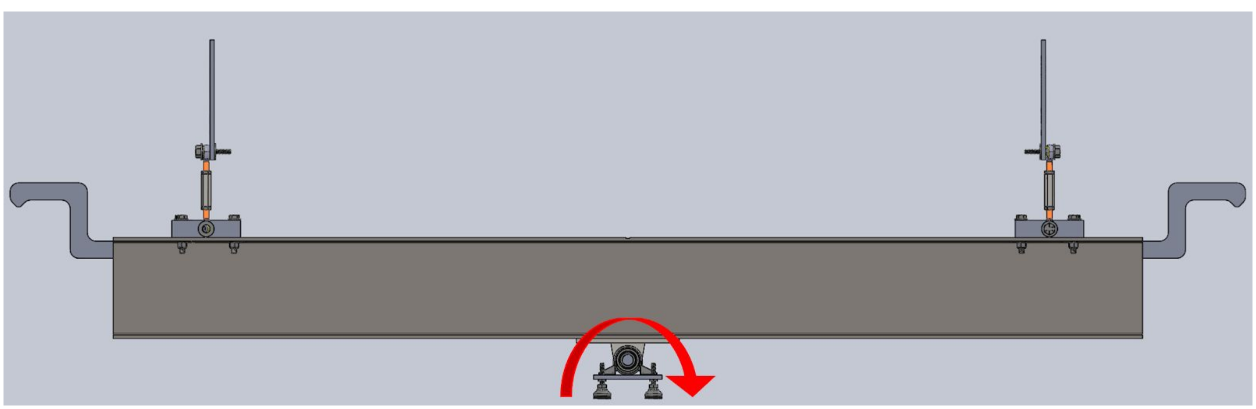


Figure 32. Fulcrum point design and rotation shown

The bearing chosen has a 5/8" inner diameter so the shaft going through these bearings was also specified to 5/8th diameter outer diameter. The bearings online have a static radial load capability of 3500 lbs and a dynamic radial load capability of 710 lbs. The safety factor for these bearings with the load cases on the jig came out to be over 6. The calculations are shown below in Table 11.

Table 11. Calculations for Bearings

Pivot Arm Bearing Calculations		
	Value	Unit
Dynamic Radial Load Capacity	710	lbf
Static Radial Load Capacity	3500	lbf
reliability	0.95	
desired life (LD)	10000	hours
speed of shaft (nD)	10	rpm
10th percentile life (L10)	1.0 E+07	
x_d	6.0 E-01	
x_o	0.02	
theta - x_o	4.44	
b	1.48	
a_f	1.20	
load	475	
a	3.00	
c10	567	
SF	**6.2**	

The shaft was specified to have a diameter of 0.625 inches. The bearings won't need to be press fit on either side of the shafts, since there is a set screw on the bearing that locks the bearing onto the shaft. The shaft will have to be pressed onto then welded to the lug which is welded to the plate that bolts to the bottom of the I beam. Figure 33 shows the entire assembly with the shaft highlighted in blue. Table 11 shows the calculation for this shaft giving a SF of 1.8.

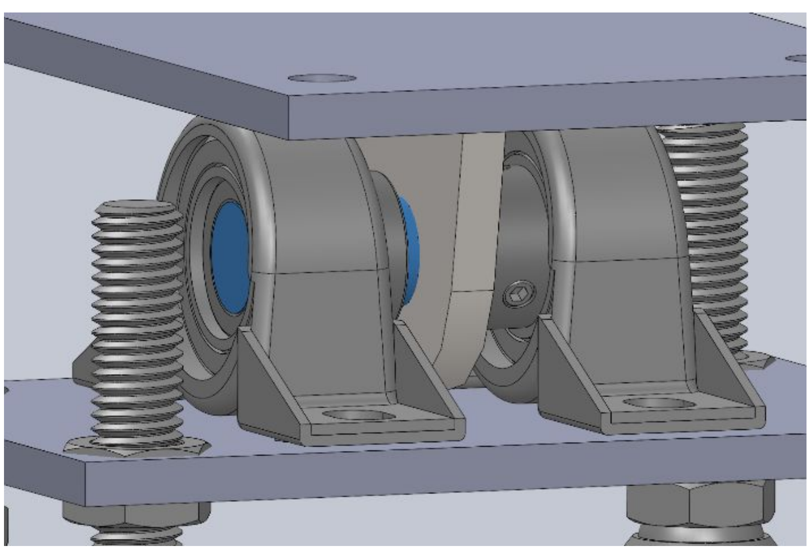


Figure 33. The shaft in the central fulcrum point assembly

Table 12. Calculate shaft diameter for fulcrum point assembly

Shaft Calculations		
Car Mass	418	lbs
Weight Distribution (F)	50	%
Carr Mass Front	209	lbs
Cylinder Length	2.20	in
Yield Stress ASI 1018 Low Carbon Steel	63100	psi
Area	0.307	in^2
Radius	0.312	in
Diameter	0.625	in
Bending Stress	34900	psi
Shear Stress	1360	psi
Total	34900	psi
SF	**1.808**	

Torsional Loading & Stiffness

The old torsional stiffness measurement method hung weights off of buckets to put the car in torsion. We thought about many different ways to load the front axle. Our PDR loading method choice is shown below in Figure 34, where we would add weights to one side of the I-beam, similar to how weights are put onto a bar at the gym.

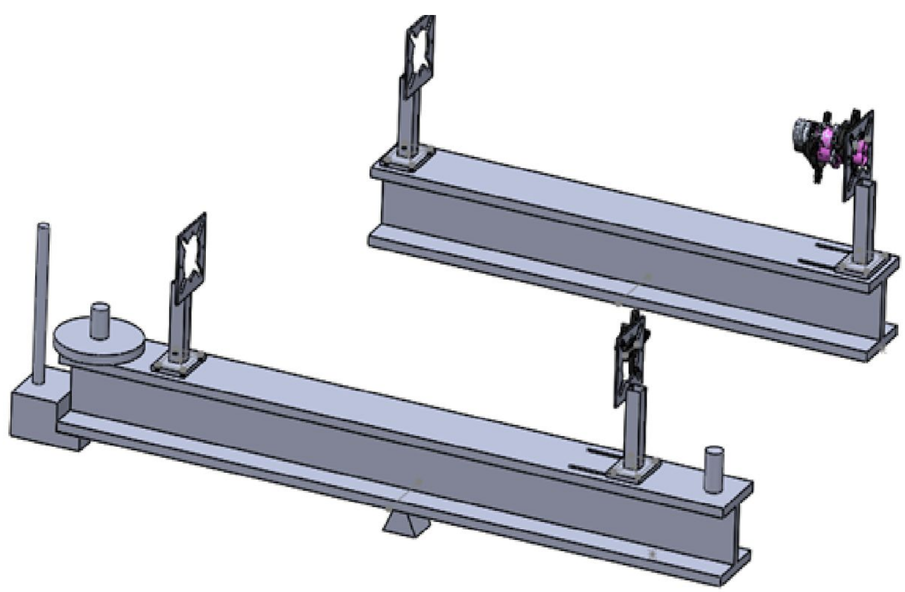


Figure 34. Preliminary CAD with fixed rear and fulcrum design. Jack can be seen at far left with scale underneath

Since we were going to use the I beams that the Formula SAE team already had and previously used for torsional stiffness testing, the length was limited to 61”, and we figured that we would need more space to accomodate for track width adjustments.

We then switched our loading method to use a jack and a scale. As seen in Figure 19, the jack would go on one side of the jig and lift it up to create the torsional twist. This would require a single person to use a simple jack and a scale to get the appropriate loads. At first we were going to use a bottle jack to apply the loads, but we ended up using a scissor jack. The jack is placed onto a bathroom scale, since we need to be able to apply at least 100 pounds of force on the car. The scale is used to tell us how much force we are using to twist the car. Once the jack is set up, we zero the scale then start loading up the chassis. With the decision to use a jack and a scale, we wanted to ensure that we knew exactly where the load is being applied to improve precision of the test; it is important to be able to determine how far away from the axis of rotation the force is applied to determine the moment. A point load would ensure that the force is localized at one point rather than distributed across the entire top surface of the bottle jack. Therefore, we designed a waterjet part to apply the force at, shown in Figure 35. This will be a waterjet part made of steel so that it can be welded to the 1018 steel I-beam. We welded on the load applicators on both sides of the front I-beam since we wanted to be able to apply the torsional load on both sides of the car.

Both of these methods (Figure 34 and 35) put the car in torsional loading around a central fulcrum point. This fulcrum point would allow for the jig to be balanced at the center of the car. The point would be the distance between the front track width that the jig is set to. A tape measure can be used to locate this point along the I-beam. More about the set up will be in a later section.

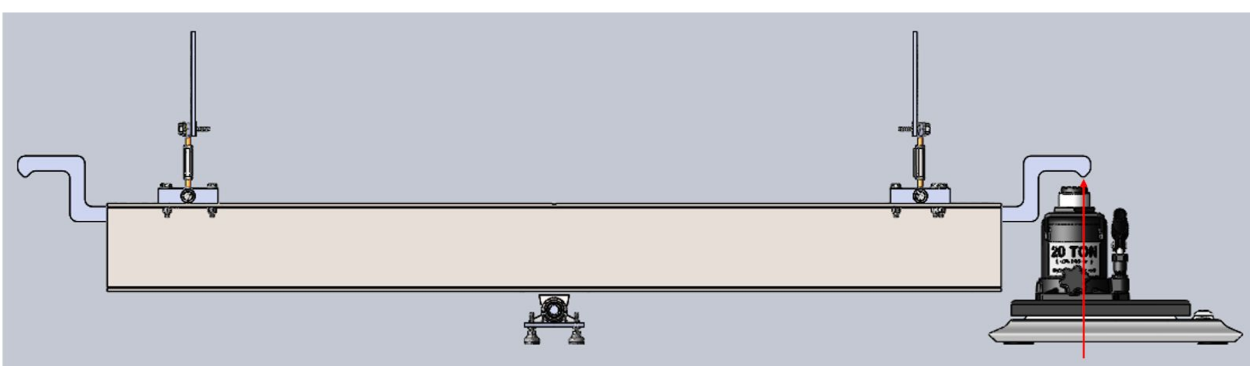


Figure 35. Front detailed view of fulcrum design and jack on the left

We figured that our jig needs to be fundamentally stiff for our purposes. One concern we had was that the jig compliance would affect torsion test results, but if we make the jig stiff enough, it can be assumed as rigid. We care mostly about the car, chassis, and suspension components, so want the jig compliance to be the last thing that we worry about.

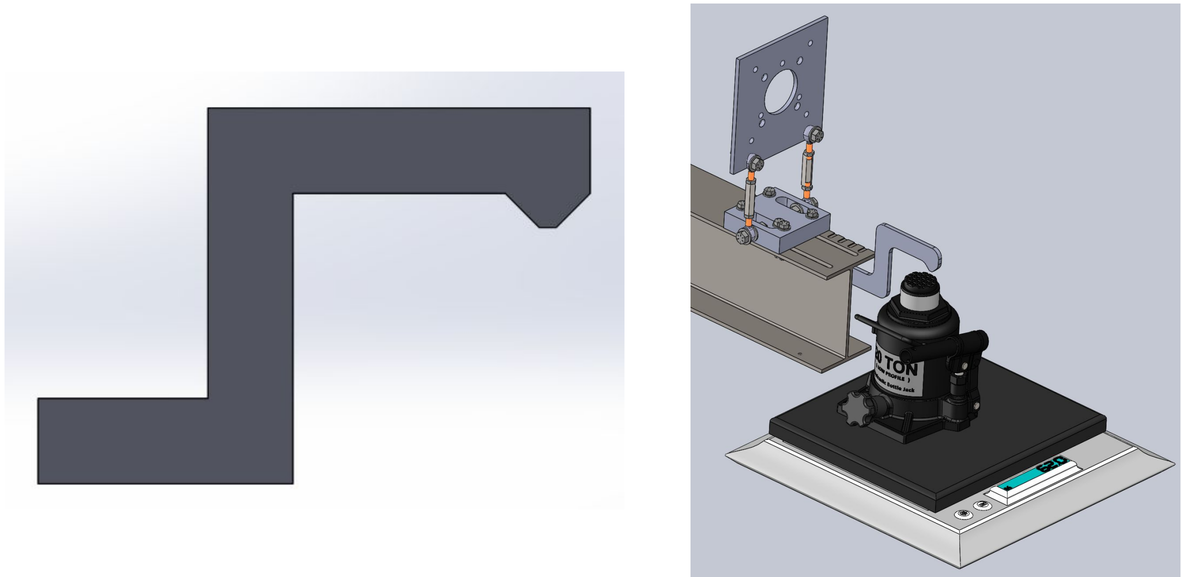


Figure 36. The load application waterjet part attached to the I beam (top) Force application assembly and bottle jack (bottom)

Although we initially planned to use a hydraulic bottle jack to apply the load, we ended up using a simple car scissor jack. We put the scissor jack on the scale and zeroed the scale before we started running the test. A picture of the setup in shown in Figure 37.

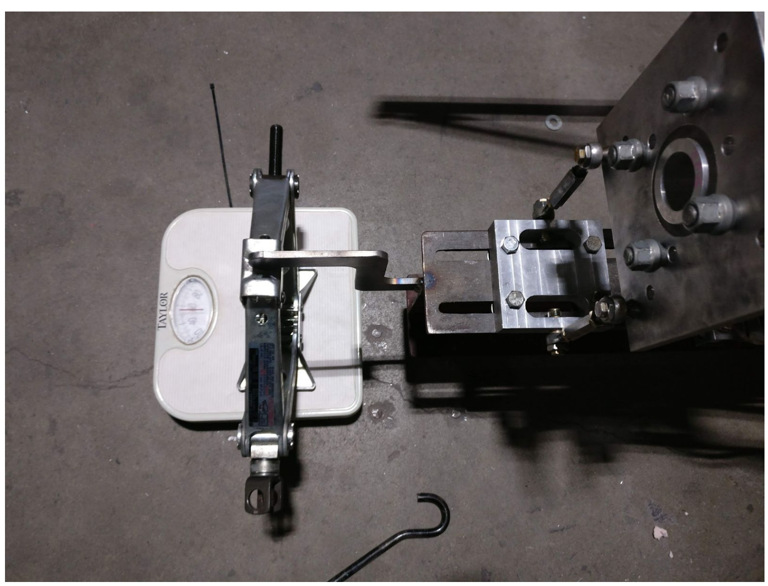


Figure 37. Load application method with about 55 pounds of force applied

We determined that the deflection of the load applicator can be ignored. The amount of deflection from the load applicator does not matter because it does not contribute to the deflection of the car.

Jig Stiffness Effects on Measurements

One of the major considerations when looking at different designs is the stiffness of the jig itself. If the jig is compliant, it may adversely affect measurements. There are a few different approaches that can be used to remedy this:

1. Design a jig that is stiff enough to assume infinitely stiff. This is generally the approach used, and is the one used in the previous jig. This is a simple method since there is no compensation that needs to be made for compliance in the jig. The downside, however, is that no jig is truly infinitely stiff, and will always affect results to some degree that may or may not be disregarded. Also, the weight and cost of jig would be a lot more than that of a somewhat compliant jig.
2. Find stiffness in jig and account for this in measurements. This could be done by running an experiment where jig compliance is measured by taking multiple points along beam. In future tests of chassis stiffness, the jig stiffness could be factored out.
3. Three locations will be measured to take measurements. There will be dial indicators at the front hubs, rear hubs and at the center of the chassis to get proper measurements.

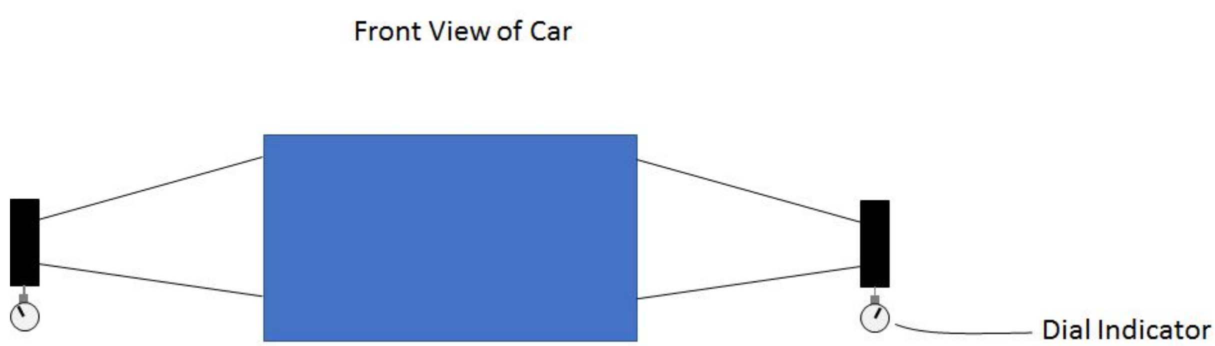
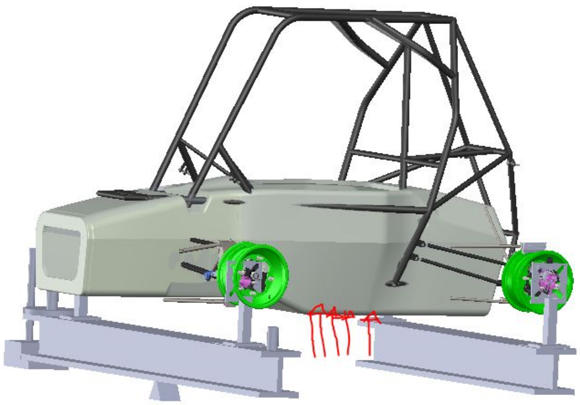


Figure 38. Test setup using 2 dial indicators to account for jig deflection

With the torsional load applied, the data will be collected with multiple (number still pending) dial indicators placed at the bottom of each of the car chassis. This will allow us to linearly measure the deflection along the chassis to see how the chassis is flexing with the applied loading. Figure 39 shows the location of the indicators on the underside of the chassis (in red) and Figure 40 shows another similar set up with multiple dial indicators on the left and right side of the car chassis.

Figures 39 and 40. Dial indicators located on chassis to get deflection

MANUFACTURING

Manufacturing of this project required a multitude of methods and lots of planning. We hadn't planned to manufacture anything Spring or Fall 2018, instead we spent time making sure that all of our parts were manufacturable in-house and developed processes for all the parts. We had previously thought about making prototypes, but due to funding, we only had one shot at making it right.

Figure 41 below shows the detailed parts and which manufacturing processes are needed to complete them. The drawings in Appendix E shows the name for each individual part. These were all presented during the in-class Critical Design Review.

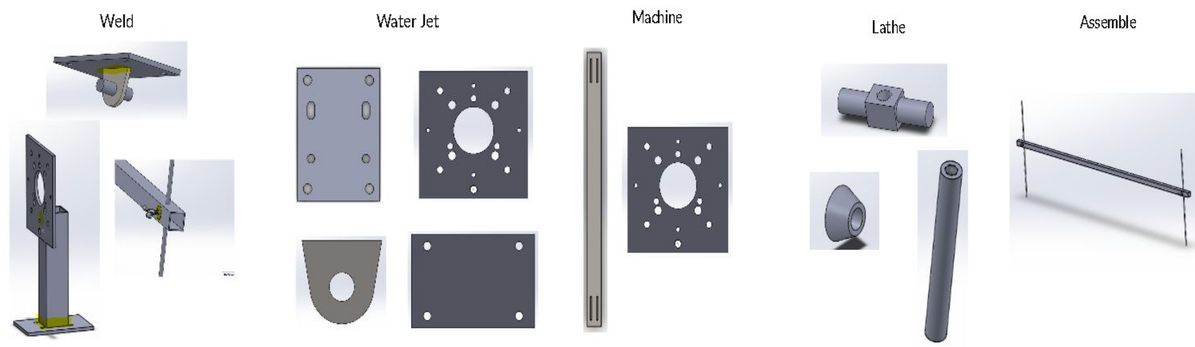


Figure 41. Detailed Design Manufacturing

Hands-on manufacturing for the project kicked off during Cal Poly Racing's Build Week. Build Week took place during the first week of winter break, right after fall quarter ended. Students from Cal Poly Racing stay at school for about a week and help manufacture parts for all the new cars that were designed in the fall. Since our project is going to help both teams, we decided to utilize the manpower that build week provided. It was a win-win situation since jobs and parts were needed to keep people busy throughout the week.

Figure 42. All the manual machines are occupied during Build Week

Drawings were created during dead week and finals week as the design was wrapped up. The team split up the drawings that needed to be made. An example of a drawing that had to be made is in Figure 43. This was one of the more complicated drawings since there are many features on the I-Beam.

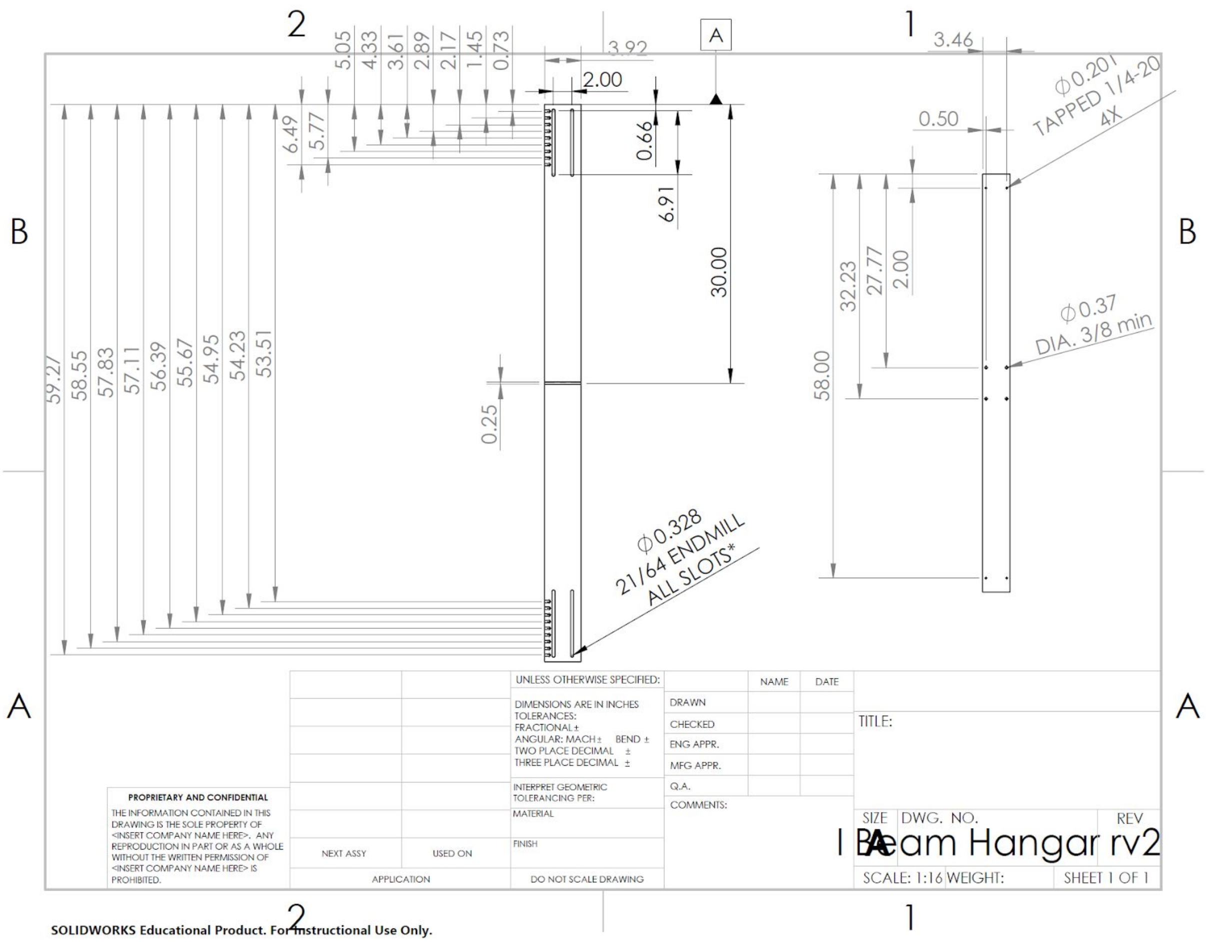


Figure 43. I-Beam Drawing

I-Beam Manufacturing

The I-Beams that the team already had were used because they were already available and suitable for our purposes. The flanges that make the "I" shape were perfect for putting long slots in for trackwidth adjustment. Using square tube would've been much more difficult as the width of the tube would have to be much wider to allow for slots to be milled in without hitting the walls. Secondly, fastening the hub arms to the square tube would have been difficult since there is no opening other than the two ends. Either way, purchasing I-beams or square tubes over five feet long would have been over one-hundred dollars each, without shipping.

Using the I-beams that the team currently has also provides no risk to the teams. There is currently a way to measure the car's torsional stiffness which uses the I-beams, but no features that currently exist on the I-beam were tampered with. So, the I-beams could still be used to test the torsional stiffness of the car using the old method if absolutely necessary.

Once it was decided that we would use I-beams for this project, we know that machining the I-beams would be tricky. This task was not achieved during Build Week due to a lack of available machines during the week. Our team did not get around to machining the I-beams until Week 4 of winter quarter. Machining the I-beams took about two or three work days. At first, one of the Bridgeport manual mills were going to be used to machine the I-beams. However, it was quickly realized that the table was going to be too short. The mill with the longest table was the Lagun mill, so we switched over to that mill to machine the I-beam.

The original plan was to toe-clamp the I-beam to the manual mill and start machining, but Kyra Schmidt from Human Powered Vehicle suggested using two vices to hold the I-beam, since she had to do something similar to machine a large piece of metal like us. Raymond spent about an hour squaring the two vices. They can be seen in Figure 44 below; one directly under the I-beam where the slot is being machines, and one under Omar's right arm. To square the two vices, one was set up initially and squared, then the second one was set up and squared relative to the first one. Setup had to be done a couple times to accomodate for how the I-beam needed to move across the mill table for different operations. Once the vices were squared up, the I-beam was placed in the vices and tightened down. To make sure that the I-beam was square, a magnetic dial indicator off the quill was used. The dial indicator was pressed against the side of the I-beam and moved along the x-direction. A 0.065" steel shim had to be used on one side of the vice to make the I-beam parallel within 0.005" to the x-direction of the table. Figure 44 has a picture of the shim clamped against the I-beam in the vice.

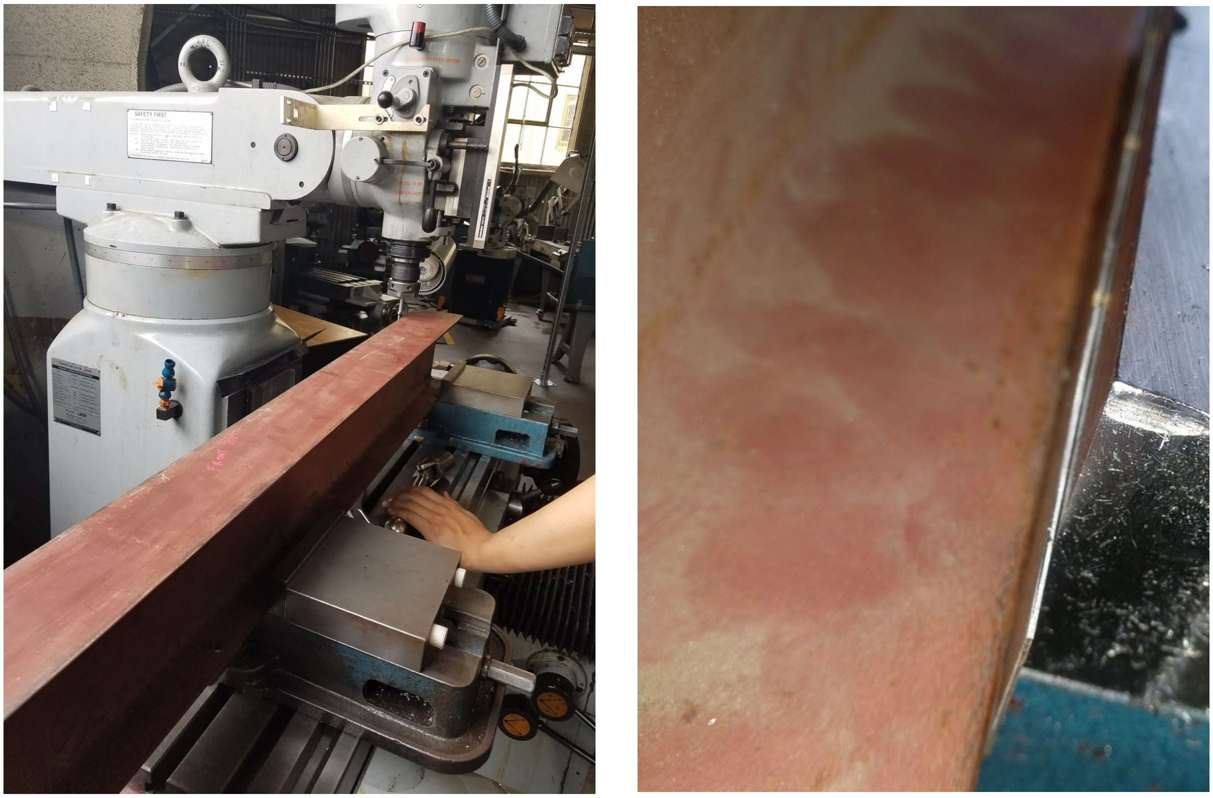


Figure 44. Shimming the I-beam

The diameter of the slot was spec'd to be 21/64”, which is a clearance for a 5/16 bolt. The shop did not have an end mill of that size, so a 3/8” end mill was used. So, there is much more clearance (about 0.600”) between the bolt and the slot width, but we deemed this okay since it would allow for correction in potential misalignment between the hubs that the adapter plates mount to. The next smallest size available was a 1/4” end mill. We did not want to do multiple passes so we did not use this end mill.

Figure 45. Working on machining the I-beams

Since the I-beams were machined in-house, and we were limited by the x-travel of the mill, there was no way we could machine all the features without moving the I-beam somewhat in the vice. So, all features were machined on one corner and side (i.e. right corner, top side), then the I-beam was "slid" across the table to do the other corner (i.e. left corner, top side). Then, the I-beam was flipped and the same process was repeated. The second I-beam followed a similar manufacturing procedure. While machining, it was noticed that the speed of the end mill was very important. We ran the end mill at 1600 rpm, which was obtained using the 4V/D convention. (V for steel is 200, D of the end mill was 0.5"). This speed proved to work pretty well. If the speed was off, it would cause the I-beam to vibrate a lot and the end mill to chatter as we milled the slots. Raymond ended up having to hold the I beams as close to the slots that were being milled to help minimize the vibrations from only clamping on the bottom half of the I-beam. A slow 5 inches/minute autofeed in the x-direction was used when machining the slots. This helped with not having to manually crank the x-feed over and over again. Thirty thou depths were cut with each pass. A photo of machining the slots is shown below in Figure 46.


Figure 46. Machining slots into the I-beam

The last operation done on the I-beams was to drill holes on the bottom side for mounting the pivot point fulcrum assembly. This was a bit complicated since the mill table in the y direction (left to right) was not long enough to reference all the holes off the same datum. So, the first two holes were drilled on a mill then the last two were match drilled with the pivot point plate.

Once all the machining of the I-beams was complete, a file was used to smooth out the edges of the slots and a deburring tool was used to clean the edges of the drilled holes.

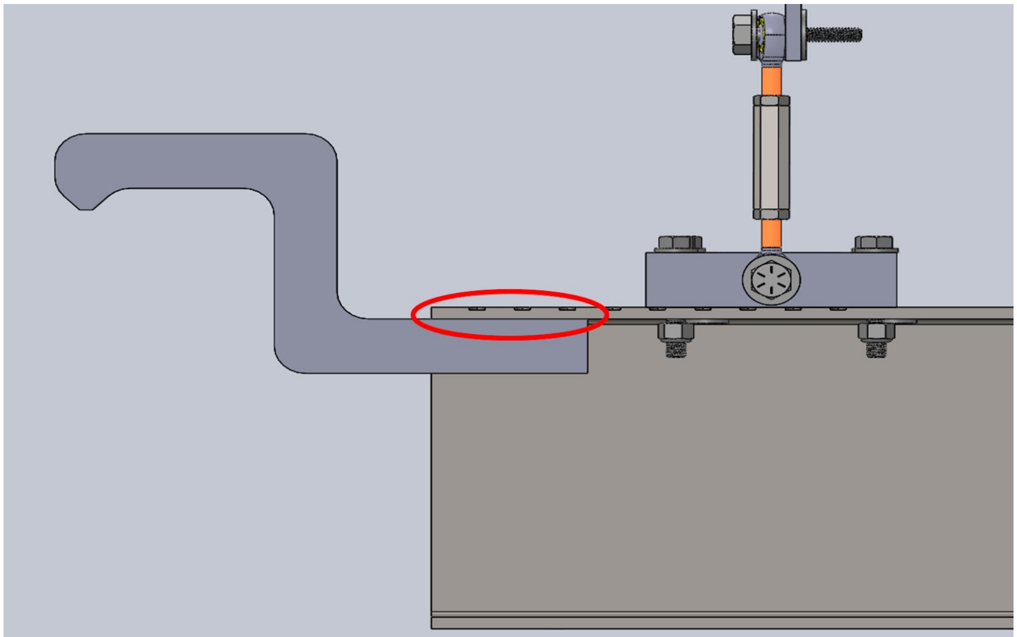


Figure 47. Load applicator location in CAD

The front I-beams then needed to have the load applicators welded onto each side of the beam. The I-beams were welded on about 2.5 inches in from each side of the I beam. The load applicators were located along the z axis using the fillet of the I beam, so the applicator was butt up against the fillet before welding.

Figure 48. Load applicator welded onto the side of the I beam

Load applicators were welded on both sides of the front I-beam. Ideally they would be welded in the middle of the I-beam (along the x-axis) but they were instead welded on the same side.

Waterjet

Another manufacturing tool our team utilized was water jetting. Initially, we wanted to get a majority of our parts waterjet by Charisma Design Studio, which is a shop that has two waterjet machines owned by a Cal Poly Racing alumni's family. Our team sent stock to be waterjet to their shop with other stock from Formula and Baja SAE during winter break, hoping to get them all cut and back by the beginning of winter quarter. However, Charisma was very busy during the holiday season and was only able to cut some of Formula and Baja SAE's requests. Fortunately, we were still able to try the school's waterjet at the IT shop on campus. We were able to get our steel cut on the waterjet week two of winter quarter (the IT shop was not open week 1). Pictures of our stuff getting cut is shown in Figure 49.

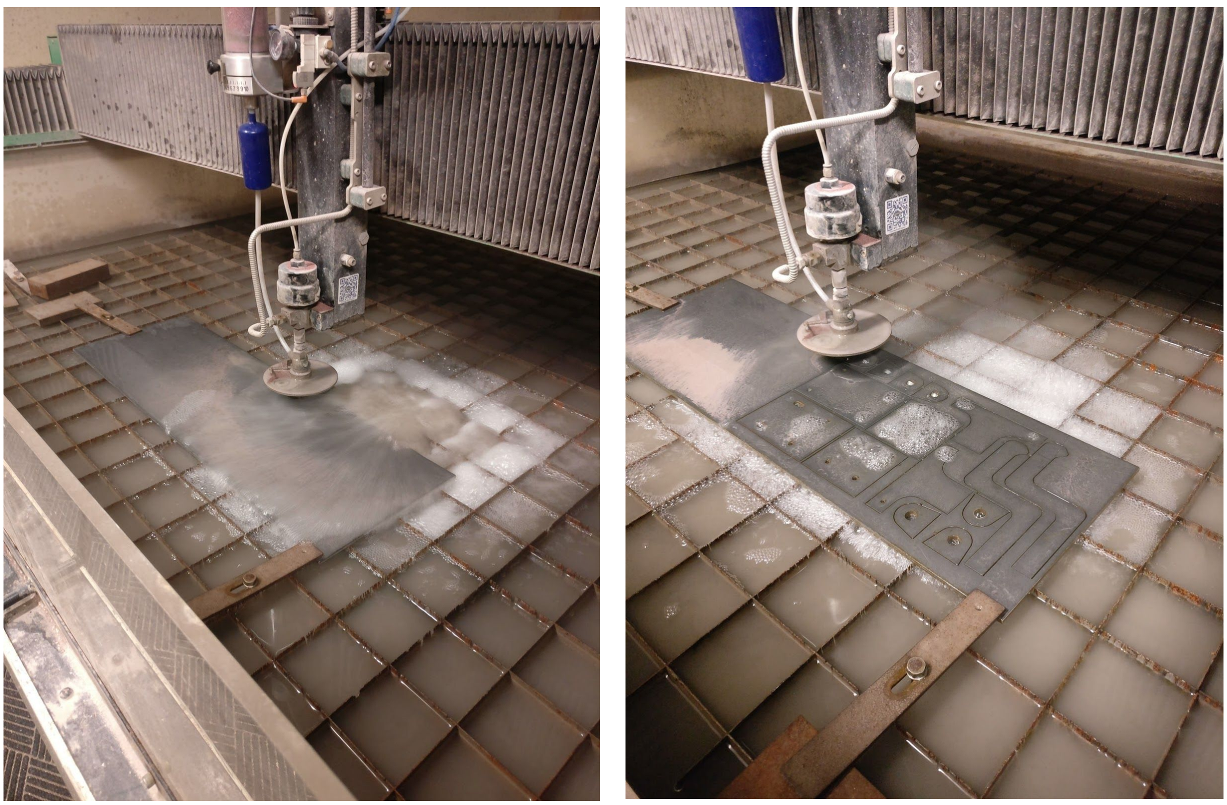


Figure 49. Cutting material at the school's waterjet

Parts were nested into assemblies, and we tried to minimize the space between parts to conserve as much material possible in case we needed to cut more later on. Once the nested assemblies were made, DXFs needed to be made since that is the type of file that the waterjet takes. Drawings of the nested assemblies are shown below in Figure 50.

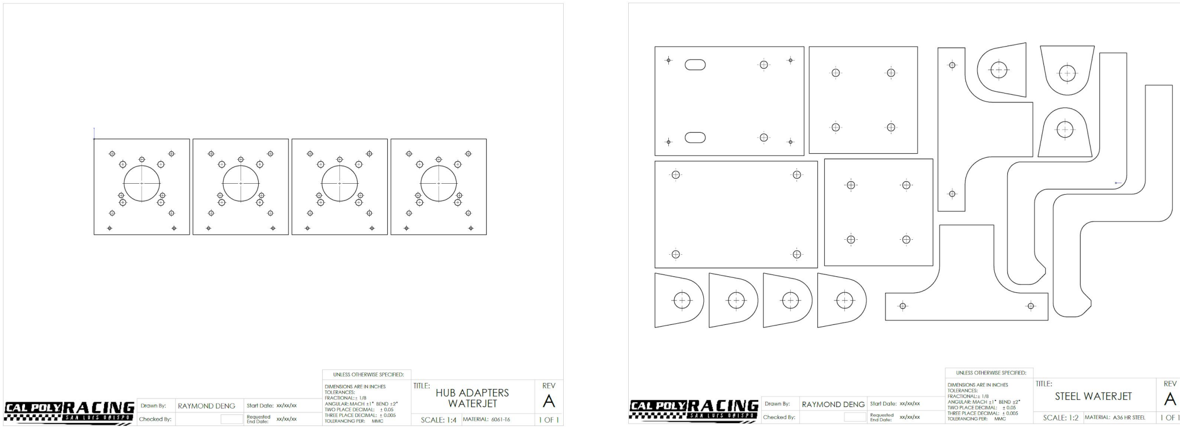


Figure 50. Waterjet drawings

All holes on parts that were waterjet were undersized since the waterjet usually has a kerf. An extra 0.050” was taken away from the diameters of the holes so we could drill them out later on to get exactly what hole size we want. Positionally the waterjet does a good job of blasting out the holes, but the kerf needs to be accounted for (especially with thicker material, such as the 0.25” steel we were cutting). The edges of most parts were also sanded down to get rid of the kerf.

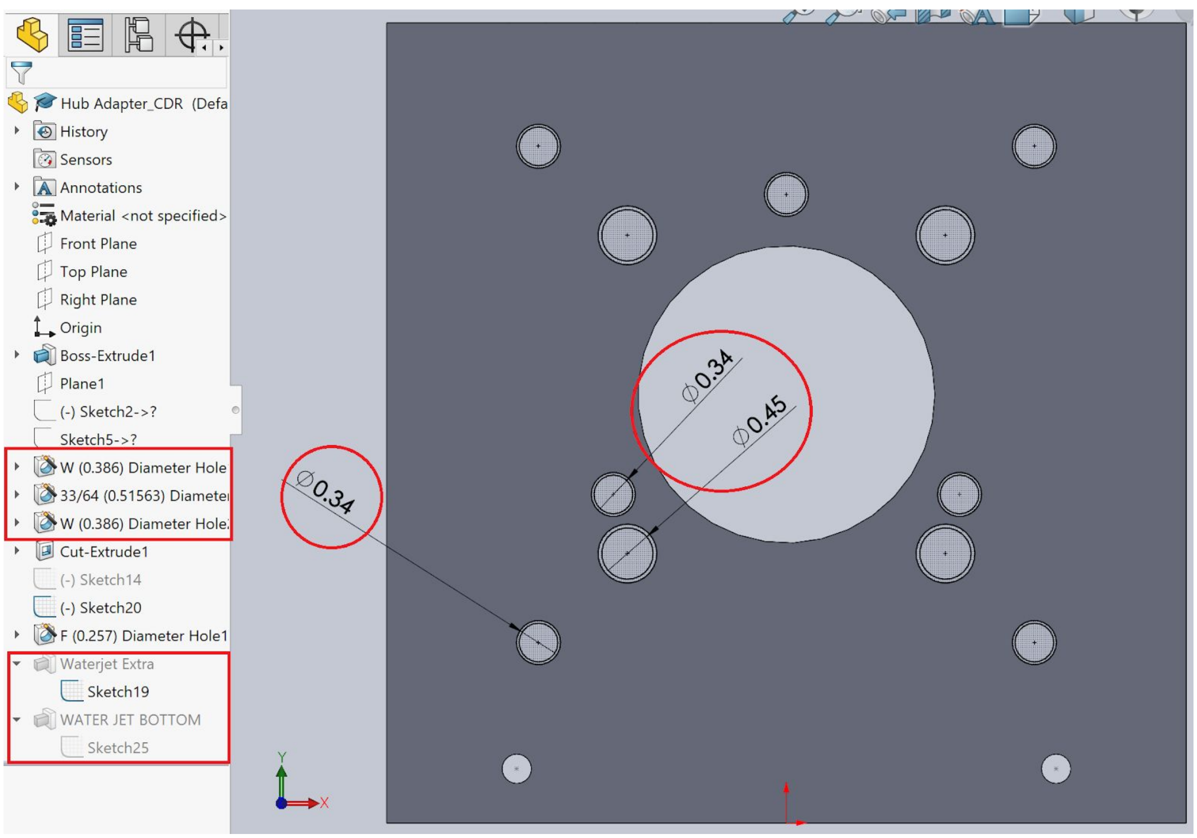


Figure 51. Undersizing holes for the waterjet

Most of the things we waterjet came out great. Once everything was cut, we needed to post-process them by drilling out the holes to size and grinding the sides down flat due to the kerf.

A quick dilemma that was present was the fact that the Cal Poly machine shop did not have the 33/64th drill bit specified. One of the machinist knew that the size of the hole needed to be 1/2in so they decided to drill with a 1/2in drill bit; without indicating this change. Thus when testing the fitment of the adapter plates to the said Baja vehicle, it did not fit properly. Upon some time wasted on understanding the problem, it was determined that this undersized value did not allow the proper clearance for the threads. Therefore a 17/32nd drill was chosen for adequate clearance.

One problem we ran into was having the wrong bolt pattern on the rear hub stand arms. The bolt pattern was incorrect in CAD when we made the nested assemblies so the wrong size was cut. We noticed this problem when we tried to jig up the rear hub stand for welding, shown in Figure 53. Figures 52 and 53 show the issue that we had. We had to fix the plate in CAD then re-nest a new assembly to get it waterjet.

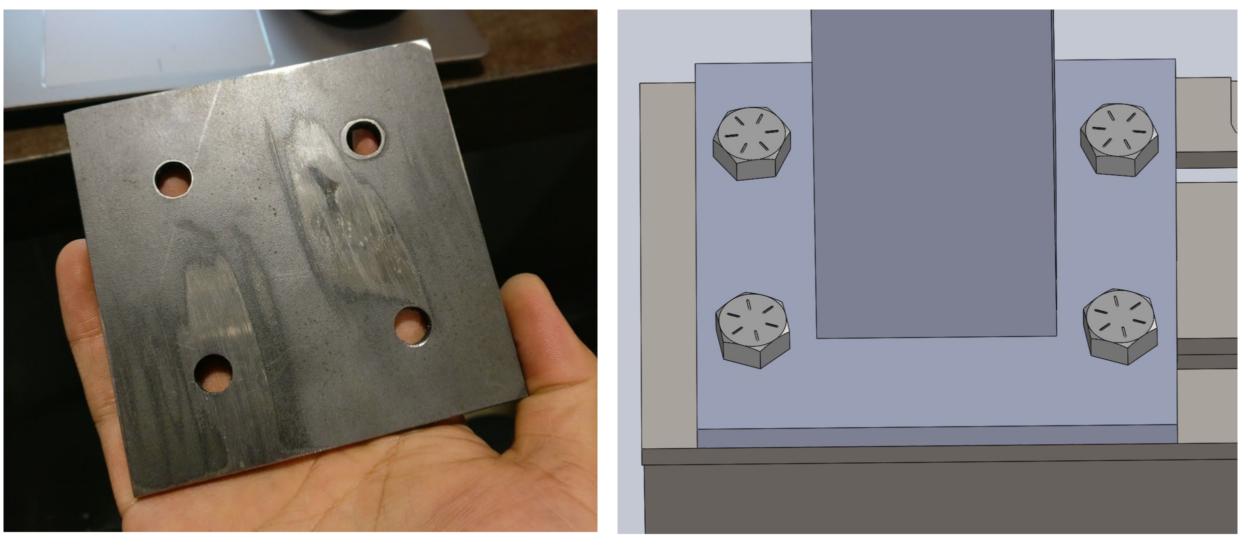


Figure 52. Incorrectly cut (left) and correct (right, in CAD) rear hub stand plate

A mess up we had was with the rear hub support arm plates. The bolt pattern changed in CAD after the DXF was made for the waterjet so the plate was cut incorrectly. The real life error compared to the correct bolt hole locations in CAD is shown above in Figure 52. Figure 53 below shows how we realized that the bolt pattern was incorrect.

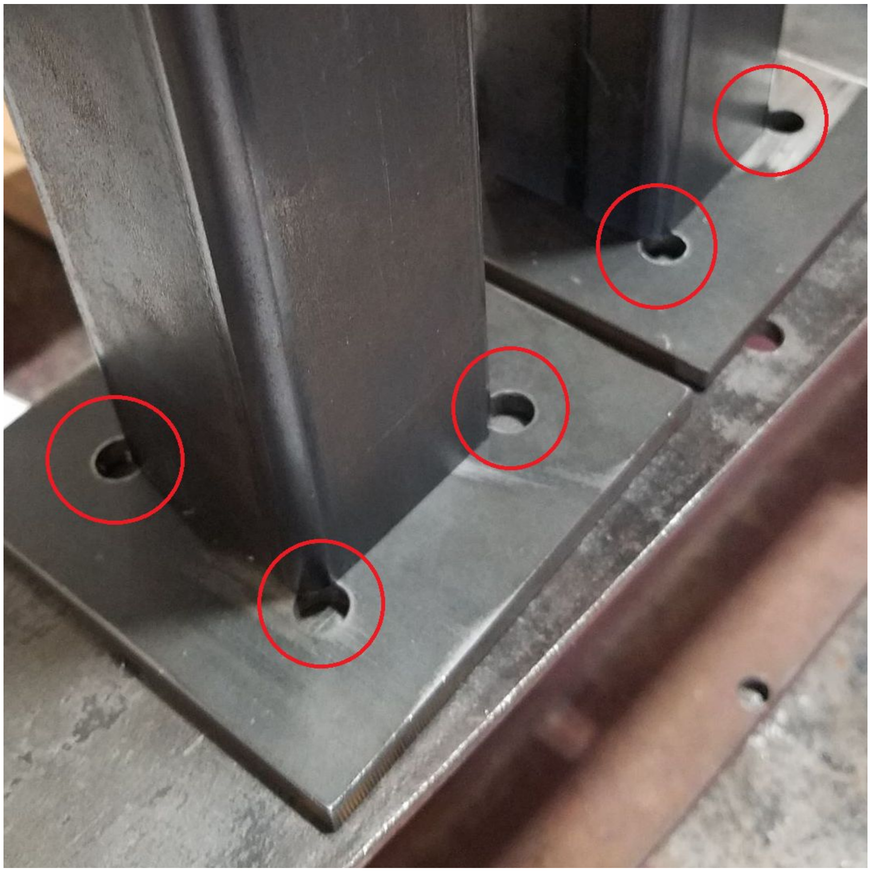


Figure 53. Incorrectly cut rear hub stand plates

Shaft Manufacturing

The shaft that the pillow bearings mount to was made out of 1018 steel. It needed to be steel so it could be easily welded to the lug which was apart of the fulcrum point assembly. The drawing of the shaft is shown below in Figure 54.

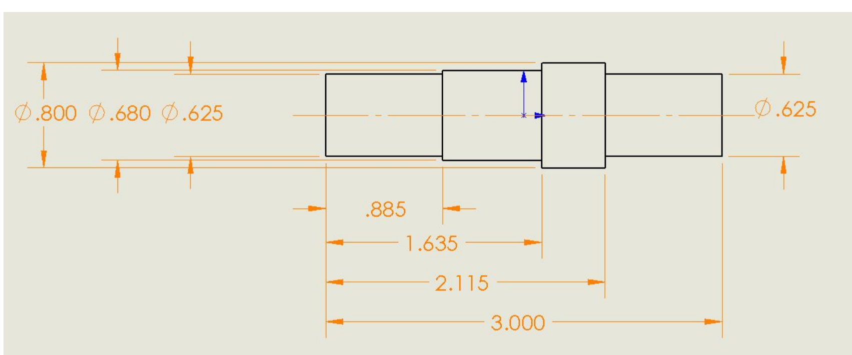


Figure 54. Fulcrum point pivot shaft drawing

We ordered a 1 foot long 1” OD steel shaft and cut about 4” of shaft to on the cold saw before we put it on the lathe. Once on the lathe, it was faced to length, then the shaft was turned down in multiple operations to the various diameters specified in the drawing.

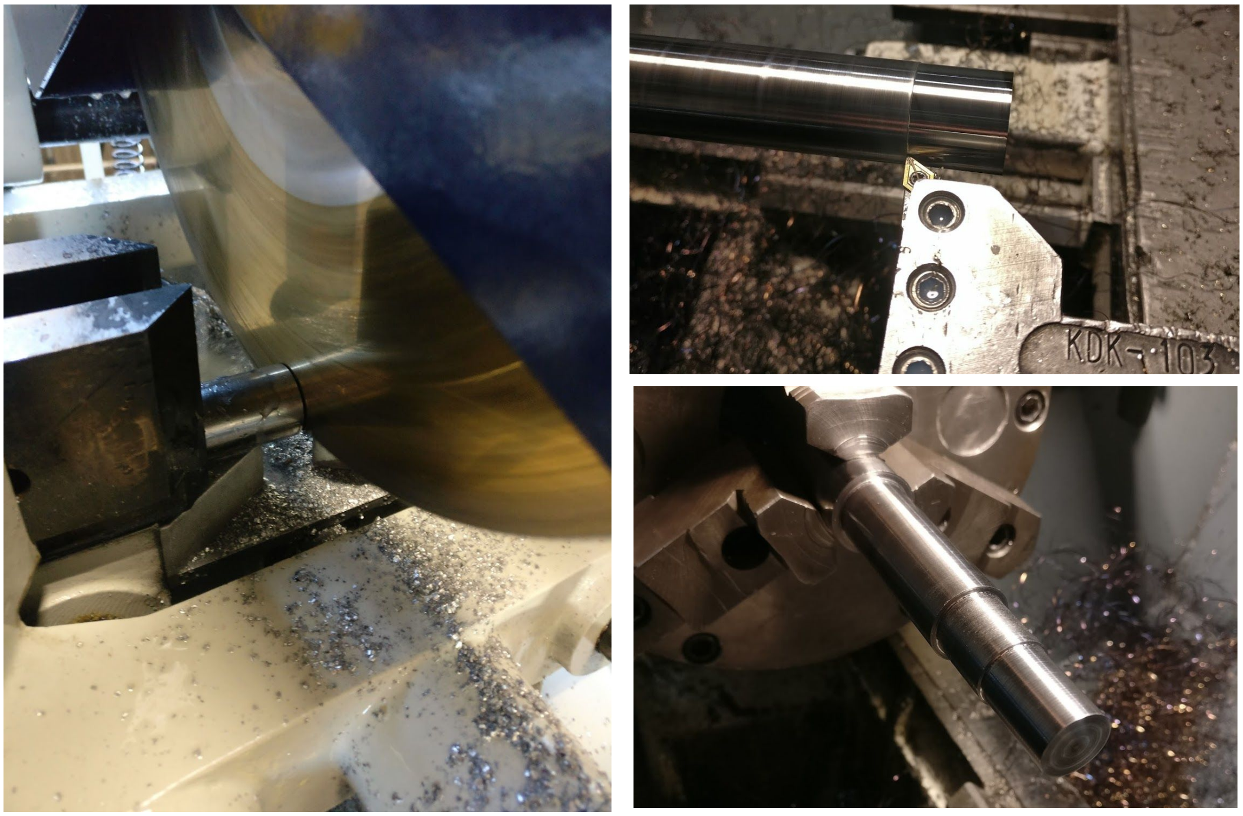


Figure 55. Shaft manufacturing photos

The diameter of the section of the shaft where the lug gets pressed on came out correct. The diameters of the shaft for the bearing were slightly oversized so they needed to be tossed back onto the lathe after the lug was welded on. Fortunately, the pillow block bearings did not need a press fit onto the shaft, so the final diameter of the bearing diameters on the shaft were not incredibly high tolerance. So, the shafts were slowly turned down until the bearings slid right over the shaft. The bearings have two set screws that lock the bearings onto the shaft, and they ended up working really well.

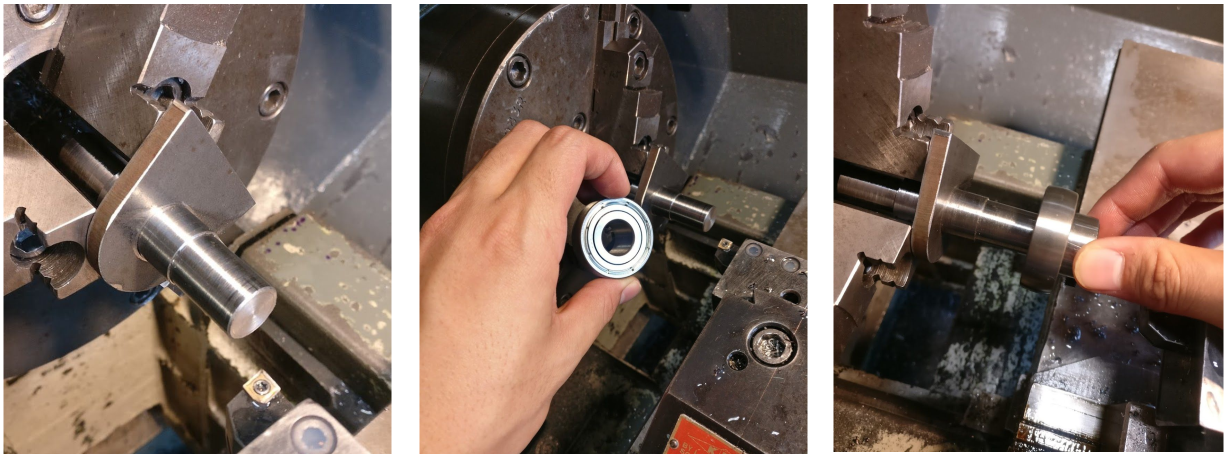


Figure 56. Turning down the fulcrum point shaft to fit the pillow block bearing

Once the shaft and lug assembly was completed on the lathe, the assembly was to be welded onto the base plate that bolts onto the I-Beam.

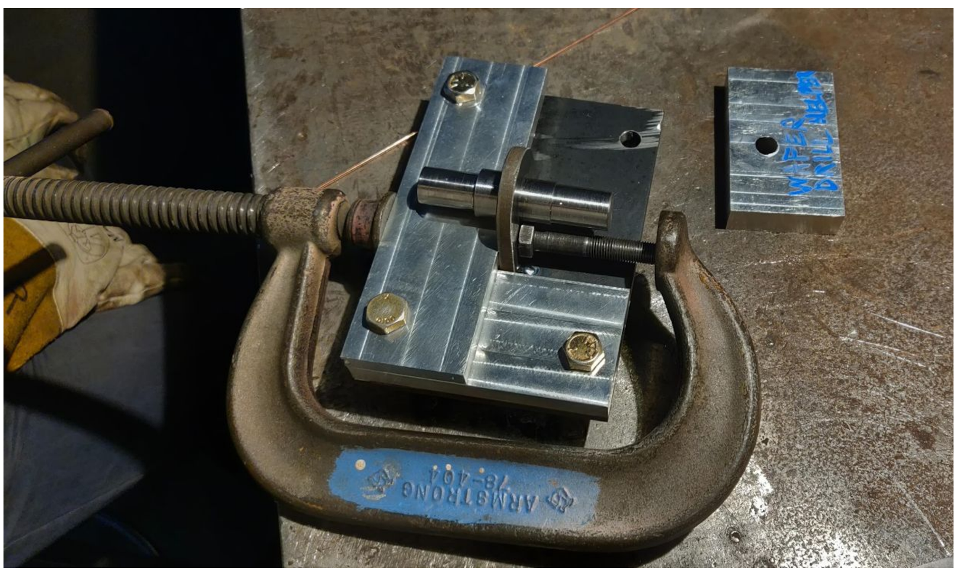


Figure 57. Lug welding setup

With the assistance of some new members on Formula SAE, weld jigs were made so that we could properly locate the lug on the plate and to help ensure that it was welded perpendicular to the base plate. The fulcrum base plate and lug jigged up is shown above in Figure 57.

Adjustable Tie Rods

To adjust the height of the adapter plates on the front arms, adjustable tie rods were made. Hex stock was used since a wrench can go over it, and was cut, faced to length, drilled, and tapped. A couple pictures of manufacturing the tie rods was shown in Figure 58. The faced-down hex rod was tapped on one end with a right-hand 5/16-24 thread, and a left-hand 5/16-24 thread on the other side so that proper adjustment could be made since one thread will need to turn clockwise while the other thread will need to turn counterclockwise. Figure 59 shows the links and adjustment ranges.

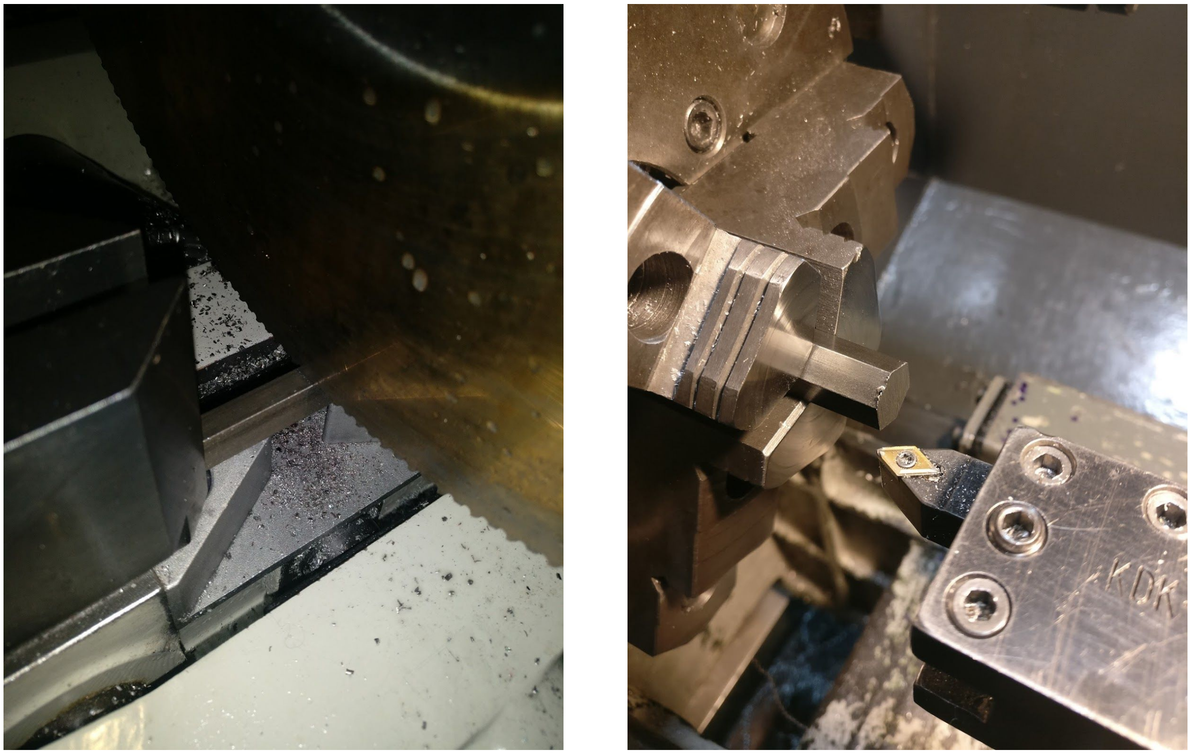


Figure 58. Manufacturing hex stock for adjustable rods

Figure 59. Front arm hex stock adjustment

Rear Support Arm Manufacturing

Square stock was used for the rear support arms. A 2” x 2” square with a wall thickness of .100’ ensured there was not deflecting or buckling would occur. The stock was first cut on the tile saw for rough length then milled to get a tolerance deviation of 0.009’ between the two parts. Since the parts left to right mattered more then the actual part coming within specification, this was deemed an appropriate tolerance. Figure 60 shows the stock being cut on the tile saw and the finished pieces.

Figure 60. Omar cutting the square tube stock (left) and the final cut tubes (right)

To ensure that the cut square stock was located in the middle of the rear base plate when welding, jigs were designed to bolt to the existing waterjet holes. Figure 61 shows the jig in CAD. This would ensure that the location of the stock would be centered and clamped properly. Once the square stock was tacked to the base plate, a caliper was used to check the distance from each side to ensure that the measurement was true. Then a full bead was welded to complete the task.

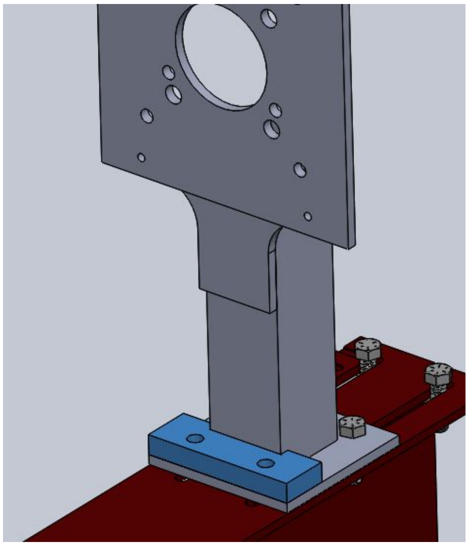


Figure 61. Jig in place for proper welding location (left), final rear support arms (right)

Dummy Shock Manufacturing

For testing the cars, so-called “dummy” or “false” shocks had to be made in order to test the cars. If the normal shocks were put on the car, they would take all the twisting load and would make the data really noisy and/or hard to use. So, we ourselves had to manufacture the Formula dummy shocks, pictured on the left in Figure 62. The procedure for making the dummy shocks were as follows:

1. Cut the circular rods (0.032” 4130 steel) to length
2. Cut hex bungs on the lathe (these were done by a Cal Poly Racing sponsor, MMI)
    a. Drill holes in the hex bungs and tap them to 5/16-24 threads (one left-hand, one right-hand)
3. Weld the hex bungs onto the ends of each rod
4. Chase the threads
5. Thread in jam nuts and rod ends on both ends of the car

Once the dummy shocks were completed, they were installed in place of the normal shocks that we use to drive the car. Three out of the four installed dummy shocks can be seen in the picture on the right in Figure 62 (the fourth one is covered up by the roll hoop).

Figure 62. Dummy shocks (left), dummy shocks pointed out on the car (right)

These shocks are essential to running the test and need to be installed and spaced correctly to get good data.

Dummy shocks were also made for the Baja car. Members of the suspension team on Baja made them using big steel rods. The manufacturing process was similar, but they threaded in their rods ends straight into the steel rods, where Formula threaded theirs into bungs. A picture of the dummy shocks on the car is shown below in Figure 63.

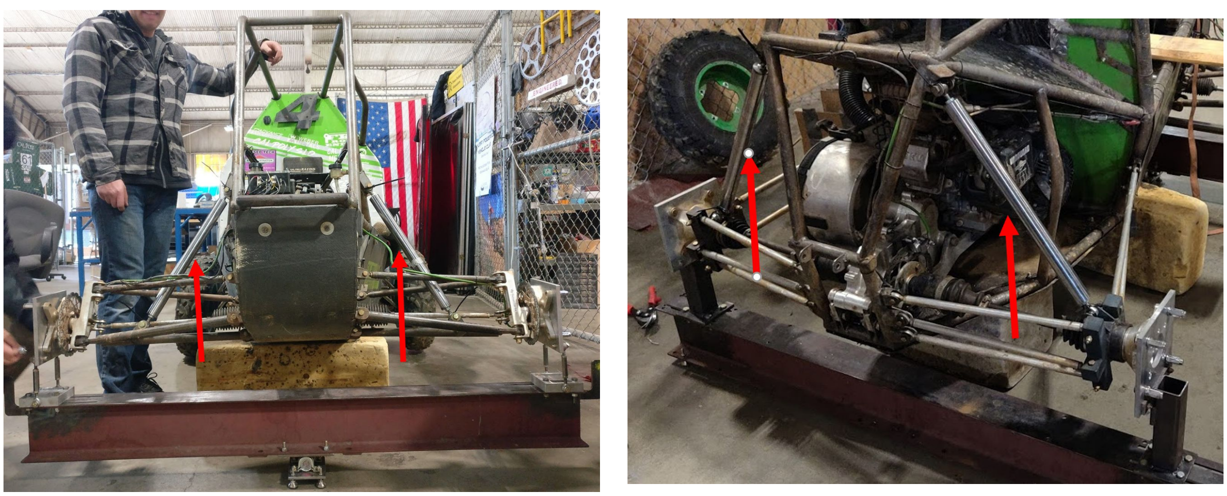


Figure 63. Dummy shocks on the 2018 Baja car; front (left) and rear (right)

Testing & Validation

In this section, we will be covering the details regarding testing of the Cal Poly Racing's vehicles. A fully detailed testing procedure and safety document is in Appendix G. An abridged version of the procedure with pictures of the set up during the tests we ran is detailed and shown in this section of the report.

2018 Formula Electric Car Test

The original goal of the project was to be able to test the combustion, electric, and Baja vehicles for Cal Poly Racing. Unfortunately, we were not able to test the 2018 electric car, because the team needed to salvage the suspension rod ends that most of the suspension links used. However, we did set the electric car up on the jig as a test fit, as shown below in figures 64-66.

Figure 64. Formula SAE 2018 electric car on foam blocks

Figure 65. Setting up measurement devices for electric car test

Figure 66. Electric car set up on jig

We were not able to test the electric car because at the time the dummy shocks were not made. So we figured that we should at least set up the car as if it were ready to test to see if we would run into any issues that we could fix if needed. Most things on the set up went well and we planned to test the car another day. However, as aforementioned, we ended up not being able to test the electric car since the suspension was removed. Fortunately, this test proved that our jig would work for varying vehicle parameters.

2018 Formula Combustion Car Test

The combustion car was tested on Thursday, February 21st, 2019. This test took a long time since it was our first actual time running the test and taking measurements, and we ran into small hiccups here and there while running the test. Those hiccups are mentioned in the following subsection. Dummy shocks were changed a day before by the Formula SAE team to make sure everything was ready for testing the next day.

We started by rolling the 2018 combustion car outside of the Formula testing cage and putting it next to one of the club area tables, out of the way from the walkway from the hangar doors to the machine shop fenced entrance. In order to mount the jig to the formula car, first the whole car was lifted using foam blocks as seen below. Then, the rear I-beam was mounted to the hubs.

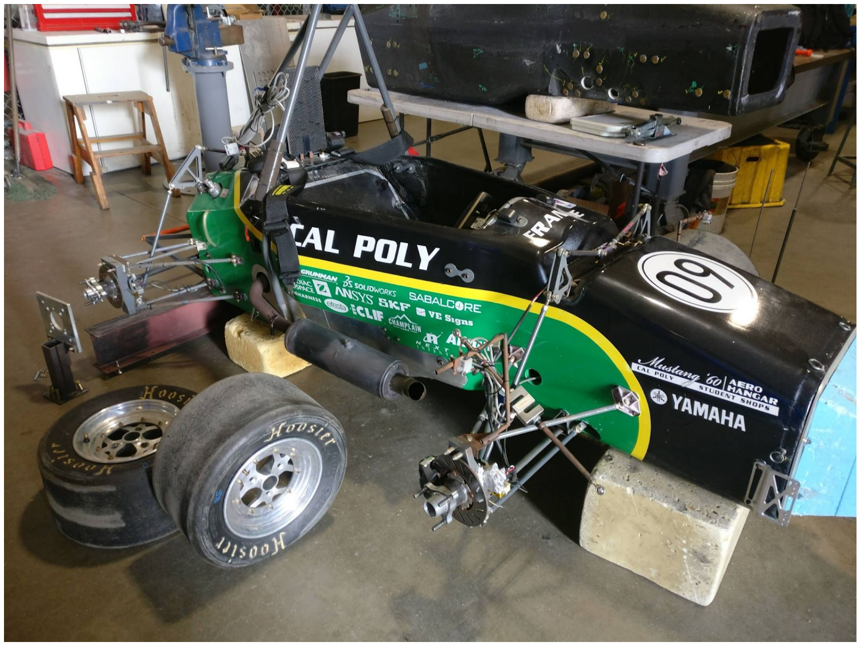


Figure 67. Working on mounting rear I-beam first

Then, front I-beam was lifted using the jack to position the hubs to the correct height to match the holes on the adapter plates.

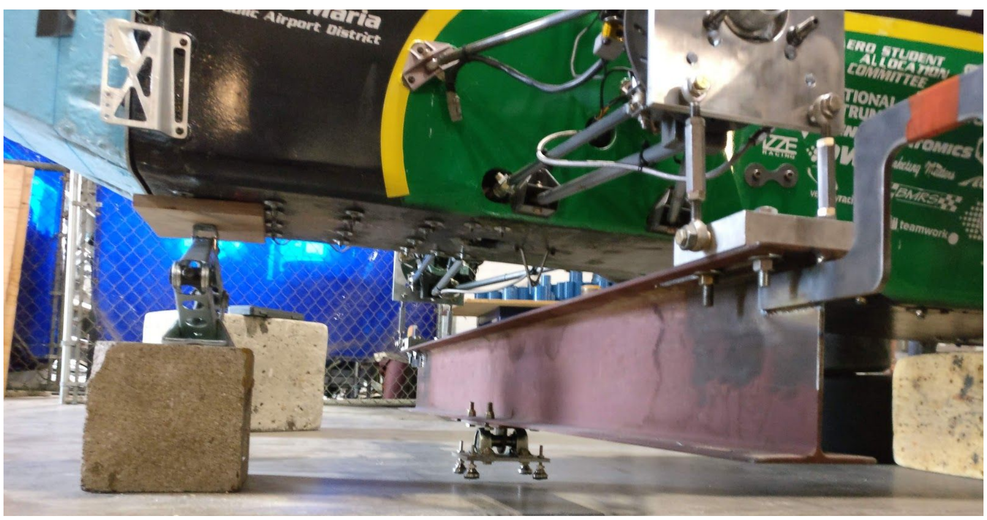


Figure 68. Working on mounting the front I-beam

To set up the measurement devices, a ratchet strap was used to fix the square tubing that spanned the width of the chassis to the vehicle. Dial indicators were set up at the ends of the tubing for chassis deflection measurements as well as on stands to measure hub deflection.

Figure 69. Chassis measurement tool (left) and hub measurement tool (right)

We noticed that the front I-beam started to lift when we applied around 150 lb of jacking force. In order to combat this, we needed to weigh down the car. The first attempt at doing so was by having Raymond sit in the car, as seen below in Figure 70. After a couple measurements, we decided to instead fill the car with weights in order to have a more constant and stable car for measuring.

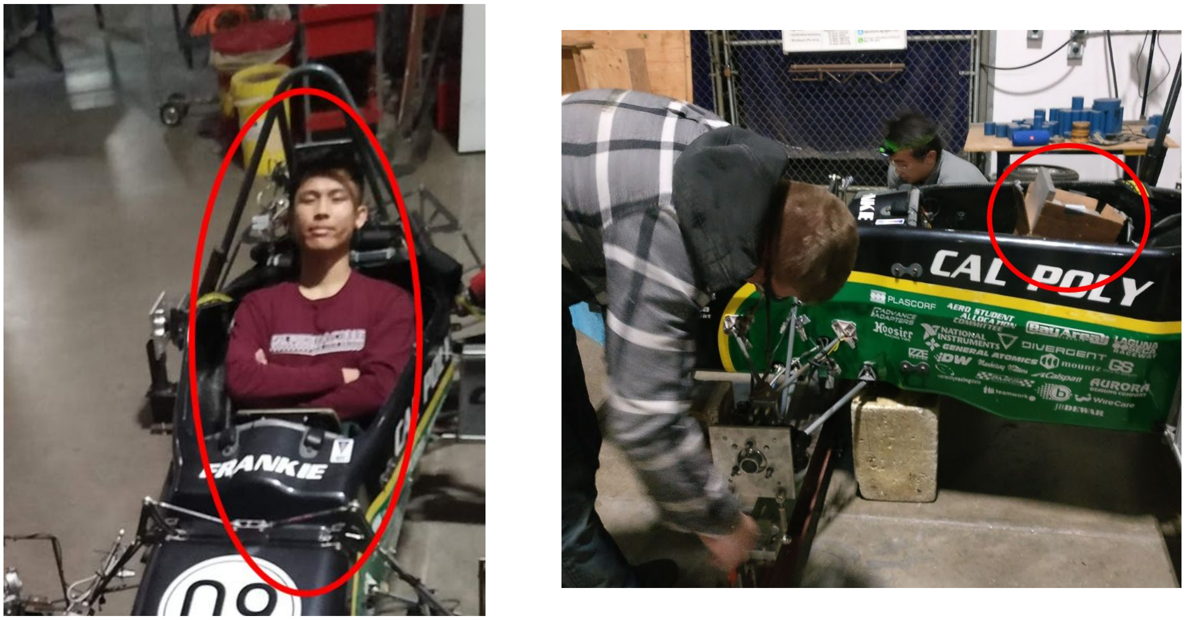


Figure 70. Weighing car down methods

Finally, measurements were taken using a jack and mechanical weight scale underneath the jack to measure the force applied. The distance of the moment arm was taken from point of contact to the middle of the I-beam. All the distances across dial indicators were measured right before applying any load. Forced was applied in increments of 20 lb and up to 100 lb, and taking dial readings along the way. We also checked for hysteresis by going down from 100 lb in decrements of 20 lb. Then, a second trial was repeated for better statistical data. The same procedure was done to the Baja car.

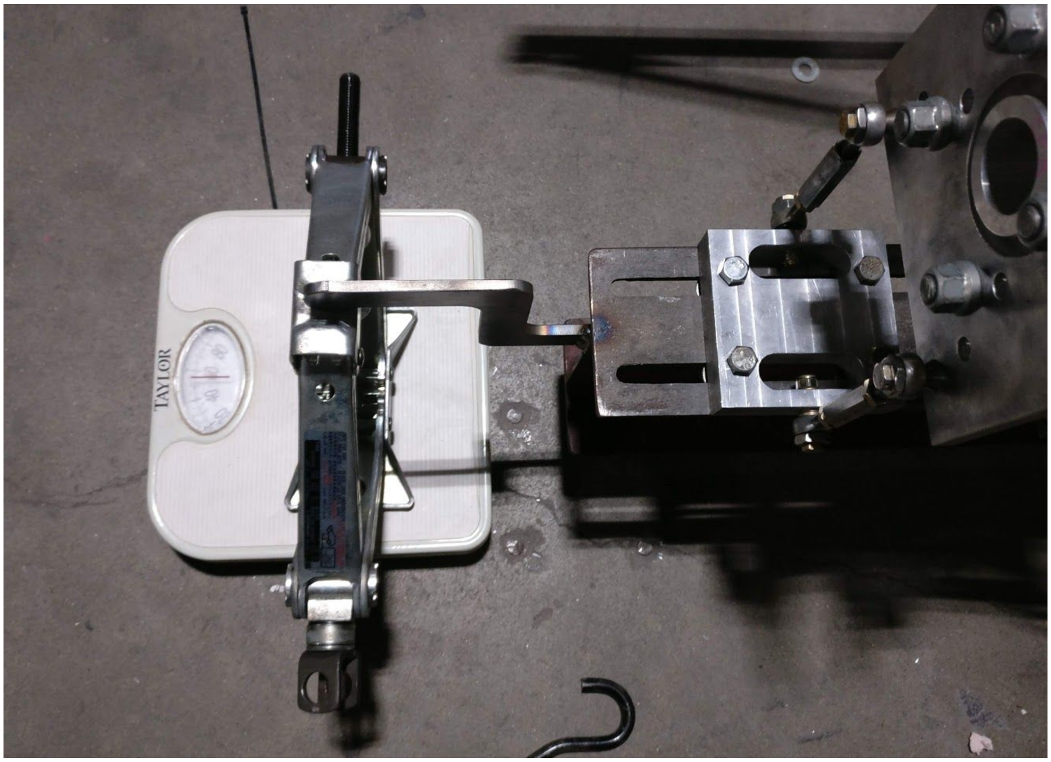


Figure 71. Scissor jack with mechanical weight scale on bottom

The first idea from PDR was to measure how much the rear would rotate and subtract that from all the other measurements along the chassis so that we could avoid weighing down the car. Then, it was suggested that we add weight to counteract the force of the jack and make the rear completely fixed, but adding about 150 lbs of weight proved to somewhat of a hassle. For future testing, we suggest anchoring the jig to the ground using a drop-in anchor and a threaded rod to avoid the the hassle of adding weights, specially when testing chassis without an engine in it. By using this method, we can absolutely be sure that neither front or rear woud lift as we increase the force of the jack.

2018 Baja Car Test

On February 29, 2019, we were able to test Baja's 2018 car. We had originally planned to test the car a few days prior, but they did not have dummy shocks made so they needed to make them. Baja had the shocks installed beforehand so when we met to run the test, we just had to roll the car out and start the test. Once we rolled the car into place, we jacked up the front and the rear and removed the tires. The front I beam assembly followed the standard procedure, and the setup is shown in figure 72 below.

Figure 72. Front I beam set up

Figure 73. 2018 Cal Poly Baja SAE vehicle with dummy shocks

The rear I beam assembly installation proved to be a little more troublesome. The hubs were not clocked at the same angle, and since their real axle is locked via a spool, we had to take the hub nut off of one of the rear hubs and then turn the hub until it fit into the jig. Figure 74 below shows the initial problem we had with the rear left hub not aligning with the jig.

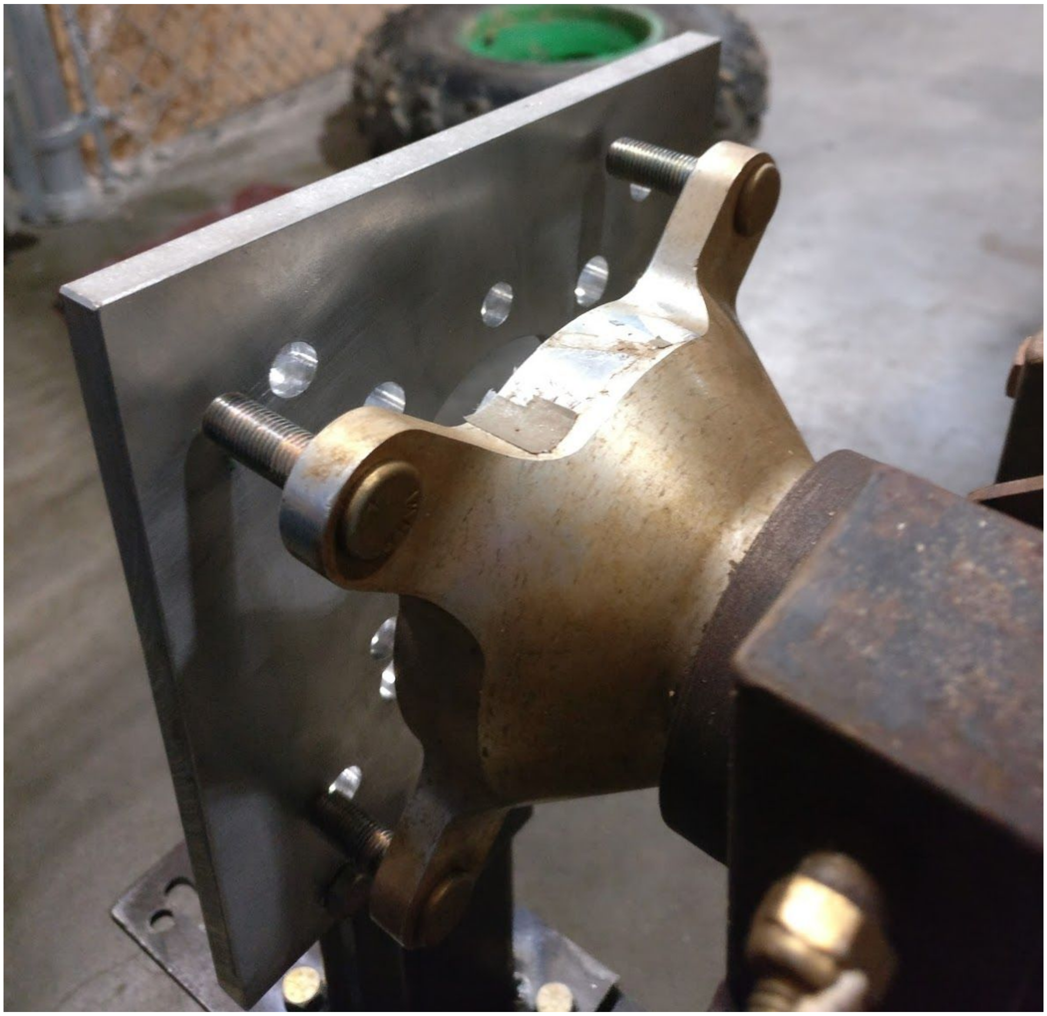


Figure 74. Rear left hub not fitting

Since none of us were on Baja SAE or were very familiar with their car, we called their team lead this year, Nicholas Capdevila, to come and give us a hand. We thought about removing one of the driveshafts, but instead opted to remove the hub nut to be able to turn the hub until it fit into the jig. A cotter pin used as a safety precaution for the hub nut had to be cut to remove the nut, then we were able to turn the rear left hub until it fit into the jig.

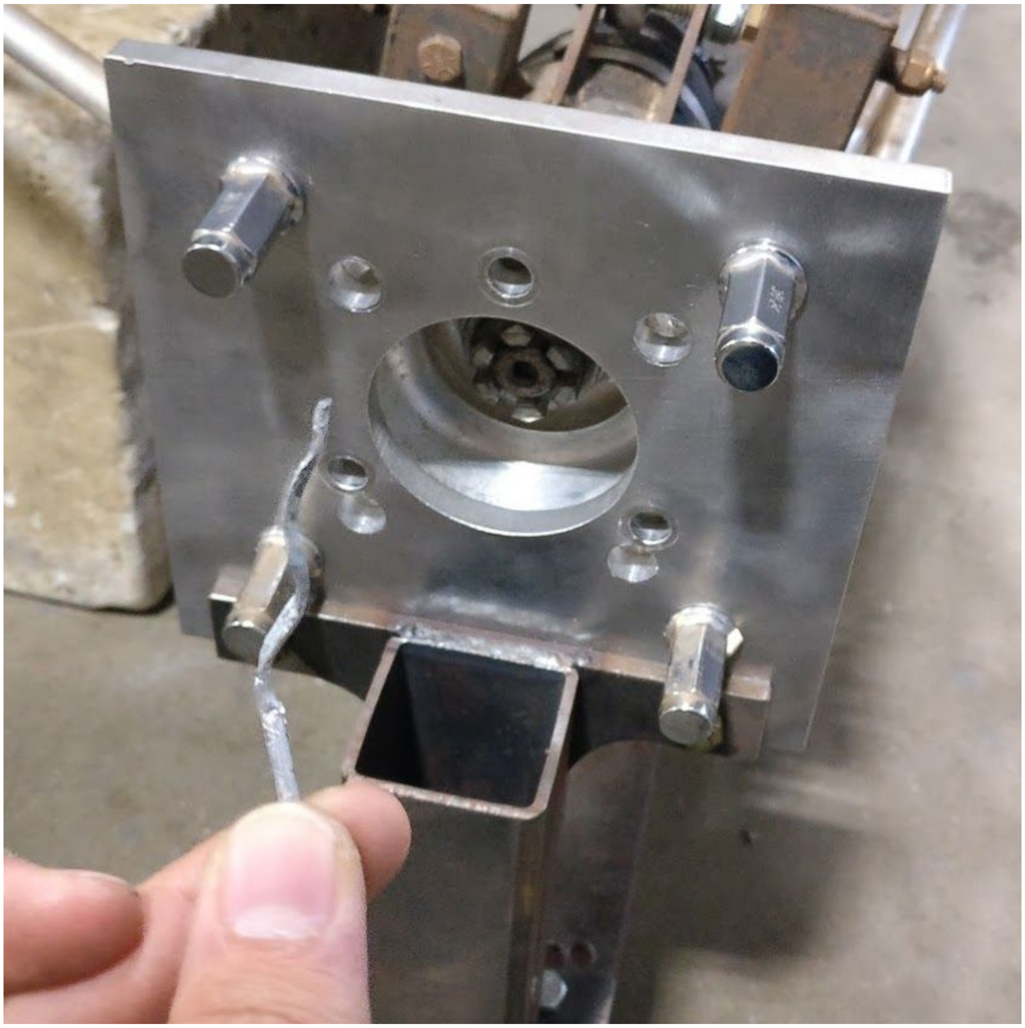


Figure 75. Removed cotter pin and fitting hub

As expected and similar to the combustion car test, we had to add weights to the car to prevent the jig from lifting up. For the combustion car, it was much more obvious where the weights went (in the cockpit); but for Baja's car we had to add a wooden brace to the frame to put weights on, since the weights themselves would crush the lightweight carbon fiber seat.

Figure 76. Wood bracing used to hold extra weights

Once the jig was fully set up, the same test procedure was run on the 2018 Baja car. We loaded up each corner to 100 pounds in increments of 20, then back down as well. This was done twice per each corner of the car. We did not take the car off, reassemble the entire jig, and rerun the test to check hysteresis; since this was already done for the Formula combustion car test.

The results of the 2018 Baja car test can be found in the Testing Validation & Data Analysis section. Although this test was not run on the 2019 Baja car that will be going to two competitions, we now know that the test will work on the new car. As we had mentioned earlier, we will be testing the 2019 car after the report is due, but the proof of concept for the Baja car has been accomplished. This data will help Baja close the loop on their designs and hopefully score better at their competitions' design judging event.

TESTING VALIDATION & DATA ANALYSIS

Methodology

The data gathered from the tests was the deflection of each dial indicator at each given load, ranging from 0 to 100 lb at 20 lb increments. Taking multiple values - instead of a single beginning value and a single end value - allows us to analyze the linearity of the system. The test could be run by either placing the load applicator on the left side of the car, or on the right. Part of the reason the jig was designed like this was to allow to test for slop in the system. Switching the side being loaded allows the user to test through the "deadzone", where the system is unloaded - i.e when certain components transition from being loaded in tension to compression or vice versa. It is important to measure for slop because this affects the real life response of the vehicle, and was not tested for in the previous iteration of the jig. This also allows the user to compare the stiffness of the car when loaded in opposite directions. In fact, we found later that the Baja car exhibits different stiffness when loaded in different directions.

Additionally, we account for any hysteresis by taking measurements while loading as well as unloading the vehicle.

The order of tests for each car was as follows:

Formula car:
1. Load right side
2. Load right side again
3. Load left side
4. Load left side again
Disassemble and reassemble jig
5. Load right side
6. Load left side

Baja car:
1. Load right side
2. Load right side again
3. Load right side a third time
4. Load left side
5. Load left side again
6. Load left side a third time

To interpret the data, we input it into an Excel spreadsheet. To calculate stiffness of any section, we use data from four different points (e.g. one on each hub to calculate hub to hub torsional stiffness). To calculate the total angle of twist takes the following set of calculations, using hub to hub torsional stiffness as an example:

1. To get the angle of twist of either the front or rear set of hubs, take the inverse tangent of the total deflection of the hubs divided by the distance between the dial indicators.

$$\theta = tan^{-1}(\delta_{right} - \delta_{left})$$

2. To get the total angle of twist of the car, one must subtract the rear hub angle of twist from the front hub angle of twist,

$$\theta_{total} = \theta_{front} - \theta_{rear}$$

The chassis angles of twist are calculated in the same manner.

Though we measured both chassis and hub deflections, the focus of the analysis in the following section is chiefly on hub to hub torsional stiffness, since this is the only parameter that needed to be analyzed for to ensure the jig operates properly. The method chosen for analyzing chassis torsional stiffness is dependent on the future chassis analyst's objectives.

To get the final value of the chassis stiffness, we take the slope of the linear regression line between the angle of twist and the applied moment. This nets an effective spring rate. This method was chosen because it is the most directly applicable value in terms of vehicle response. It also effectively deals with measurement noise while maintaining accuracy.

Objectives and Results

The results from testing the Formula vehicle are shown below. The column "side loaded" indicates which side we put the jack and scale on. It is important to note that after the 4th trial, we disassembled the jig and reassembled it, as a test to ensure the jig setup does not contribute significantly to measurement error.

Table 13. Results from testing the Formula vehicle

Trial	Side loaded	Hub to hub stiffness [ft-lb/deg]
1	Right	1977
2	Right	2130
3	Left	1645
4	Left	2077
5	Right	1755
6	Left	2027

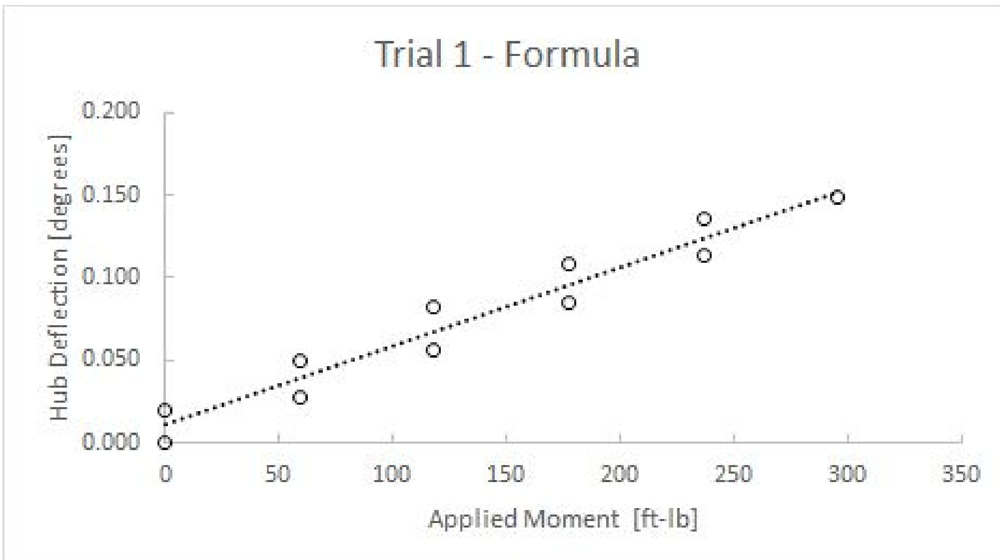


Figure 77. Stiffness of 1977 ft-lb/deg

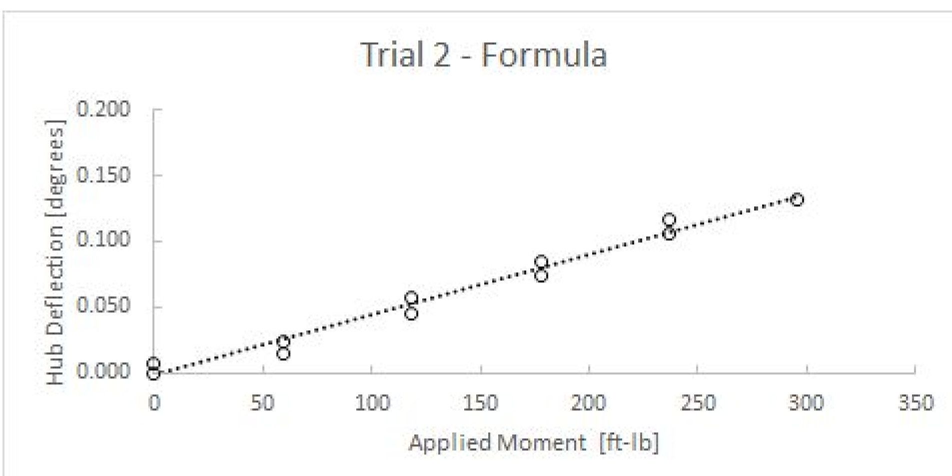


Figure 78. Stiffness of 2130 ft-lb/deg

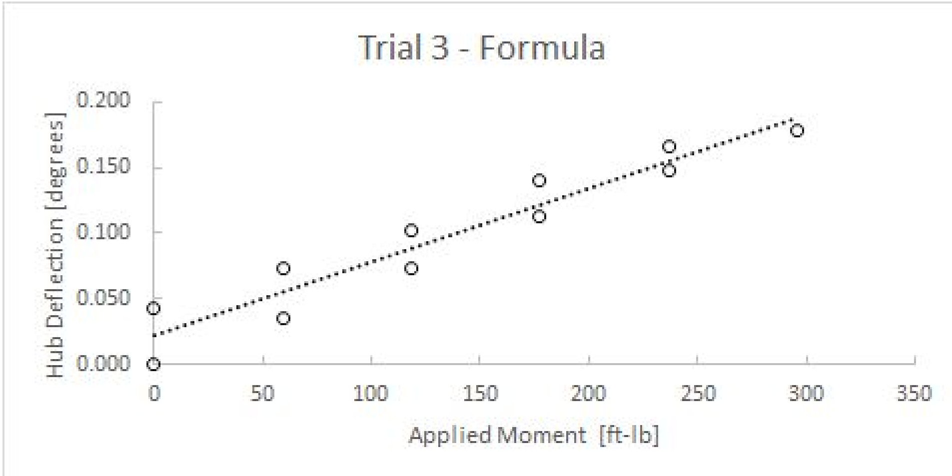


Figure 79. Stiffness of 1977 ft-lb/deg

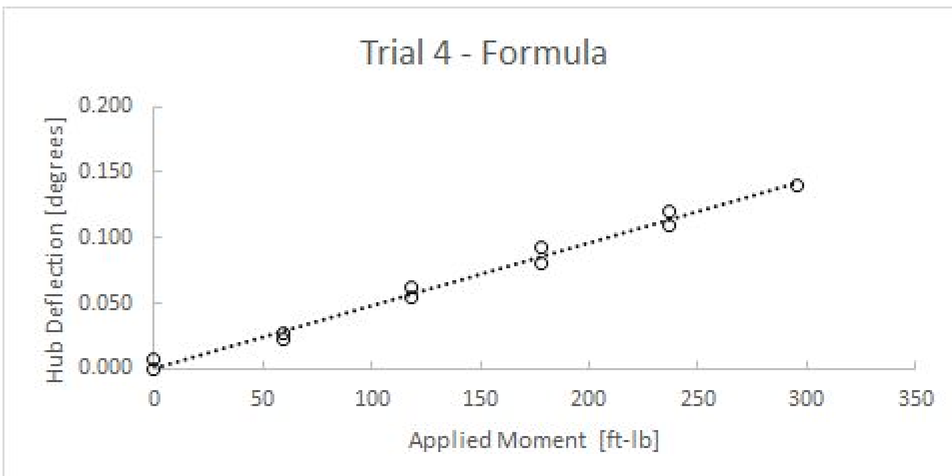


Figure 80. Stiffness of 2077 ft-lb/deg

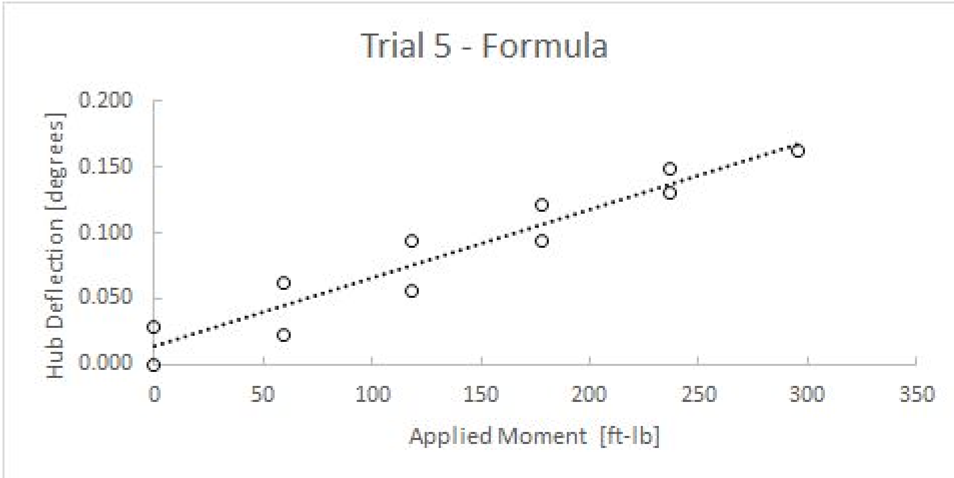


Figure 81. Stiffness of 1755 ft-lb/deg

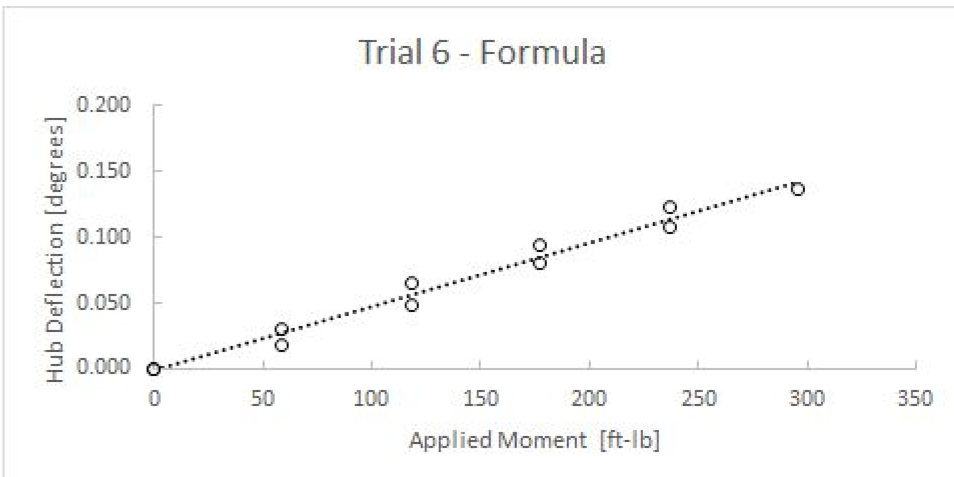


Figure 82. Stiffness of 2027 ft-lb/deg

The results from testing the Baja vehicle are shown below.

Table 14. Results from testing the Baja vehicle

Trial	Side loaded	Hub to hub stiffness [ft-lb/deg]
1	Right	1099
2	Right	1000
3	Right	1032
4	Left	1090
5	Left	1237
6	Left	1253

The plots for the Baja car torsional stiffness are very similar to that of Formula's. They can be shown in figures 77-82.

With these tests, we had a few objectives in mind:

1. Fitting the cars and basic functionality

Our main objective was to ensure that both cars (Formula and Baja) fit on the jig, and could be tested properly. This includes obtaining data for hub to hub stiffness, as well as chassis stiffness. We achieved this objective with a few minor hiccups which are discussed in another section.

2. Repeatability and consistency (precision)

We wanted to ensure that the test was repeatable and consistent. The first way we tested this was by running the test two times in a row with the same setup. This is to ensure that any given measurement will be similar to another, thereby eliminating the need to run the tests several times and collect an average. For this section of the analysis, we must disregard any of the "initial" trials, i.e., the first trial on one side, since this first measurement will have significant variability due to slop and unsettled components. Looking at the Baja car, trials 2 and 3 are 3.2% apart. Similarly, trials 5 and 6 are around 2.1% apart. Unfortunately, this does not fall within our initial goal of 2%. However, after additional consideration and discussion with chassis analysis and vehicle dynamics experts, we concluded that this is still an acceptable and useful range of precision - most Formula and Baja vehicles are not particularly sensitive to torsional stiffness changes within this range; generally a change of 50 ft-lbs would be considered negligible. And after seeing how small variability can affect results, we decided that a value closer to 5% precision may have been more realistic.

The second method we tested this was by disassembling the entire jig and reassembling it again. These results were a bit less conclusive, since we neglected to take slop out of the system before running the tests. Either way, the average of the two values (1891 ft-lb/deg) was within 5% of the average of the two other most closely representative trials, which were the 1st and 3rd trials (1811 ft-lb/deg). This is a good indication, but may require additional future testing to ensure an acceptable level of certainty.

3. Accuracy with respect to previous results

With the Formula car, we wanted to make sure our results were similar to the results from previous years. Specifically, the CP18C had a hub to hub torsional stiffness of approximately 1850 ft-lb/deg as determined in ANSYS FEA, as well as testing using the previous torsional stiffness jig to validate this value. With analyzing our data below, the final value for the torsional stiffness of our vehicle as measured by our jig was 2103 ft-lb/deg, which is 13% higher than the previously tested torsional stiffness. This value was calculated by taking the average of the 2nd and 4th trials (excluding all other trials for inaccuracies due to slop). This is much higher of a value that we hoped for, and is certainly not an acceptable level of accuracy. There are a few potential causes we think may be causing this discrepancy, the first being that the previous measurements were incorrect. The main potential source of error from the previous torsional stiffness jig was that the deflection of the rear of the jig was not accounted for. Deflection in this area would cause the measurements to seem like they are less stiff than they actually are. As mentioned previously, we eliminated this potential source of error by putting additional dial indicators on the rear of the car as well. If we had not done this, the final value would have been about 5% less stiff. While this does not account for the entire 13% difference, it may have had some influence. The second - and much more influential - source of error is in the dial indicator mounting deflection. We did not realize until after running the test on the Formula car, but the dial indicator mount experienced an amount of deflection, which will in turn cause the vehicle to seem stiffer than it actually is. To test and quantify this theory, we measured the deflection of the dial indicator at the expected reading change (~0.050”), and found it deflected around 0.003”. This equates to a total error of around 8%, putting us pretty essentially exactly at the expected 13% difference. The second issue of the dial indicator mount deflection was corrected during the Baja car test by shortening the extension of the mount arm, so this value should be more accurate.

4. Effects of slop

We wanted to additionally test the slop in the car, to determine if this has a significant effect on measurements. In the future, it may be necessary to account for this slop when running the test or interpreting data, by loading and unloading the vehicle before taking final measurements. For example, on the Formula vehicle, trial 3 (1645 ft-lb/deg) and trial 4 (2077 ft-lb/deg) were both loaded on the left side, yet there is a large (25%) difference in stiffness. One potential explanation for this is that there was slop in the system before/during trial 3 from being loaded on the right side immediately prior, which caused the vehicle to exhibit these characteristics. Another example of this is on the Baja car, trial 4 (1090 ft-lb/deg) and trial 5 (1237 ft-lb/deg), which is a 22% difference in stiffness. Again, both of these trials were run in succession, and the prior trial (trial 3) was performed on the other side of the car, meaning there may have been slop in the system before/during trial 4 which caused this discrepancy.

5. Loading the right side vs left side of the vehicle

Finally, when observing the data, we noticed that the Baja car exhibits different stiffness on the right as compared to the left side of the car. When loaded on the left side, the stiffness is 1245 ft-lb/deg and when loaded on the right it is around 1060 ft-lb/deg, which equates to a 15% difference. Our best explanation for this is, once again, slop in the system. What is referred to as "zero load" may actually be loading the car in one or the other direction, since the balance of the car will inevitably be tilted to one side or the other - in other words, the center of gravity of the car will be slightly offset from the rotational axis of the jig, causing the car to lean to one side when unloaded. This will in turn accentuate the effects of slop when loading one side of the car, while diminishing them on the other. While this is just a theory, it still needs to be confirmed for accurate results.

PURCHASING & ORDERING

We wanted to use all the resources we had available before we purchased any materials. Our budget was only $850 and we wanted to stay under that. We went through the Cal Poly Racing cages and were able to find some specific items and raw stock that we could use. With that, the below table shows the estimated cost values based on purchasing all new materials.

The ordered parts (not material stock) will all be coming from McMaster Carr, which has a quick lead time so we will be waiting until winter break to order components from there. The spec'd out material stock in Table 15 below will be ordered on November 26th, 2018 because OnlineMetals has a discount on that day for Cyber Monday.

Table 15. Preliminary Cost Evaluations

Component	Material	Thickness	Dimensions (in)	Quantity	Online Specs	Cost	Total Cost
I Beam	Steel	NA	60	2	6’	48.57	97.14
Waterjet Material	4130	0.125	4x4	1	18”x18”	65.48	65.48
Square Stock Rear	4130	0.125	4x4	2	1”x1”x12”	7.97	15.94
Adapter Plates	4130	0.125	4x4	1	18”x18”	65.48	65.48
Front Adapter Bolt	NA	5/8-24	1	1	Pack of 10	11.99	11.99
Circular Stock	4130	0.625	12	2	.625”x12”	5.74	11.48
I-Beam Bolt	Grade 8	5/16-18	1	1	Pack of 50	11.74	11.74
Level Feet	Zinc-Plated Steel	0.25	1	4	1-1/4" Long 1/4"-20 Threaded Stud	5.78	23.12
Bearings	N/A	0.625	1.125	8	Per	10.95	87.6
Rod Ends	Steel	0.625	4	4	Per	10.81	43.24
Wing Nuts	Grade 5	0.3125	0.5	1	Pack of 100	7.41	7.41
Wing Nuts	Grade 8	10-24	1	8		3.97	31.76
Jack	NA	NA	NA	1	NA	25.6	25.6
Scales	NA	NA	NA	1	NA	NA	NA
Dial Indicators	NA	NA	NA	3	NA	26.99	80.97
						Subtotal	**579.08**
						Total (1.25x)	**723.85**

A rough Bill of Materials was created once the design was finalized. Figure 83 below shows the bill, which includes the part, material for the part, size/dimensions, quantity, and source. As aforementioned, we tried to source as much as we can from what the team already had, whether that be scrap stock for jigs, I-beams that the team previously used for testing torsional stiffness, or old unused tubing that subsystems weren’t using for the cars this year.

Part	Material	Size	Quantity	Where
dial indicator supports	welded steel	random	N/A	misc. hangar stock
I-beams	steel	N/A	2	have
rear arm base supports	random steel	24" x 12" x 1" x 0.25"	1	online metals
rear arm square tube support	1018	2" x 0.125" x 3'	1	https://www.onlinemetals.com/merchar
lateral measuring jig square tube	1018	1" x 0.65" x 5'	2	https://www.onlinemetals.com/merchar
rear i-beam tipping support bar	1018	1" x 2" x 0.125", 1 foot long	1	https://www.onlinemetals.com/merchar
rear i-beam tipping support welded plate	1018	0.125" thick	N/A	hopefully find in hangar
main pivot shaft	4130	random length	3	https://www.onlinemetals.com/merchar
pivot assembly plate and lug	mild steel	12" x 24" x 0.25"	1	https://www.onlinemetals.com/merchar
hex stock	1018	0.6875", 2 ft long	1	https://www.onlinemetals.com/merchar
dial indicating rounds	stainless	0.25" OD, 0.049" wall, 3 feet	1	https://www.onlinemetals.com/merchar
adapter plates	6061 Al	0.25" thick		
front arm bases (has 2 slots)	random Al	4" x 4" x 1"	2	
x weld jig	random Al	done		
y weld jig	random Al	done		
bearings	-	-	2	
leveling feet	-	-	8	
Wing bolt	-	-	10	https://www.mcmaster.com/91404a540
Weld nut	-	-	10	https://www.mcmaster.com/90596a025

Figure 83. Rough Initial Parts List

The first big order made was from OnlineMetals. Since OnlineMetals has an annual Cyber Week sale (during the week of Cyber Monday), we capitalized on it and ordered during that week and got 25% off our total order. The order came out to about $200, much of which came from the shipping cost. The stock ordered from OnlineMetals is shown below in Figure 84. The order was sent to Mustang 60 since that is where many of the mechanical engineering student project shipments are sent.

ORDER NUMBER: 2345032 ORDER PLACED: 11-30-2018

item ▼	cut fee	price	qty	total
2" OD x 0.12" Wall A36 Hot Rolled Mild Steel Square Tube - 36"		$15.46	1	$15.46
1" x 2" x 0.12" A36 Hot Rolled Mild Steel Rectangle Tube - 12"		$6.16	1	$6.16
1" OD x 0.065" Wall A36 Hot Rolled Mild Steel Square Tube - 60"		$5.39	2	$10.78
1" Cold Finish 4130 Alloy Steel Normalized Round Rod - 11"	$1.50	$11.48	3	$35.94
0.6875" 1018 COLD ROLL STEEL HEX ROD - 24"		$7.63	1	$7.63
0.6875" 1018 COLD ROLL STEEL HEX ROD - 24"		$7.63	0	$0.00
0.25" OD x 0.049" Wall T304 Seamless Stainless Tube - 36"		$7.20	1	$7.20
0.25" A36 Hot Rolled Plate - 12" x 36"		$50.91	1	$50.91

Figure 84. Online Metals Order

Once ordered, the stock arrived to Mustang 60 in waves since different stock materials come from different warehouses nationally. The order was picked up once everything arrived and brought up to the hangar. The material was set aside until Cal Poly Racing's Build Week, and in the meantime, drawings were made as parts were finalized. The final cost of the OnlineMetal orders was $196.99.

~~sr-prj~~	Swivel Leveling Mount	6111K147	Swivel Leveling Mount	Swivel Mounts	https://www.mcm	$6.03	8	$51.74	$54.13
~~sr-prj~~	Low-Profile Mounted Sealed Steel B	5913K62	Low-Profile Mounted Sealed Stee	Bearings	https://www.mcm	$10.95	3	$35.23	$36.86
~~sr-prj~~	Steel Round-Base Weld Nut	90596A025	Steel Round-Base Weld Nut	Weld Nuts	https://www.mcm	$7.41	1	$7.95	$8.31
~~sr-prj~~	Zinc-Plated Iron Wing-Head Thumb	91510A153	Zinc-Plated Iron Wing-Head Thun	Wing Bolts	https://www.mcm	$13.20	1	$14.16	$14.81

Figure 85. McMaster Order

The last order we had to make was from McMaster-Carr. We got all our specialty nuts, bolts, and hardware from here. The McMaster order was fully sponsored by the team. Fasteners needed for this project were taken from the extra fasteners that Formula SAE had from overestimate ordering in years previous. The McMaster-Carr order final total was $114.13.

We had initially estimated that the dial indicators would be around $200. We submitted a MESFAC proposal for them and they fortunately were approved. This put the total cost of the project at $311.12. If the dial indicator cost would've been included, the total cost would have been $524.88. Our project cost estimate without taxes or shipping was $579.08, and $723.85 if those two things were factored in. We were fortunately under our estimated cost by about $200, under our initially budgeted estimate of $875; and fortunately a good portion of funding came from external sources.

RECOMMENDATIONS

After reviewing our progress and mistakes, some suggestions and improvements for further tests include the following in Table 16. Although we were happy with some areas that this jig significantly has improved from previous years, there are some areas that could need some improvement. Most of the detailed analysis was thoroughly analyzed in the testing section witbut here is a brief recap in the table below for simpler changes that could be made without further in depth investigation on the analysis for root cause.

As for the manufacturing, everything went very smooth and on point. The manufacturing just took longer than anticipated but that is usual. Only thing to comment on manufacturing would have been to have payed more attention to detail. Most of the changes would be with the fundamental design process and sources of error spoken to earlier.

Table 16. Basic Improvements and solutions

Problem	Errors	Solution
The dial indicator stands deflected about 0.003" at the range of measurement used	This caused the dial indicators to read smaller deflections than intended. This resulted in the final measurement being about 8% stiffer than it should have been.	We welded a thicker rod to help with some deflection. This would cause the cross section area to be thicker helping with the deflection (current solution) Other possible long term solutions include: -The addition of gussets on the support stands could help with deflection on the holders -Use shop magnets to help minimize the deflection -Fix the support stands to the floor via an insert in the ground
The I-Beam lifted off the ground during loading.	This places a limit on how much load can be put on the car.	-Add weight into the chassis to ensure the I-Beams do not lift (current solution) -Fix the I-beams to the Ground via set screws in the floor (potential solution)
Measurement device does not reach the full height of the Baja car. I.e., the Baja car was taller than the rod length so could not	This required us to take measurements at the bottom of the chassis behind the steering rack. Ideally we would want	Manufacture longer rods for chassis measurements to ensure that the support brace can reach the top of the tow.

reach forefront of chassis structure.	the measurement at the front of the chassis at the tow hitch since this will give the highest deflection of the chassis.	
Hardware not standardized.	Causes longer set up time with different tools for all the hardware.	Spend more money and order proper hardware rather then use the Formula old hardware.

CONCLUSION

Torsional stiffness is important to characterize the handling of any vehicle. To improve the design of each new SAE vehicle, we want to be able to validate our FEA calculations with real life testing for our own knowledge, to design better cars in the future, and for design judging at competition. To this end, our jig can be used to acquire useful data, including hub to hub torsional stiffness, as well as chassis torsional stiffness.

At the beginning of this project, we set out to develop a jig that could be run for all Cal Poly Racing vehicles in the past and future to test torsional stiffness. We decided to make design changes that would allow for variable track width, camber, toe and wheelbase to adapt to any car possible. We were able to overcome the different variations and create a jig that not only would yield a better methodology and set up but be more useful for teams understanding of torsional rigidity. We had a very detailed thought process for the test procedure and set up to ensure that our jig would be reliable and a good source for chassis data for any team in the future.

During manufacturing season, we were able to utilize the help of many members in Cal Poly Racing; and we were able to manufacture everything in-house. While we did run into minor hiccups that delayed our timeline, we were still able to complete all our tasks at hand by designing a jig and coming up with the methodology for torsionally testing the Cal Poly Racing vehicles.

Since there were a few hiccups during our manufacturing season, we started testing about 2 or 3 weeks later than expected. We were still able to test the 2018 Formula combustion car and the 2018 Baja car, but unfortunately was not able to test the 2018 Formula electric vehicle as the suspension of that car was taken apart to build the new cars. We were able to show that different cars could be tested on our jig and this was one of our main goals for this project. After looking at the data from the tests we ran, we saw some inconsistencies and lack of precision and repeatability. We have made suggestions on how we can potentially improve our measurements so that we can get the most accurate data possible.

Overall, we are happy with the final product and the work put into this project. We know that we set out to complete a task to help Cal Poly Racing and achieved that through our Torsional Stiffness senior project. We have set a benchmark for teams to further investigate the areas of improvement for chassis stiffness in years to come with our robust and simplified jig.

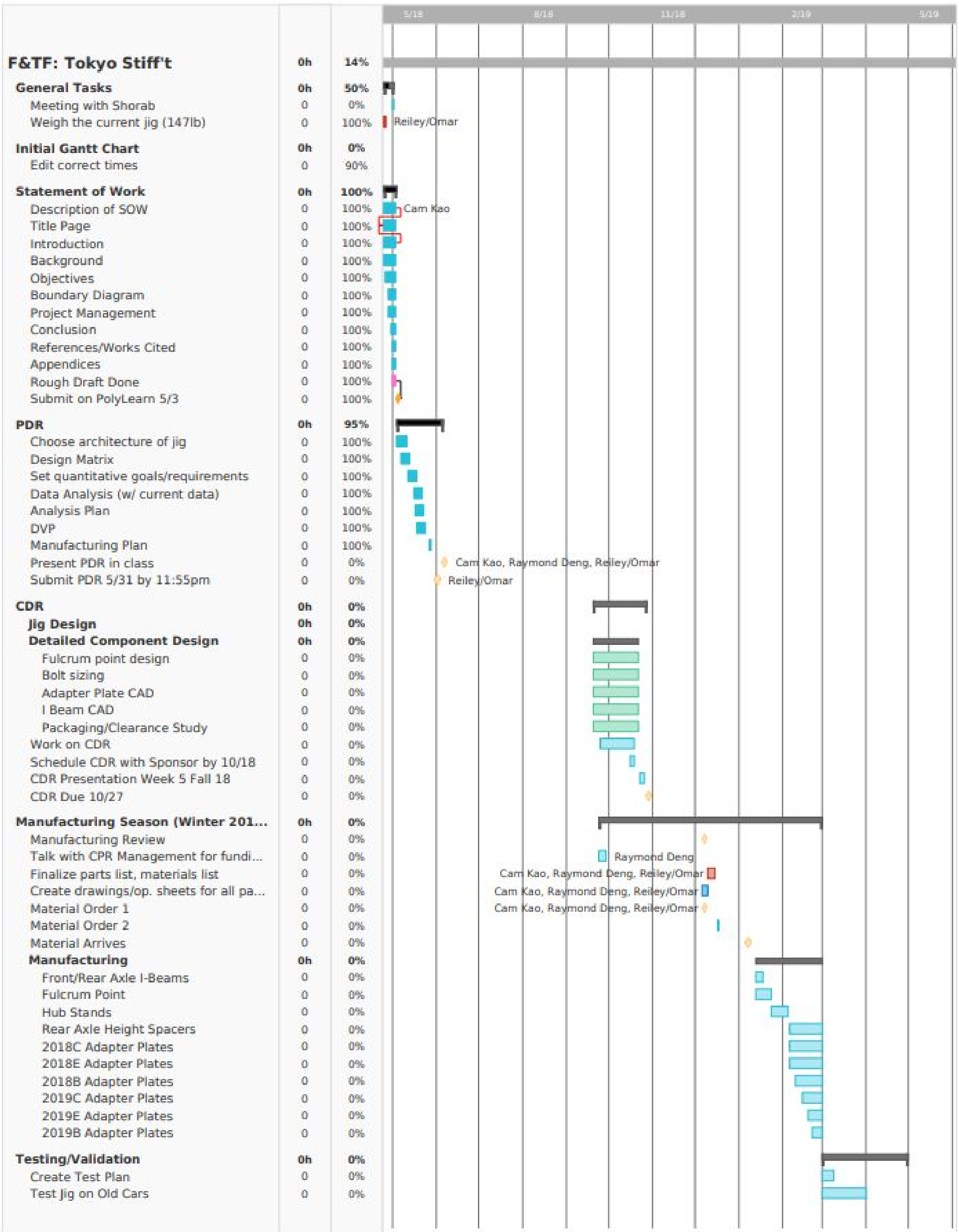
Table 17 outlines the specific requirements for our project. In the far right column we have determined that we have met all criteria from our original PDR goals to show that we have successfully completed our project.

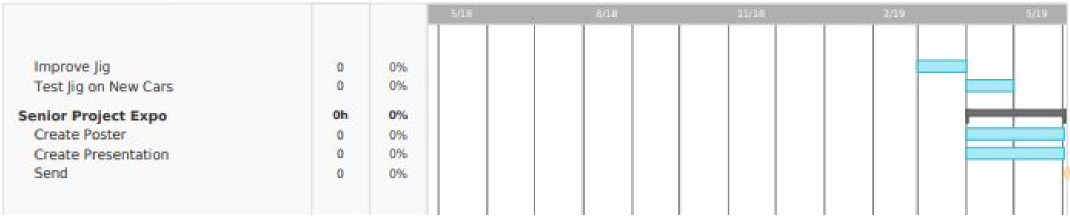
Table 17. Jig requirements and parameters.
*Requirement changed after revaluation, as discussed in the testing section

Parameter	Requirement	Tolerance	Risk	Compliance	Completed
Percent error	5%*	Max	H	T,S	Yes
Mobility	150lb per person	Max	M	T,I	Yes
Cost	$850	Max	H	A	Yes
Weight	300 lb	Max	M	T,A,S	Yes
Height of car	1 ft	Max	M	T,I	Yes
Assembly time	60 min	Max	H	T,I	Yes
Measurement points	3 points	Min	M	T,A,I	Yes

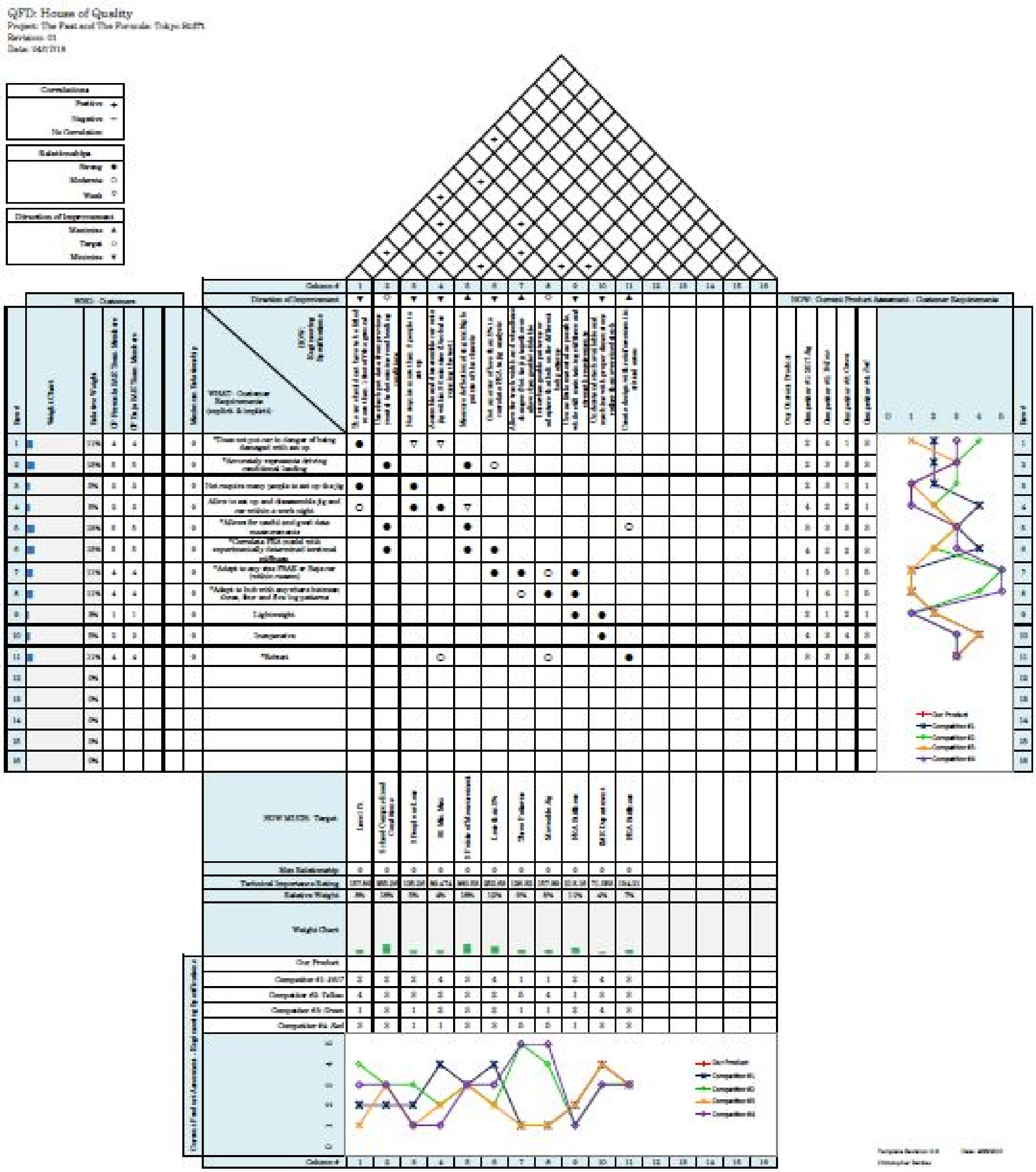
APPENDIX

Appendix A: Gantt Chart

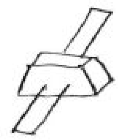
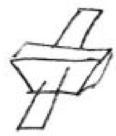
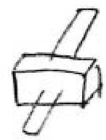
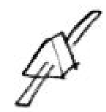



5/18
8/18
11/18
2/19
5/19
Improve Jig 0 0%
Test Jig on New Cars 0 0%
Senior Project Expo 0h 0%
Create Poster 0 0%
Create Presentation 0 0%
Send 0 0%

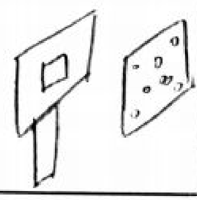
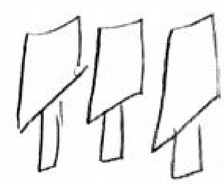
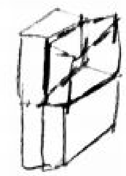
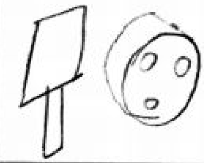
Appendix B: QFD



Appendix C: Fulcrum Pugh matrix

Concept / Criteria				N/A		
	1	2	3	DATUM	4	5
Manufacturing Difficulty	-	+	-	S	-	-
Design Challenge	+	+	+	S	-	-
Adjustability	+	+	+	S	-	-
Ease of Use	+	+	+	S	-	-
Balance	+	+	+	S	-	-
Presumed Accuracy	S	S	S	S	-	-
Σ+	4	5	4	0	0	0
Σ-	1	0	1	0	6	6
ΣS	1	1	1	6	0	0

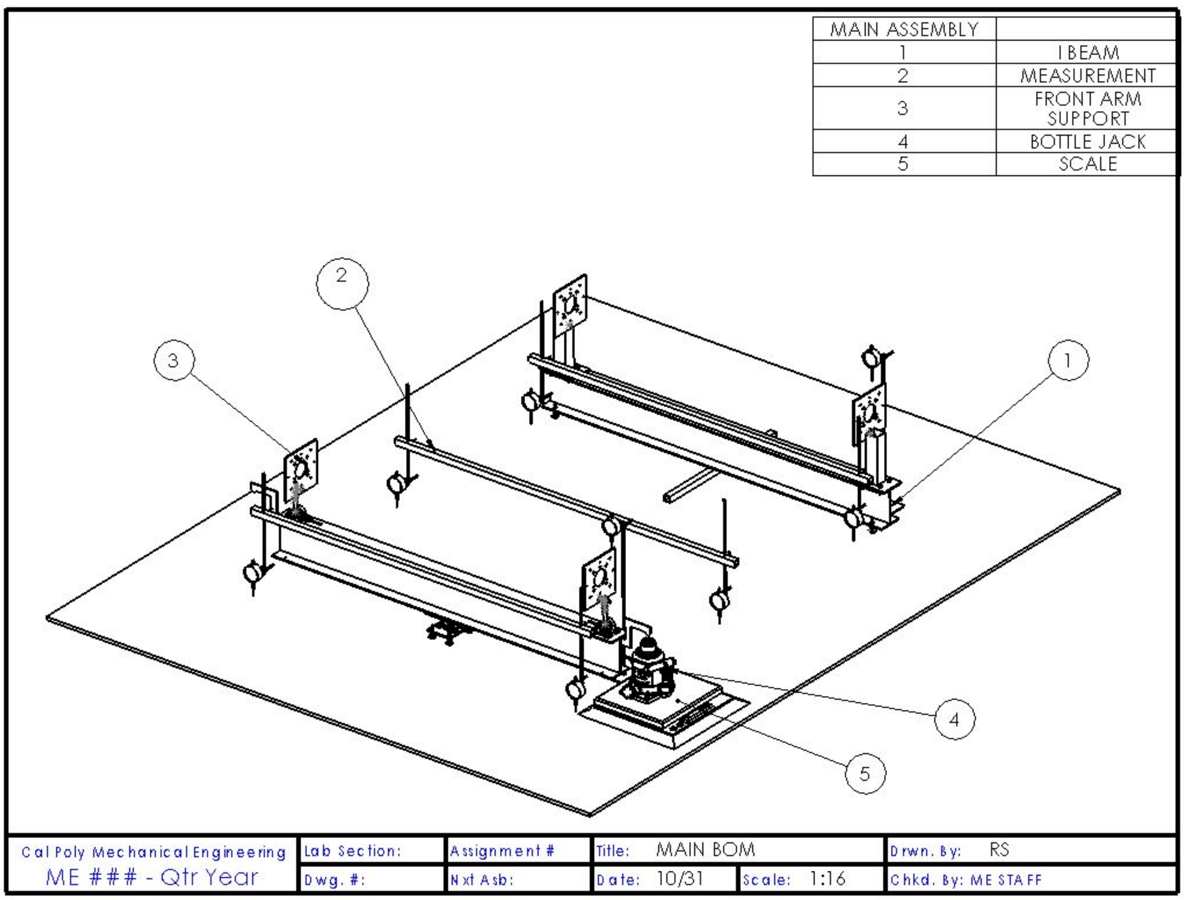
Appendix D: Hub pattern Pugh matrix

Concept				
Criteria	DATUM (Plate)	2 (Multiple)	3 (CNC)	4 (Adapter)
Manufacturing Difficulty	S	-	-	-
Cost	S	-	-	-
Weight	S	S	-	-
Ease of Use	S	S	+	S
Deflection	S	S	+	S
Dimensions	S	+	S	S
Σ+	0	1	2	0
Σ-	0	2	3	3
ΣS	6	3	1	3

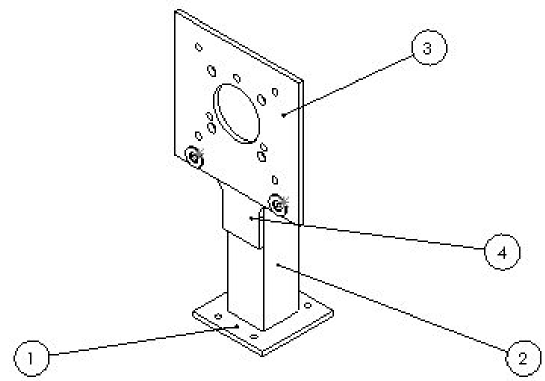
Appendix E: Assembly Drawings

NOTE - All individual drawings will be in a zip file attached as a PDF in the end of this report. If a part is a waterjet part, it will be specified on the drawings and the appropriate file location will be on Cal Poly Racing's data storage server GRABCAD. The location of theses file in the file server can be found here:

GrabCAD\Miscellaneous\Senior Project_Schraeger_Deng_Kao_Roman

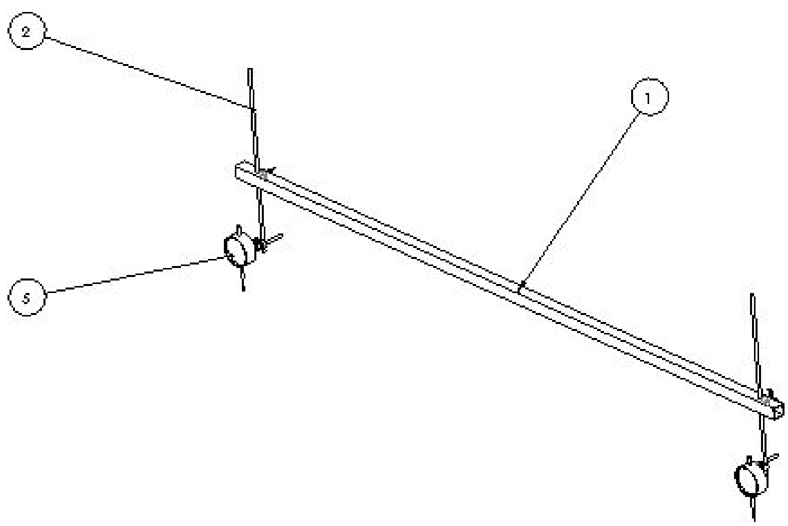


REAR SUPPORT ARM	NAME	QUANTITY
1	BASE	1
2	SUPPORT ARM	1
3	PLATE	1
4	MATING PIECE	1



Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: REAR SUPPORT ARM		Drwn. By: RS
ME ### - Qtr Year	Dwg. #:	Nxt Asb:	Date:	Scale:	Chkd. By: ME STAFF

MEASUREMENT	NAME	QUANTITY
1	BASE	1
2	SUPPORT ARM	1
3	DIAL INDICATOR	2



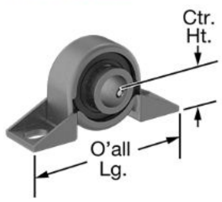
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: MEASUREMENT		Drwn. By: RS
ME ### - Qtr Year	Dwg. #:	Nxt Asb:	Date: 10/31	Scale: 1:8	Chkd. By: ME STAFF

Appendix F: Specification Sheets

Bearings

Low-Profile Mounted Sealed Steel Ball Bearing

for 5/8" Shaft Diameter



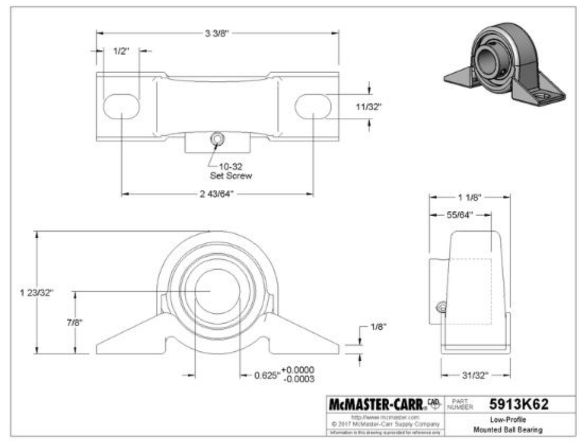
Each — ADD TO ORDER

In stock
$10.95 Each
5913K62

System of Measurement	Inch
Mounted Bearing Type	Base Mount
Bearing Type	Ball
For Load Direction	Radial
Housing Material	Steel
Bearing Material	Steel
Seal Type	Sealed
Inner Ring Type	Standard
Shaft Mount Type	Set Screw
Set Screw Thread Size	10-32
Number of Set Screws Included	2
For Shaft Type	Round
For Shaft Diameter	5/8"
ID	0.625"
ID Tolerance	-0.0003" to 0"
Center Height	7/8"
Overall	
Height	1 23/32"
Length	3 3/8"
Width	1 1/8"
Mounting	
Hole Length	1/2"
Hole Width	11/32"
Hole Center-to-Center	2 43/64"
Number of Holes	2
Fasteners Included	No
Radial Load Capacity, lbs.	
Dynamic	710
Static	3,500
Maximum Speed	5,800 rpm
Temperature Range	0° to 210° F
ABEC Rating	Not Rated
Alignment Style	Self Aligning
Misalignment Capability	3°
Lubrication	Lubricated
Lubricant	Grease with Lithium Thickener
Grease Fitting Included	No
RoHS	Compliant

Designed with a thin, compact housing, these bearings are good for space-constrained applications.

Bearings with steel housing are stronger than bearings with stainless steel and aluminum housings. They are self-aligning to compensate for shaft misalignment. Seals block out dust and contaminants.



The information in this 3-D model is provided for reference only. Details

Leveling Feet

Swivel Leveling Mount

Nickel-Plated Steel, Cushion & 1-1/4" Long 1/4"-20 Threaded Stud

Each

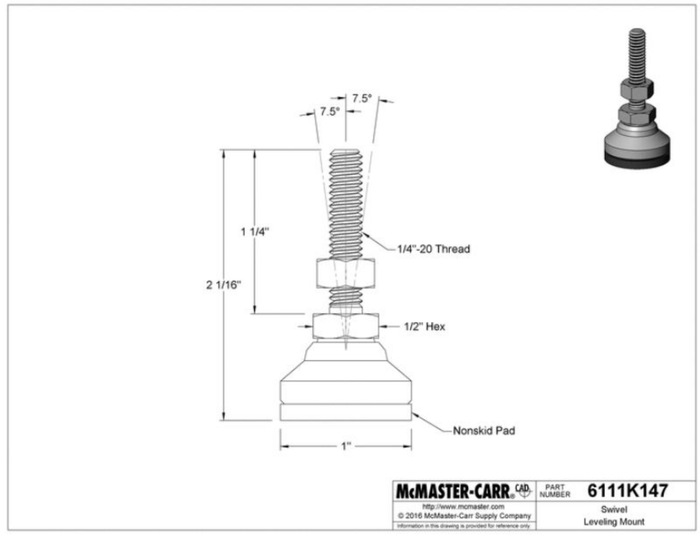
ADD TO ORDER

In stock
$5.78 Each
6111K147

Adjustability	Swivel
Mount Type	Threaded Stud
Thread Size	1/4"-20
Thread Type	UNC
Thread Length	1 1/4"
Capacity per Mount	750 lbs.
Swivel Range of Motion	7.5°
Base Diameter	1"
Overall Height	2 1/16"
Hex Nut Width	1/2"
Base Shape	Round
Base Material	Nickel-Plated Steel
Stud Material	Nickel-Plated Steel
Cushion Material	Black Rubber
Hex Nut Material	Nickel-Plated Steel
Temperature Range	-20° to 170° F
Includes	Locknut
RoHS	Compliant

Nickel-plated steel has some corrosion resistance. Mounts have a ball-and-socket design that swivels to compensate for uneven floors. In addition to leveling, mounts raise equipment off the floor for easier cleaning and inspection.

Mounts with a cushion are nonskid for an extra measure of stability.



The information in this 3-D model is provided for reference only. Details

Appendix G. Testing/Safety Procedure Document and Operating Manual

This document goes over the recommended testing procedure for testing the Formula SAE or Baja SAE vehicle on the torsional stiffness jig design in this report. Sections of this document that are highlighted in yellow will reference any part of the testing setup that concerns safety of the vehicles, and sections highlighted in green will reference any part of the testing setup that concerns the safety of the testing personnel. Time estimates and recommended number of people are also included at the end of each step.

The biggest concern with testing the Formula SAE and Baja SAE vehicles on this jig is the safety of the cars and the testing personnel. Please take caution when performing this test and follow all safety precautions and instructions listed in this document.

Formula SAE vehicle test procedure:

Pre-test Setup

1. Follow hangar safety rules. Wear safety glasses, long pants, and closed-toe shoes. If you have long hair, tie it up.
2. If this hasn't already been done so, change out the shocks on the car (2 front, 2 rear, 4 total) to dummy shocks (steel rods with rod ends).
3. Roll out the car to a flat section of the hangar. Ideally somewhere in front of the paint booth or in front of Cal Poly Steel Bridge's cage would work fine. (2 minutes, 1 or 2 people)
    a. Watch your feet when rolling the car out. You don't want to run your foot over.
    b. Be careful when moving the car around. Take extra precaution if aero is on the car.
4. Grab foam blocks from the testing cage and set them aside. (30 seconds, 1 person)
    a. Be careful to not throw the blocks around. The team does not have many of them.
5. Grab the parts for the torsion test jig and set them aside next to the car. (5 minutes, 2 people)
    a. I-beams
        i. These are heavy. May require both people to safely move them around.
    b. Hub Arms if they aren't attached to the I-beams already
    c. Wrenches
        i. 2x 7/16 wrenches/sockets
        ii. 2x 1/2 wrenches/sockets
        iii. 2x 9/16 wrenches/sockets
    d. Breaker bar
    e. Scissor jack
    f. Scale

g. Measuring equipment
    i. Measuring bars w/ dial indicators
    ii. Ratchet straps
    iii. Levels
    iv. Angle finders

Test Setup

1. Break the lug nuts loose while the car is on the ground (1 minute, 1-2 people)
    a. Lug nuts are a ⅜ long socket. Use a breaker bar.
2. Put the car on foam blocks. (1 minute, at least 2 people, 3 would be best)
    a. Lift up the front half of the car by the tires. Use your legs and not your back.
    b. Make sure whoever is lifting the car is relatively strong. There is potential for hurting themselves or the car.
    c. Place the front half of the car on a block as shown. The location of the block does not matter too much. Try to avoid bolts on the underside of the chassis as much as possible.
    d. Repeat 1a-1c for the rear half of the car.
        i. Note: The rear of the car is heavier due to the powertrain being in the back. Again, make sure whoever is lifting the car is relatively strong and capable.
3. Remove the wheels and set them aside. (2 minutes)
    a. If the lug nuts are not already broken loose, grab a hold of the wheel and break the nuts free.
        i. Be careful not to tip the car over.
        ii. Don't drop the wheels on yourself
    b. Be careful to not lose any of the lug nuts.
    c. Note that Figure X below does not have any of the suspension links attached to the chassis.

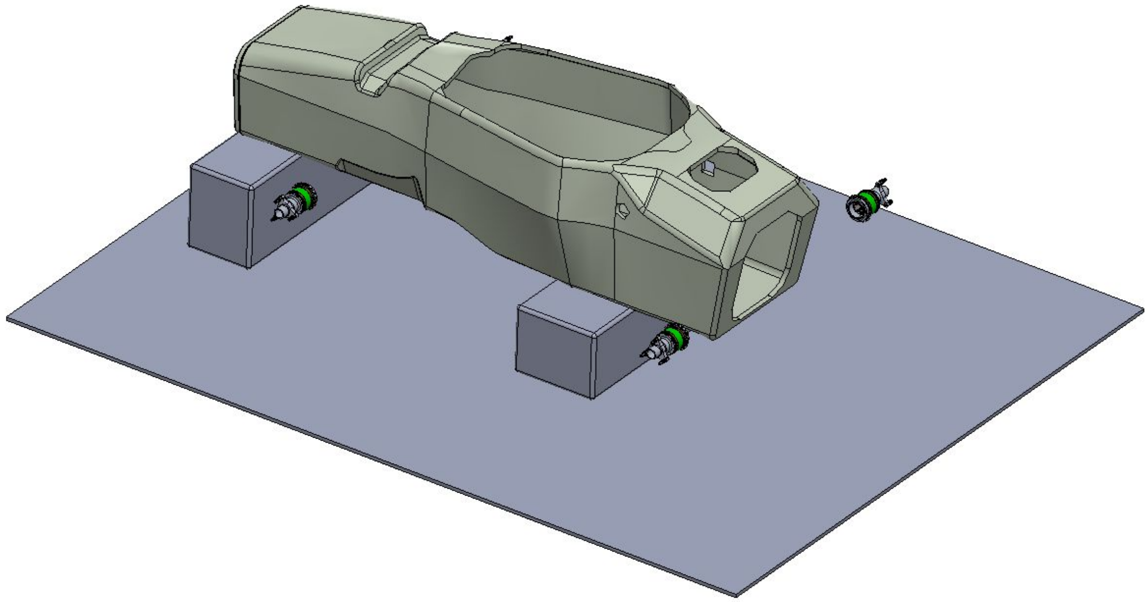


Figure G.1. Steps 1 and 2 completed.

4. Set up the rear I-beam assembly under the chassis and adjust the track width supports. (5 minutes, 2 people)
    a. Loosen the rear arm supports from the I-beam.
    b. Attach the hubs to the rear arm supports.
    c. Locate the hub arm supports laterally as best as possible, aim to center them on the beam.
        i. Note: The rear I-beam assembly does not need to be perfectly centered… but try to get it centered as best as possible.
    d. Tighten down the arms onto the I-beam.
    e. Throughout this process, be careful of pinching yourself when tightening/loosening bolts and nuts.

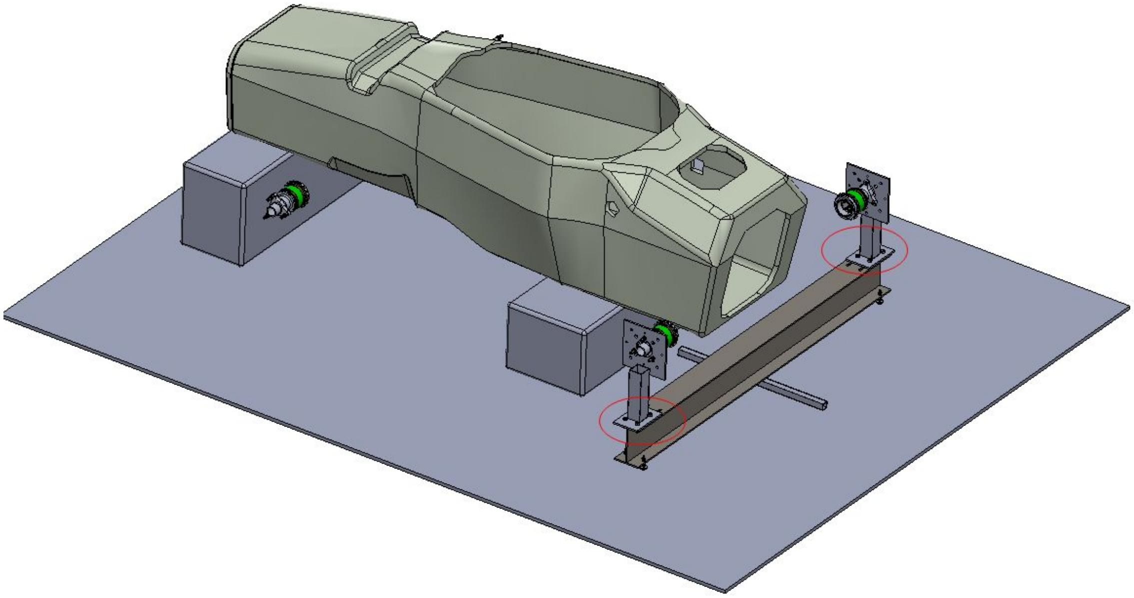


Figure G.2. Step 3 completed

5. Set up the front I-beam assembly under the chassis and adjust the track width supports. (10 minutes)
    a. Repeat steps 3a-3e but for the front I-beam assembly. For the front assembly, a lot more care has to be taken in centering the car about the fulcrum point. Use the etched centerline as a reference and the graduated increments on the track width slots to dial in the car in the center.

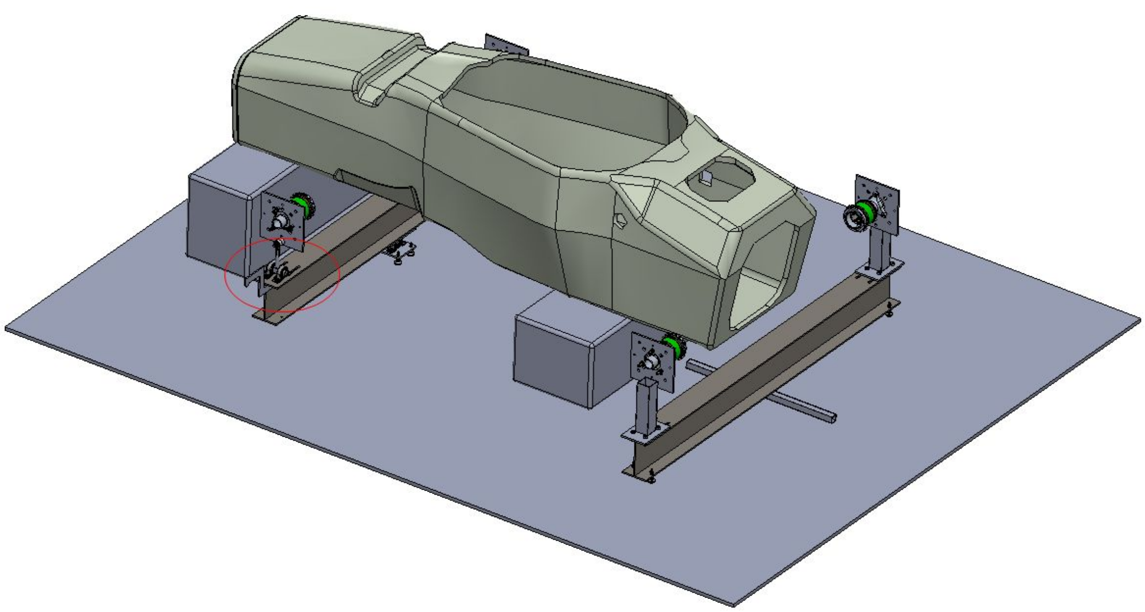


Figure G.3. Step 4 completed

6. Remove blocks
    a. Place a level on each of the I-beams
    b. Adjust the leveling feet on the front and rear until the I-beams are statically level
        i. When doing this, be careful to not tip the car over and watch for sharp edges on the I-beams.
7. Set up measurement devices & set up bottle jack (5 minutes)
    a. Set up the dial indicators on each hub.
    b. The measurement bars with the dial indicators will need to be strapped down to the chassis. Use the I-beams as datums to ensure that the measurement bars are perpendicular to the chassis.
        i. Careful to not damage the chassis or any wiring on the car. Use shop rags when possible to protect the paint/livery of the car.
    c. Set up the bottle jack on top of the scale under the load application points on the front I-beam assembly.

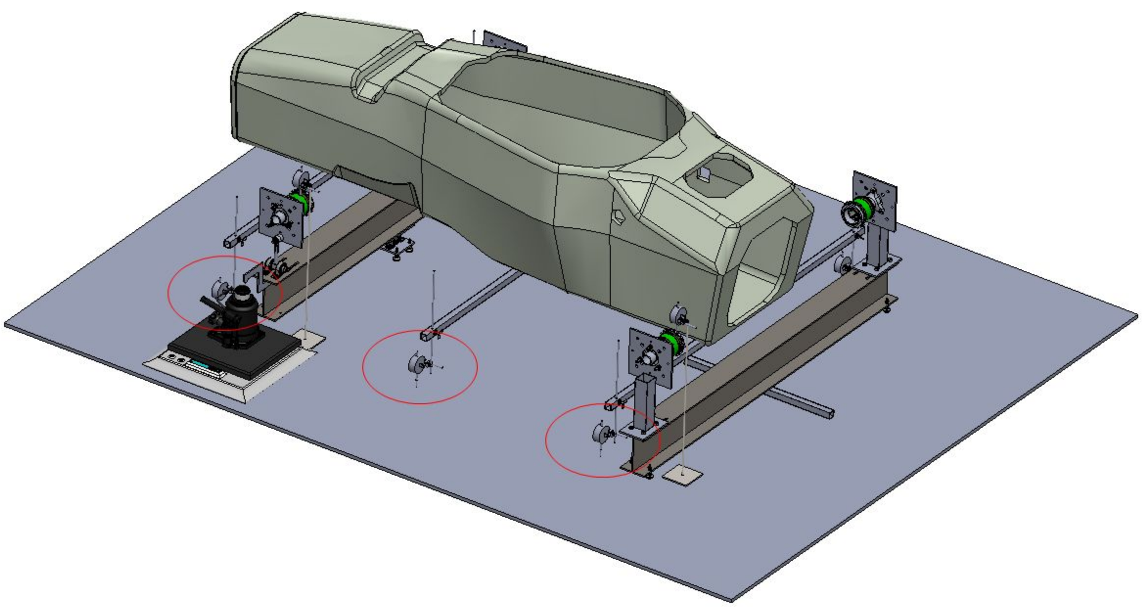


Figure G.4. Step 5 completed

8. Begin the test (20 minutes)
    a. Start applying load in small increments and measure the deflection in all the hubs after each increased load application.
    b. Take measurements while applying the load up until 200 lbs and when unloading the car.
    c. Repeat the same test on the other front hub.

9. Do the steps in reverse order to take the car off and put the wheels back on. (20 minutes)
10. Analyze results (No time estimate)
    a. Compare to FEA results of both cars.
    b. Find discrepancies and determine the root cause of them.
        i. Modify model
        ii. Modify test procedure
        iii. Modify test jig

The total estimated time for this test is 53 minutes. This includes setup, test, and teardown. In theory the test could be completed by just two people, but the more people to help the faster the whole process will go. In PDR we aimed to do the test in 30 minutes, but we did not account for disassembly time. Since then we have changed our goal to complete the setup, test, and disassembly all within 1 hour.

Appendix H: Schedule and Project Management

Table H.1. Updated Schedule

Date/Week	Task
F Week 5 - Sat	CDR Report Due
F Week 6 - Wed	Correction to CDR Complete
Phase 1	
F Week 6 - Fri	Finalize Stock in Hangar
F Week 6 - Sun	Finalize Drawings
F Week 7 - Tues	Material Orders Finalized/Placed
F Week 8	Slots in I-Beam
F Week 9	Waterjet plates on campus
F Week 10	Reevaluate manufacturing progress and plan for winter quarter
Phase 2	
Winter Break Week 1	Cal Poly Racing Build Week Goal: Have all machined parts complete I.E.: Waterjet Post Machine, I-Beam Slots, Anchor Tabs, Hex Bungs Tapped
W Week 1 T/R	Evaluate Winter Break Status Verify part manufacturing accuracy/tolerances
W Week 1 Weekend	Begin welding
W Week 2 T/R	Finalize Welding
W Week 2 Weekend	Individual Component Assemble Front Mounts, Rear Mounts, Fulcrum Point, Feet to I-Beam
W Week 3 T	Assemble Jig
W Week 3 R	Jig Compete Data
W Week 3 Weekend	Buffer to Complete
W Week 4 T	Reserved CPC18 Car to Test
W Week 4 R	Reserved CPE18 Car to Test
W Week 4 Weekend/ T	Evaluate any potential problems
W Week 5 R	Reserved Baja Car to Test
W Week 6-9	Report Writing and Updates to Jig as necessary
W Week 10	Report Due

We did not exactly follow the planned schedule, due to things that came up and limited waterjet access. A majority of our parts were waterjet so we needed time to do that. The CP18E car was the first car put on the jig itself, and it fit well. However, we needed to make some adjustments so the test was not performed on that car. Unfortunately, the Formula SAE team needed to take off all the suspension links to use the rod ends for the CP19E. So, we were unable to test the CP18E car We talked to Professor Fabijanic about it and he said it would be fine since we were still able to test the CP18C and the 2018 Baja vehicle. The CP18C was tested week 7 of winter quarter, and the 2018 Baja vehicle was tested week 8. We plan to test all three new cars - the CP19C, CP19E, and the 2019 Baja vehicle once they are completed. However, the results of that test will not be included in this report since it will be submitted before the new cars will be tested We do know that it will work well though since we've tested multiple cars already, and the worse case scenario is that new adapter plates would have to be machined.

Appendix I: Formula raw data

			FRONT				REAR				
			LEFT		RIGHT		LEFT		RIGHT		
Trial	Load side	Load [lb]	Hub	Chassis	Hub	Chassis	Hub	Chassis	Hub	Chassis	Hub to hub stiffness [ft-lb/deg]
		0	0	0	0	0	0	0	0	0	
		20	-0.0095	0.011	0.013	-0.012	0	0.002	0	-0.004	
		40	-0.0205	0.022	0.025	-0.025	0	0.005	0	-0.01	
		60	-0.0325	0.03	0.039	-0.038	-0.002	0.01	0.001	-0.015	
		80	-0.0445	0.039	0.052	-0.052	-0.002	0.017	0.002	-0.021	
		100	-0.0575	0.048	0.07	-0.068	-0.003	0.023	0.004	-0.026	
		80	-0.0515	0.036	0.066	-0.057	-0.003	0.022	0.004	-0.025	
		60	-0.0415	0.029	0.053	-0.045	-0.003	0.02	0.003	-0.021	
		40	-0.0305	0.02	0.042	-0.032	-0.003	0.016	0.003	-0.016	
		20	-0.0165	0.011	0.03	-0.018	-0.003	0.011	0.003	-0.011	
1	Right	0	-0.0055	0.002	0.015	-0.003	-0.002	0.006	0.003	-0.007	1977
		0	0	0	0	0	0	0	0	0	
		20	-0.005	0.01	0.007	-0.01	0	0.001	0	-0.002	
		40	-0.016	0.02	0.021	-0.023	-0.001	0.005	0	-0.006	
		60	-0.028	0.028	0.033	-0.036	-0.001	0.006	0	-0.01	
		80	-0.04	0.037	0.048	-0.049	-0.001	0.01	0.001	-0.015	
		100	-0.051	0.046	0.061	-0.064	-0.003	0.018	0.002	-0.02	
		80	-0.045	0.036	0.055	-0.053	-0.003	0.018	0.002	-0.018	
		60	-0.035	0.026	0.04	-0.04	-0.003	0.015	0.003	-0.014	
		40	-0.024	0.018	0.028	-0.027	-0.003	0.011	0.003	-0.01	
		20	-0.011	0.008	0.014	-0.013	-0.003	0.006	0.003	-0.005	
2	Right	0	0	0	-0.001	0.001	-0.002	0.002	0.003	-0.001	2130
		0	0	0	0	0	0	0	0	0	
		20	0.012	-0.012	-0.017	0.012	0	-0.002	0	0.003	
		40	0.028	-0.023	-0.032	0.025	0	-0.005	-0.0005	0.006	
		60	0.044	-0.038	-0.049	0.039	0	-0.01	-0.001	0.01	
		80	0.059	-0.048	-0.064	0.05	0.001	-0.014	-0.0015	0.014	
		100	0.074	-0.061	-0.076	0.062	0.002	-0.019	-0.0025	0.019	
		80	0.069	-0.05	-0.071	0.054	0.002	-0.017	-0.0025	0.017	
		60	0.058	-0.038	-0.06	0.045	0.002	-0.014	-0.0025	0.014	
		40	0.044	-0.025	-0.044	0.035	0.002	-0.01	-0.0025	0.01	
		20	0.033	-0.014	-0.03	0.024	0.002	-0.005	-0.002	0.005	
3	Left	0	0.018	0.002	-0.019	0.015	0.001	-0.001	-0.001	0.001	1645
		0	0	0	0	0	0	0	0	0	
		20	0.008	-0.009	-0.01	0.009	0	-0.002	0	0.002	
		40	0.023	-0.024	-0.023	0.021	0.001	-0.006	0	0.006	
		60	0.034	-0.033	-0.033	0.031	0.001	-0.01	-0.001	0.01	
		80	0.048	-0.044	-0.045	0.042	0.001	-0.015	-0.003	0.016	
		100	0.062	-0.058	-0.058	0.054	0.003	-0.02	-0.0035	0.019	
		80	0.055	-0.046	-0.049	0.045	0.003	-0.018	-0.003	0.018	
		60	0.043	-0.036	-0.039	0.036	0.003	-0.015	-0.003	0.015	
		40	0.028	-0.024	-0.028	0.025	0.003	-0.009	-0.003	0.011	
		20	0.014	-0.01	-0.014	0.015	0.003	-0.005	-0.003	0.006	
4	Left	0	-0.002	0.005	0	0	0.002	-0.001	-0.002	0.002	2077
		0	0	0	0	0	0	0	0	0	
		20	-0.009	0.011	0.009	-0.014	0	0.003	0	-0.003	
		40	-0.023	0.02	0.023	-0.028	0	0.006	0	-0.007	
		60	-0.037	0.026	0.041	-0.045	-0.001	0.01	0	-0.011	
		80	-0.051	0.037	0.057	-0.061	-0.002	0.014	0	-0.016	
		100	-0.065	0.041	0.072	-0.077	-0.005	0.018	0	-0.021	
		80	-0.059	0.032	0.067	-0.066	-0.005	0.017	0	-0.019	
		60	-0.047	0.022	0.057	-0.053	-0.005	0.014	0	-0.016	
		40	-0.038	0.016	0.043	-0.04	-0.005	0.012	0	-0.011	
		20	-0.027	0.007	0.029	-0.027	-0.005	0.007	0	-0.006	
5	Right	0	-0.013	0	0.014	-0.01	-0.004	0.003	0	-0.002	1755
		0	0	0	0	0	0	0	0	0	
		20	0.009	-0.012	-0.006	0.01	0	-0.005	0	0.006	
		40	0.021	-0.024	-0.019	0.022	0	-0.009	0	0.012	
		60	0.034	-0.035	-0.032	0.033	0	-0.014	0	0.019	
		80	0.048	-0.046	-0.044	0.044	0.002	-0.019	-0.002	0.024	
		100	0.062	-0.056	-0.054	0.046	0.001	-0.026	-0.004	0.03	
		80	0.056	-0.044	-0.051	0.045	0.002	-0.025	-0.005	0.029	
		60	0.045	-0.032	-0.04	0.035	0.003	-0.021	-0.005	0.026	
		40	0.032	-0.021	-0.029	0.025	0.003	-0.017	-0.005	0.022	
		20	0.018	-0.009	-0.015	0.014	0.003	-0.011	-0.005	0.019	
6	Left	0	0.005	0.003	-0.003	0.004	0.003	-0.006	-0.005	0.014	2027

Appendix J: Baja raw data

			FRONT				REAR				
			LEFT		RIGHT		LEFT		RIGHT		
Trial	Load side	Load [lb]	Hub	Chassis	Hub	Chassis	Hub	Chassis	Hub	Chassis	Hub to hub stiffness [ft-lb/deg]
1	Right	0	0	0	0	0	0	0	0	0	1099
		20	-0.019	0.031	0.021	-0.022	-0.001	0.003	-0.0055	-0.003	
		40	-0.046	0.054	0.041	-0.045	-0.001	0.006	-0.0015	-0.0055	
		60	-0.074	0.076	0.053	-0.07	-0.001	0.01	-0.003	-0.009	
		80	-0.098	0.102	0.081	-0.093	-0.001	0.013	-0.005	-0.014	
		100	-0.124	0.126	0.1	-0.119	-0.002	0.016	-0.007	-0.0185	
		80	-0.103	0.097	0.082	-0.097	-0.002	0.014	-0.0075	-0.0135	
		60	-0.083	0.067	0.065	-0.072	-0.002	0.011	-0.0075	-0.0105	
		40	-0.056	0.044	0.044	-0.042	-0.001	0.008	-0.007	-0.007	
		20	-0.031	0.019	0.026	-0.019	-0.001	0.005	-0.006	-0.004	
		0	-0.005	-0.005	0.007	0.003	-0.001	0.002	-0.005	-0.001	
2	Right	0	0	0	0	0	0	0	0	0	1000
		20	-0.024	0.027	0.023	-0.025	0	0.002	0.0015	-0.0025	
		40	-0.053	0.05	0.04	-0.05	0	0.005	0.0005	-0.006	
		60	-0.082	0.074	0.06	-0.075	-0.001	0.008	-0.001	-0.0105	
		80	-0.112	0.097	0.08	-0.099	-0.002	0.011	-0.003	-0.0135	
		100	-0.147	0.121	0.098	-0.127	-0.003	0.015	-0.005	-0.018	
		80	-0.124	0.099	0.079	-0.104	-0.003	0.013	-0.0055	-0.013	
		60	-0.102	0.077	0.061	-0.079	-0.003	0.01	-0.0055	-0.01	
		40	-0.075	0.053	0.041	-0.051	-0.002	0.007	-0.005	-0.007	
		20	-0.046	0.029	0.024	-0.026	-0.001	0.004	-0.0035	-0.003	
		0	-0.002	0.004	0	0	0	0.001	-0.002	0	
3	Right	0	0	0	0	0	0	0	0	0	1032
		100	-0.14	0.117	0.1	-0.126	-0.003	-0.036	-0.0025	-0.0175	
		0	0	0.001	0	-0.001	0	0	0	0	
4	Left	0	0	0	0	0	0	0	0	0	1090
		20	0.023	-0.024	-0.016	0.022	0	-0.003	0.0035	0.004	
		40	0.053	-0.052	-0.037	0.045	0	-0.005	0.004	0.007	
		60	0.081	-0.079	-0.058	0.07	0	-0.008	0.006	0.009	
		80	0.107	-0.105	-0.078	0.094	0	-0.011	0.007	0.0115	
		100	0.13	-0.13	-0.098	0.116	-0.001	-0.014	0.0085	-0.036	
		80	0.096	-0.095	-0.082	0.098	0.001	-0.013	0.01	0.0125	
		60	0.091	-0.086	-0.067	0.078	0	-0.011	0.0095	0.01	
		40	0.068	-0.061	-0.048	0.056	0.001	-0.009	0.0085	0.0085	
		20	0.046	-0.036	-0.028	0.035	0.001	-0.006	0.008	0.006	
		0	0.023	-0.014	-0.01	0.014	0.001	-0.003	0.007	0.004	
5	Left	0	0	0	0	0	0	0	0	0	1237
		20	0.021	-0.021	-0.015	0.019	0	-0.002	0	0.002	
		40	0.042	-0.046	-0.034	0.042	-0.001	-0.004	0	0.0045	
		60	0.064	-0.07	-0.052	0.063	-0.001	-0.007	0	0.007	
		80	0.087	-0.093	-0.068	0.084	-0.002	-0.009	0	0.0085	
		100	0.109	-0.118	-0.088	0.106	-0.003	-0.011	0.001	0.011	
		80	0.087	-0.095	-0.071	0.086	-0.002	-0.009	0.002	0.0085	
		60	0.068	-0.072	-0.055	0.066	-0.001	-0.007	0.002	0.006	
		40	0.046	-0.047	-0.037	0.045	0	-0.005	0.0015	0.0045	
		20	0.024	-0.023	-0.018	0.023	0	-0.002	0.001	0.002	
		0	0.003	-0.001	-0.0005	0.001	0	0.001	0	0.0005	
6	Left	0	0	0	0	0	0	0	0	0	1253
		100	0.106	-0.117	-0.0875	0.105	-0.003	-0.012	0.001	0.0105	
		0	0	-0.001	-0.0005	0.002	0	-0.001	0	0	

Appendix K: Design Hazard Checklist

Team: **Torsion Fixture** Advisor: **Fabijanic** Date: **May 29, 2018**

Y	N	
	x	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
	x	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
	x	3. Will any part of the design undergo high accelerations/decelerations?
x		4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
	x	5. Could the system produce a projectile?
x		6. Could the system fall (due to gravity), creating injury?
x		7. Will a user be exposed to overhanging weights as part of the design?
	x	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
	x	9. Will any part of the electrical systems not be grounded?
	x	10. Will there be any large batteries (over 30 V)?
	x	11. Will there be any exposed electrical connections in the system (over 40 V)?
	x	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
	x	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
x		14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
	x	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
	x	16. Could the system generate high levels (>90 dBA) of noise?
x		17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
x		18. Is it possible for the system to be used in an unsafe manner?
	x	19. For powered systems, is there an emergency stop button?
	x	20. 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.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Will the system have any large (>5 kg) moving masses or large (>250 N) forces? **Twisting actuation will be heavy, plus a 400 pound car.**	Strong supports for the car through the jig. Design for acceptable deflection, watch out for overturning moments. All calculations in report	09/23/18	3/14/19
Could the system fall (due to gravity), creating injury? **Jig can fail, not be constrained properly**	Design the jig for stability. Cannot have unwanted movement during tests. Blocks close to car in case of emergency	09/23/18	2/20/19
Will a user be exposed to overhanging weights as part of the design? **To be determined, as we have not decided on how we're going to load the car just yet.**	The way the current jig that the team has is loaded using overhanging weights. See detailed report for updated design.	09/23/18	2/25/19
Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design? **Lifting/jacking the car up to get it into the jig**	The car will have to be lifted up no matter what to perform a torsion test. A test procedure and safety procedure (attached) will be created to ensure that this is done right and safely.	01/06/19	3/15/19
Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use? **High humidity can rust steel. Unaffected by extreme temp conditions.**	Prime and paint jig to prevent rust and corrosion (thinking more long term).	11/01/18	2/20/19
Is it possible for the system to be used in an unsafe manner **-Someone trying to balance on jig. -Incorrectly setting up the jig(not secured right/bolted right)**	Ensure test plan has clear warnings in place, informing the user how to avoid injury. All potential trip hazards are colored in red..Simplify jig setup as much as possible.	12/07/18	2/29/19

References

[1] Track width drawing:
http://www.buildyourownracecar.com/race-car-handling-basics-and-design/
[2] 2017 Lincoln event guide:
https://www.fsaeonline.com/content/P1784888_FORMULA_lincoln_electric_guide_fe.pdf
[3] 2017 Michigan event guide:
https://www.fsaeonline.com/content/P1784258_formula_sae_michigan_event_guide_2017.pdf
[4] 2017-2018 Baja Sae Rule
http://bajasae.net/content/2018-BAJA-RULES-FINAL-2017-08-30.pdf
[5] Wheelbase drawing: https://carbiketech.com/wheelbase/
[6] Strut Bar: https://g35driver.com/forums/attachments/steering-suspension

Engineering Individual Drawings

NOTE - All individual drawings will be in a zip file attached as a PDF in the end of this report. If a part is a waterjet part, it will be specified on the drawings and the appropriate file location will be on Cal Poly Racing's data storage server GRABCAD. The location of theses file in the file server can be found here:

GrabCAD\Miscellaneous\Senior Project_Schraeger_Deng_Kao_Roman

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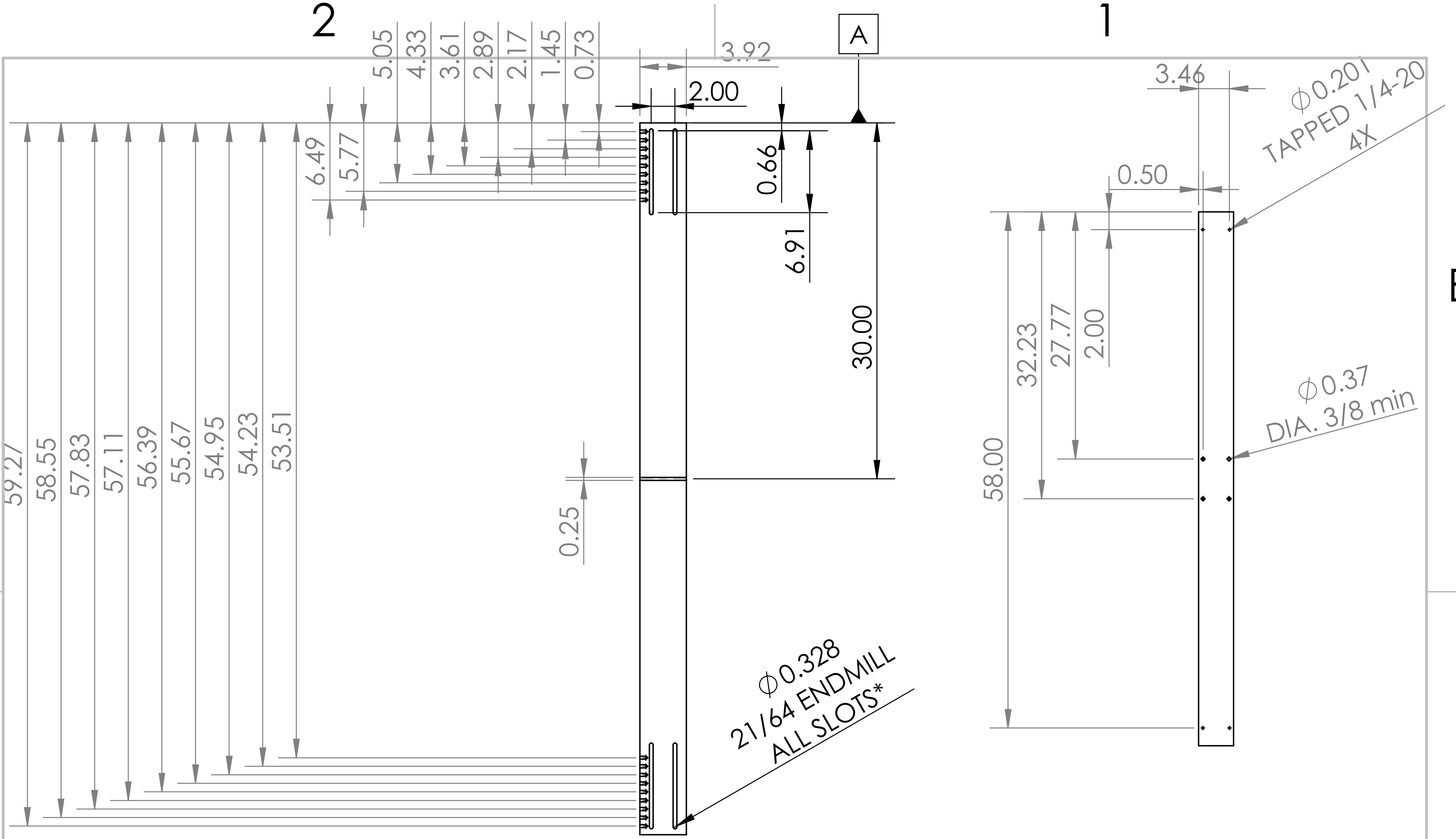

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PROPRIETARY AND CONFIDENTIAL

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WATERJET
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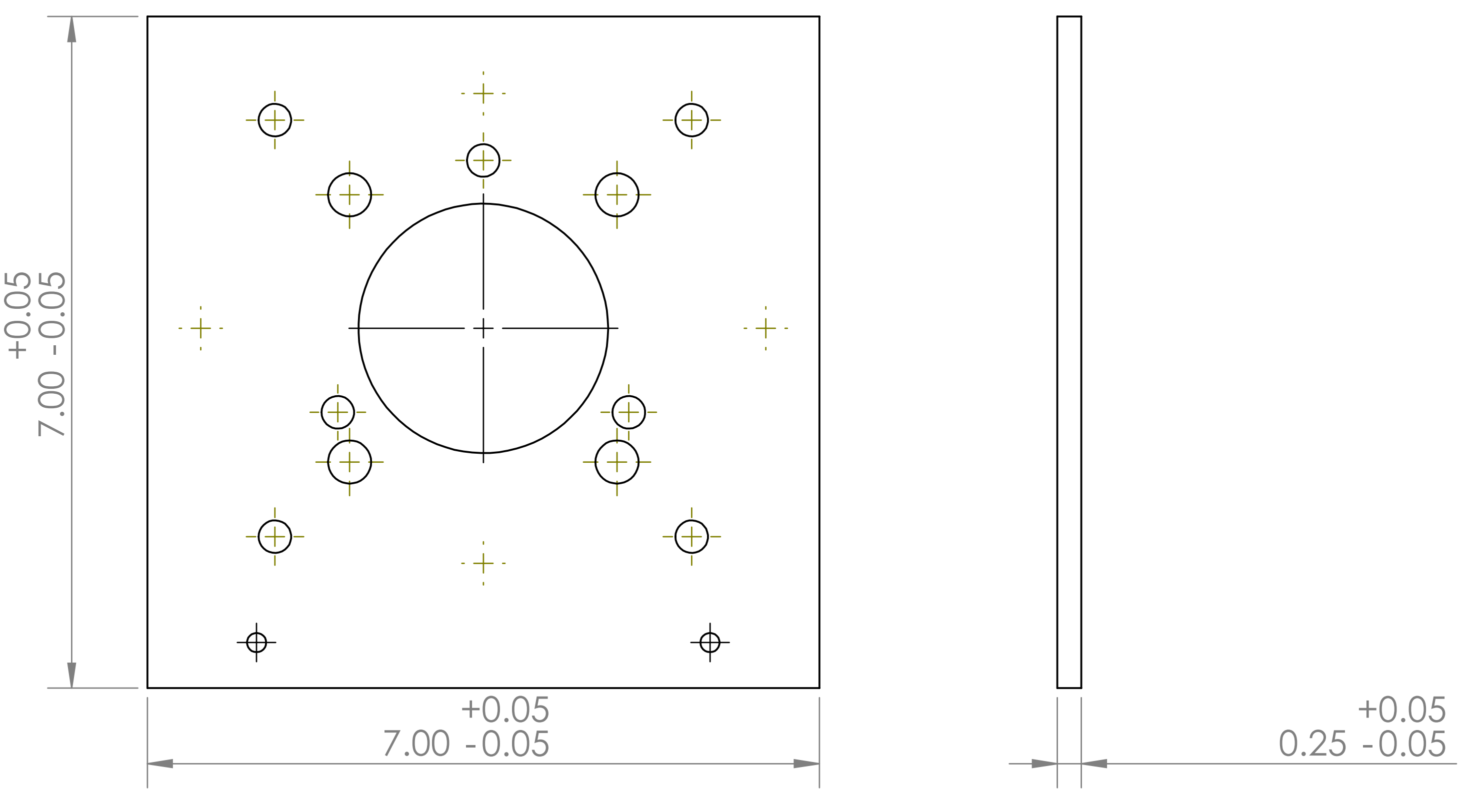

QUANTITIY 4

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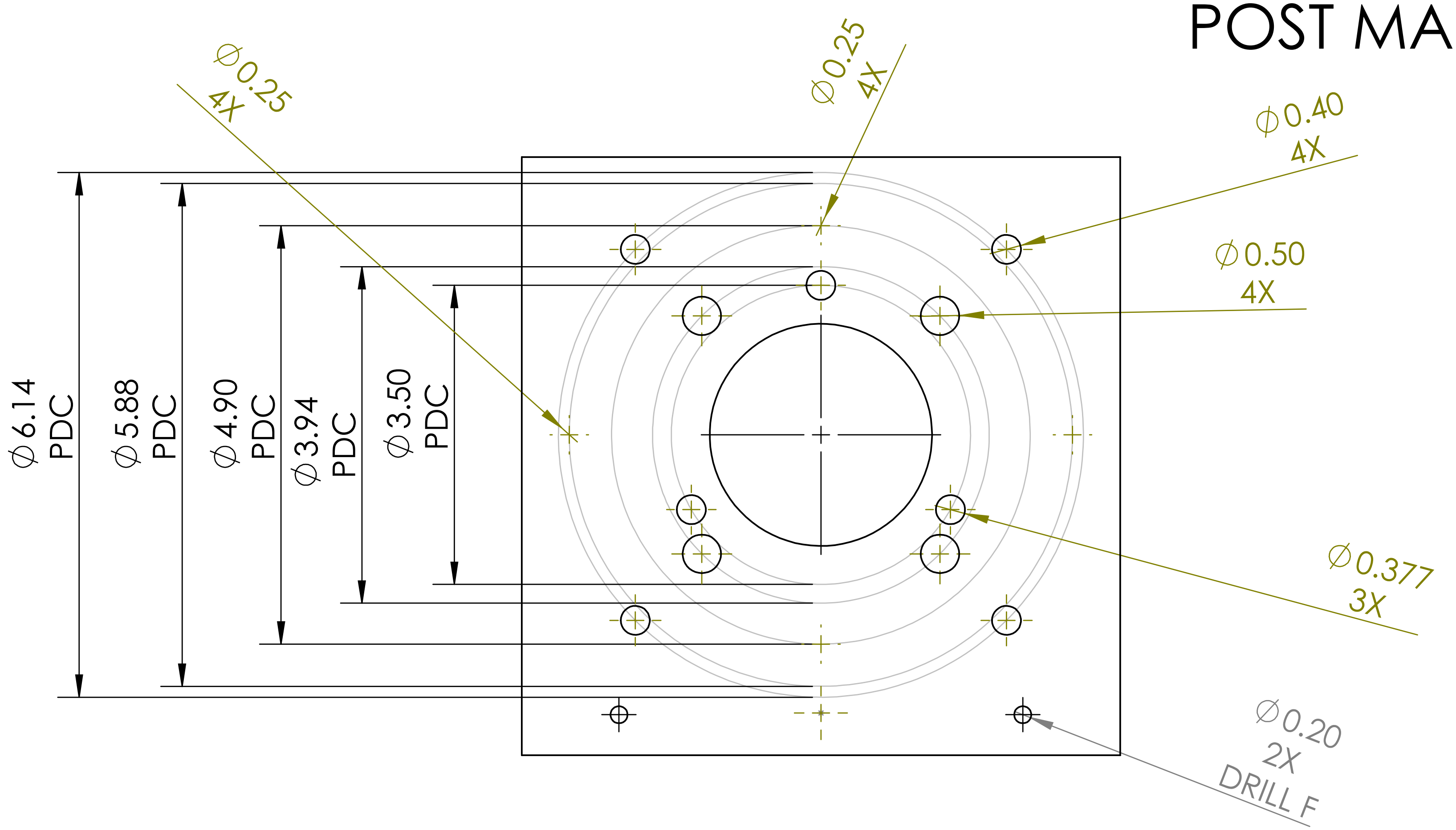

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			MFG APPR.			
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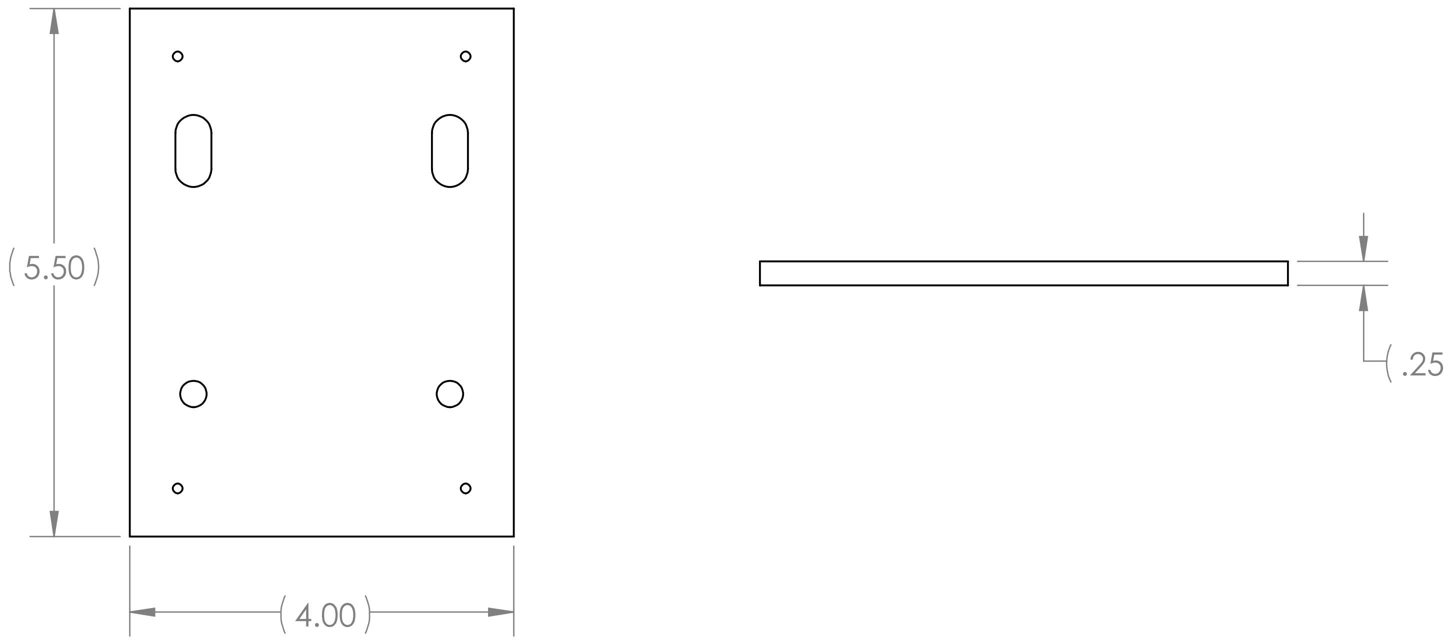
WATERJET
STOCK DIMENSION GIVEN



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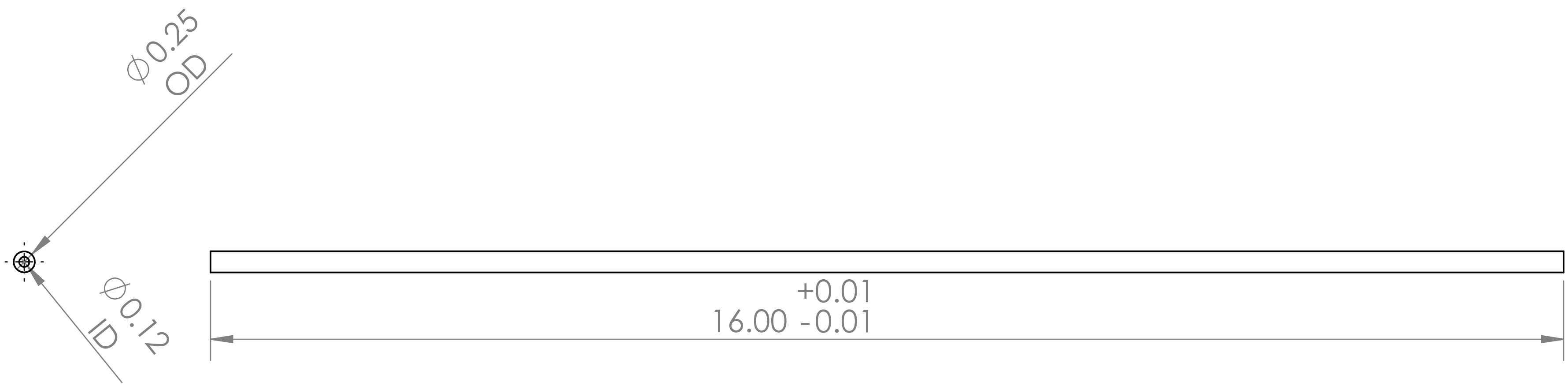
ME ### - Qtr Year	Dwg. #:	Nxt Asb:	Date:	Scale:	Chkd. By: ME STAFF



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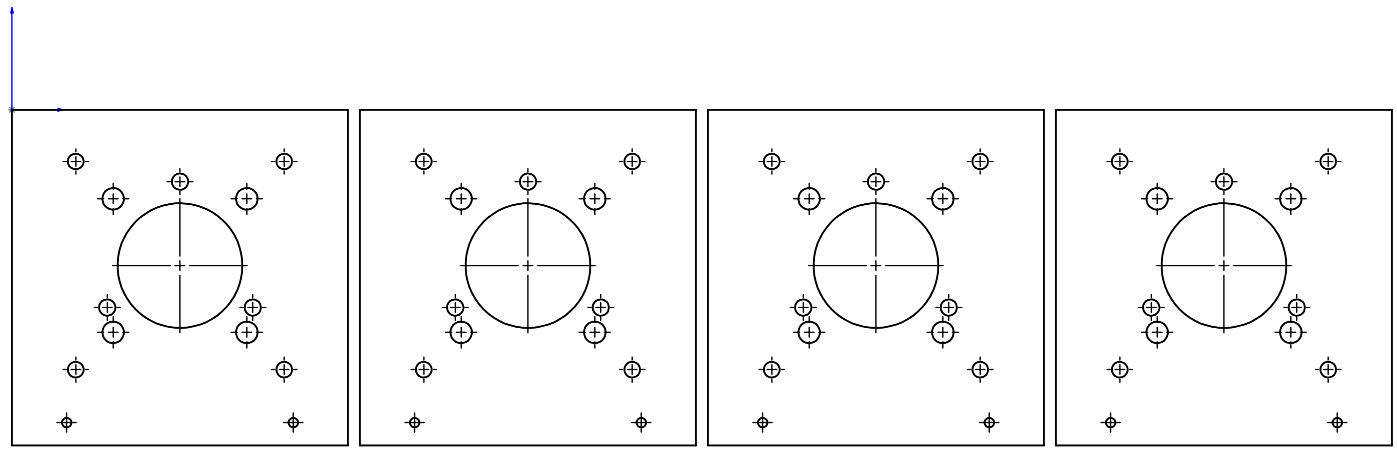
WATERJET PROFILE
QUANTITIY 4



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ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

TITLE: HUB ADAPTERS WATERJET

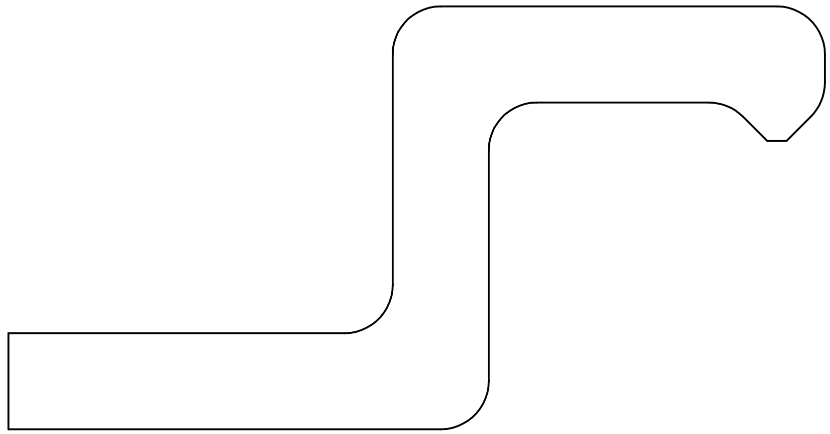
REV A

SCALE: 1:4 | MATERIAL: 6061-T6 | 1 OF 1

2 1

B B

WATERJET



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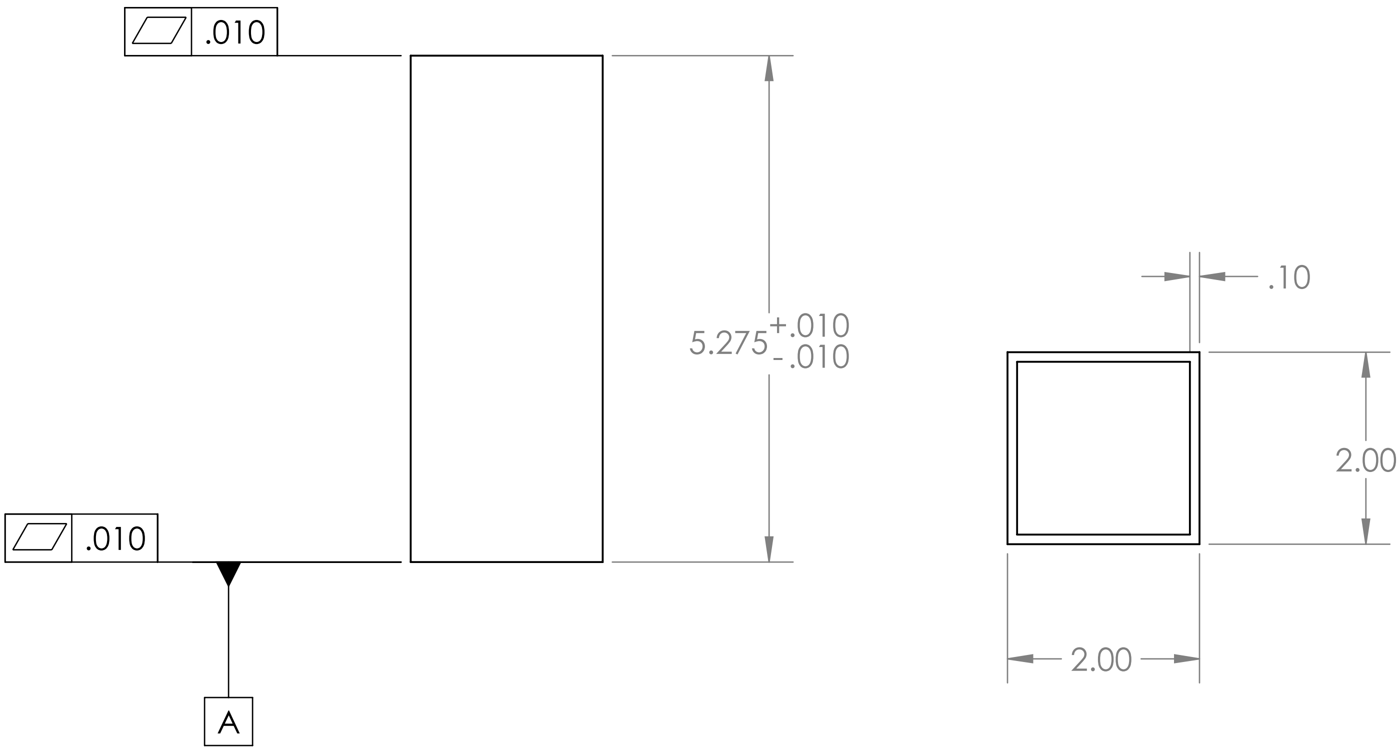

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	Dwg. #:	Nxt Asb:	Date:	Scale:	Chkd. By: ME STAFF

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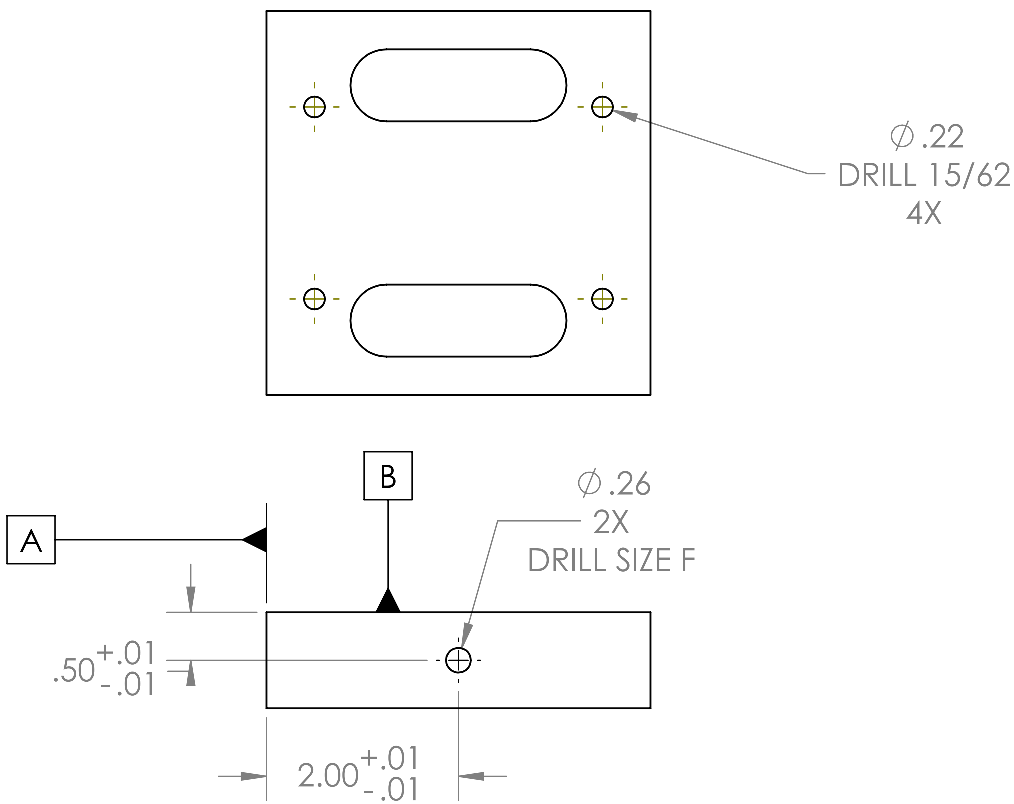

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	SCALE: 1:2	MATERIAL: 6061-T6	1 OF 1

CAL POLY RACING SAN LUIS OBISPO

Drawn By:	Cameron Kao	Start Date:	
Checked By:		Requested End Date:	

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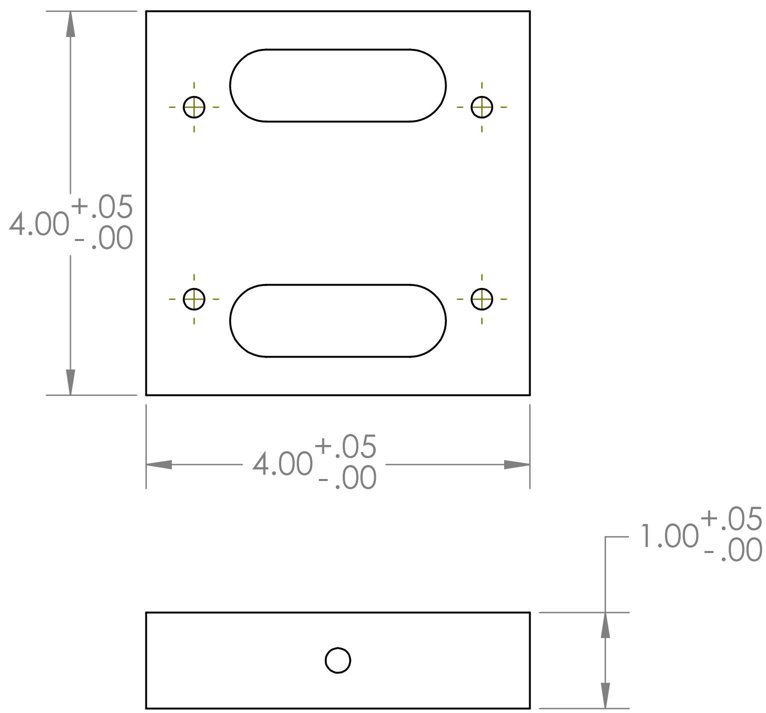

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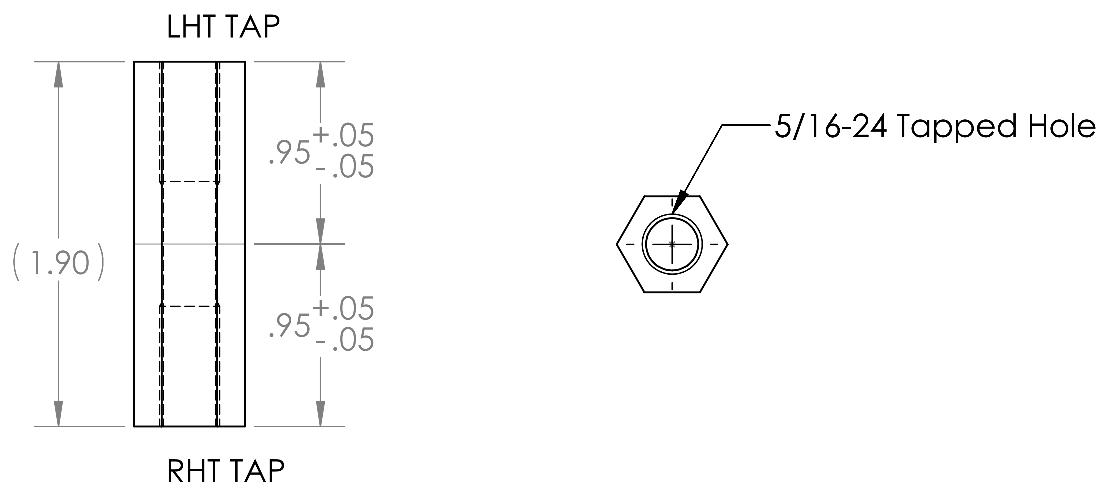
ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

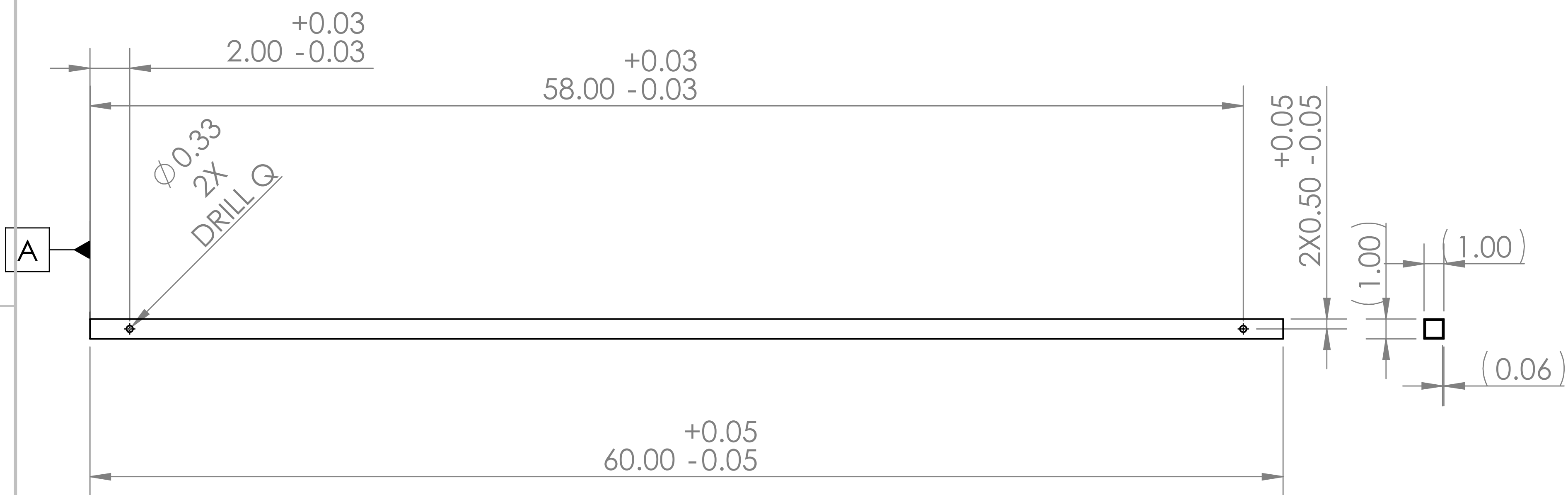
TITLE: Jig arm base		REV AA
SCALE: 1:2	MATERIAL: 6061-T6	1 OF 1



Cal Poly Mechanical Engineering ME ### - Qtr Year	Lab Section:	Assignment #	Title: FRONT SUPPORT TURN BUCKLE		Drwn. By: RS
	Dwg. #:	Nxt Asb:	Date:	Scale:	Chkd. By: ME STAFF

2 1

B B



A A

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FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

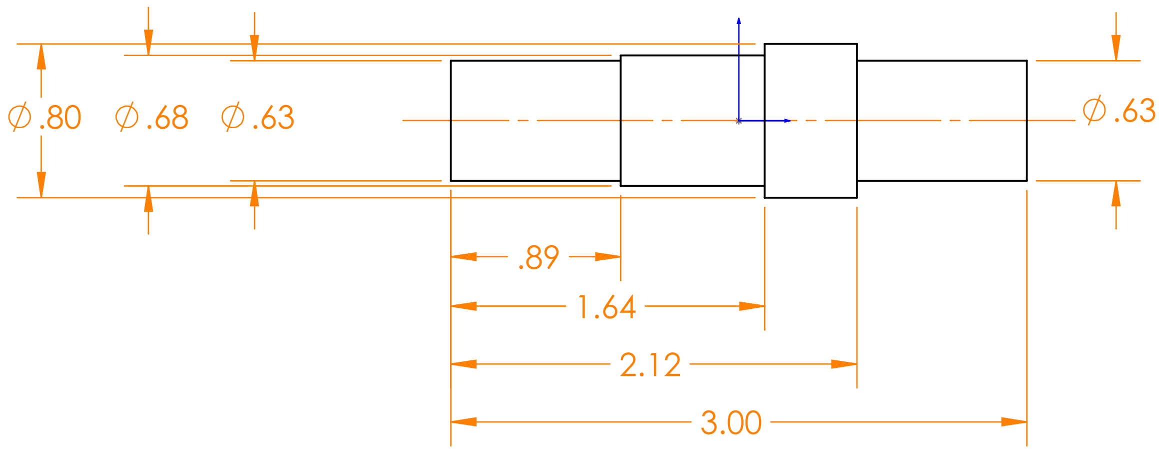
TITLE:

Measurement Arm

SIZE **A** DWG. NO. REV

SCALE: 1:16 WEIGHT: SHEET 1 OF 1

2 1



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Checked By:	NOT YET CHECKED	Requested End Date:	

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ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

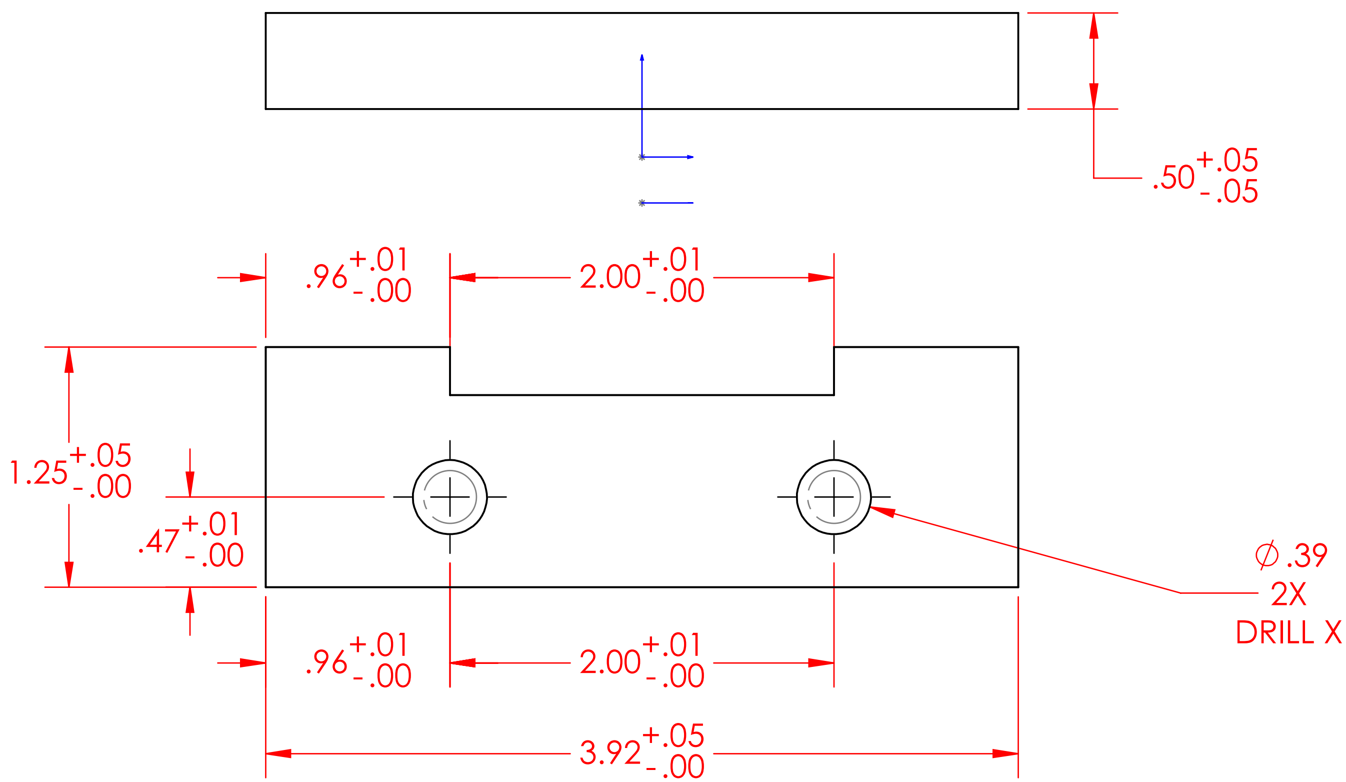
TITLE: MAIN PIVOT SHAFT

REV AA

SCALE: X:X

MATERIAL: 1" OD 4130 ROUND

1 OF 1



CAL POLY RACING
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Checked By:		Requested End Date: xx/xx/xx		SCALE: 1:1 / MATERIAL: xxxx xx	1 OF 1

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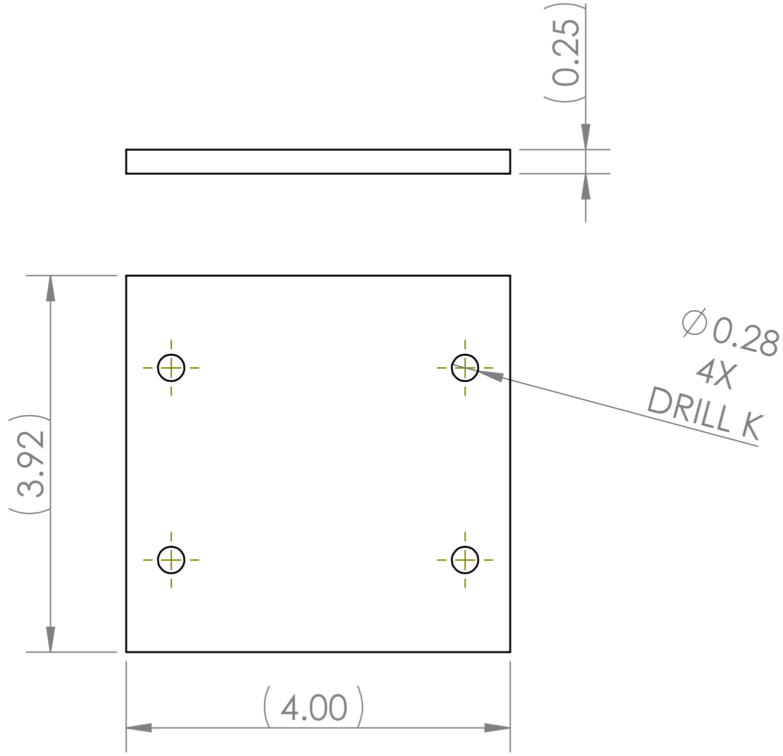

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			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			Rear Base Plate POST MACHINE
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE A / DWG. NO. / REV
NEXT ASSY	USED ON	FINISH				
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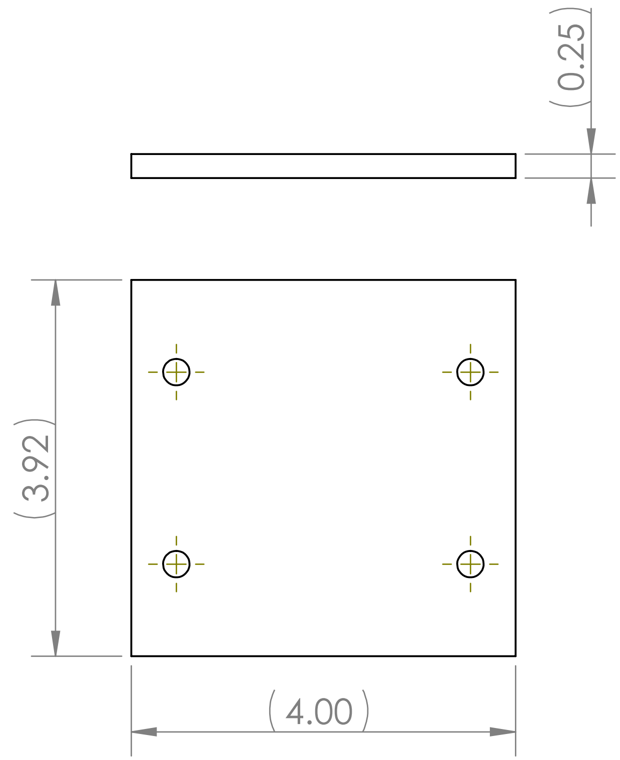

QUANTITIY 2

WATERJET PART
STOCK DIMENSIONS GIVEN AS A REFERENCE

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	RS	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

Rear Base Plate

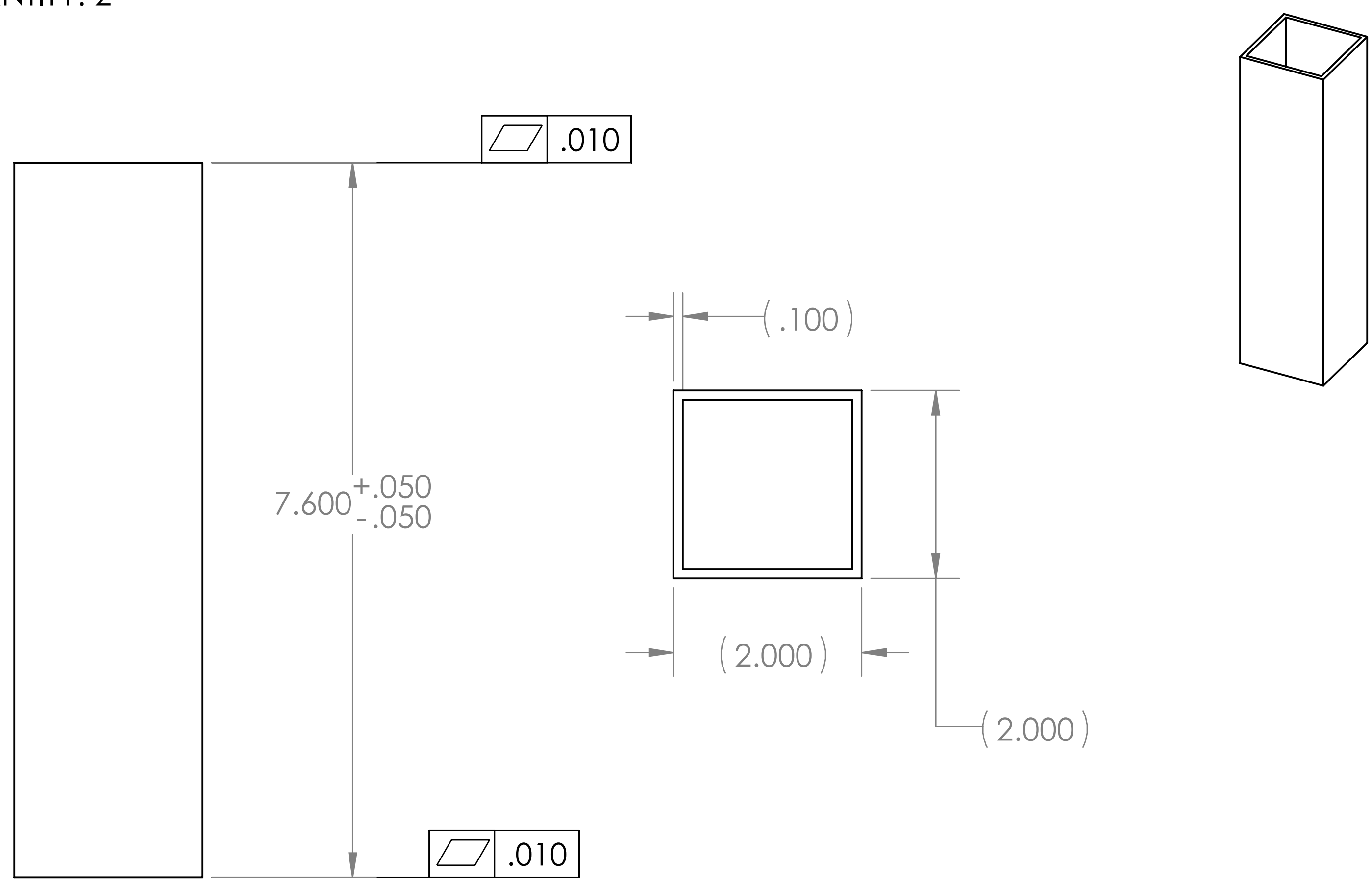
SIZE A | DWG. NO. | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

NEXT ASSY | USED ON

APPLICATION

QUANTITY: 2



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			MFG APPR.			
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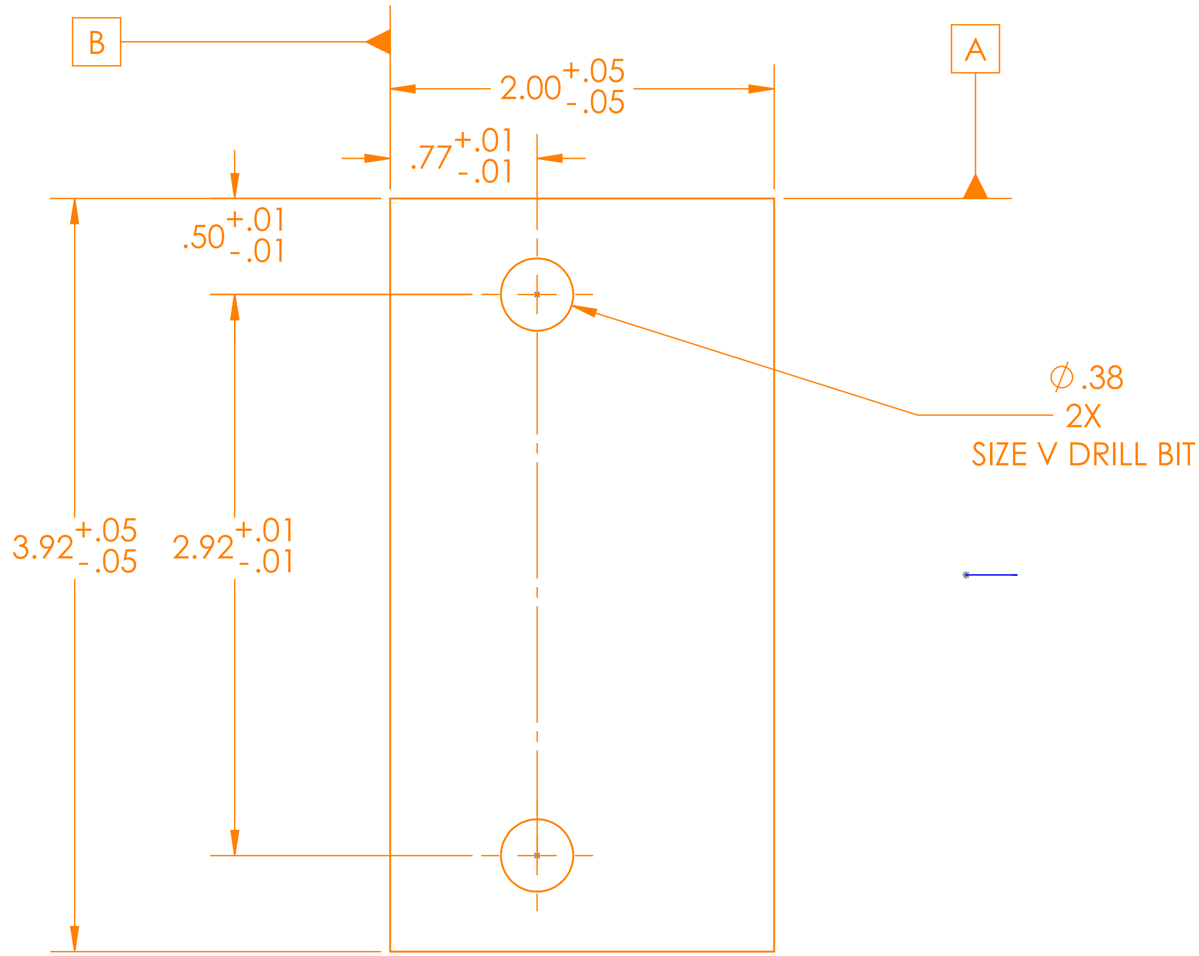

CAL POLY RACING SAN LUIS OBISPO

Drawn By:	RAYMOND DENG	Phone #:	(858) 436-6081
Checked By:	NOT YET CHECKED	Requested End Date:	

QUANTITY TRACKING:

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ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

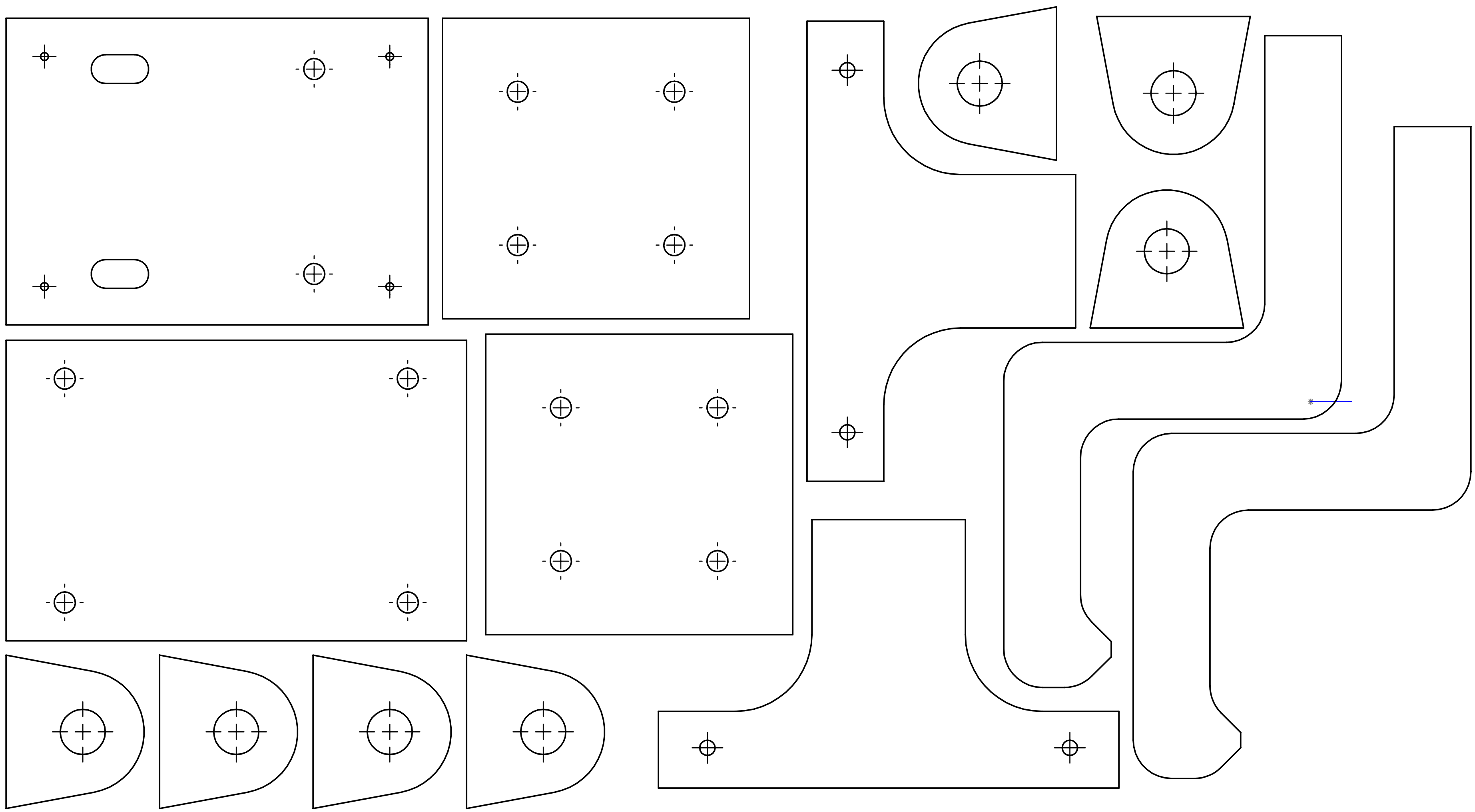
TITLE: LUG PLATE WELD JIG X

REV AA

SCALE: 1:1 MATERIAL: 6061

1 OF 1

WATERJET PROFILE



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TITLE:	STEEL WATERJET		REV A
SCALE: 1:2	MATERIAL: A36 HR STEEL		1 OF 1

CAL POLY RACING SAN LUIS OBISPO

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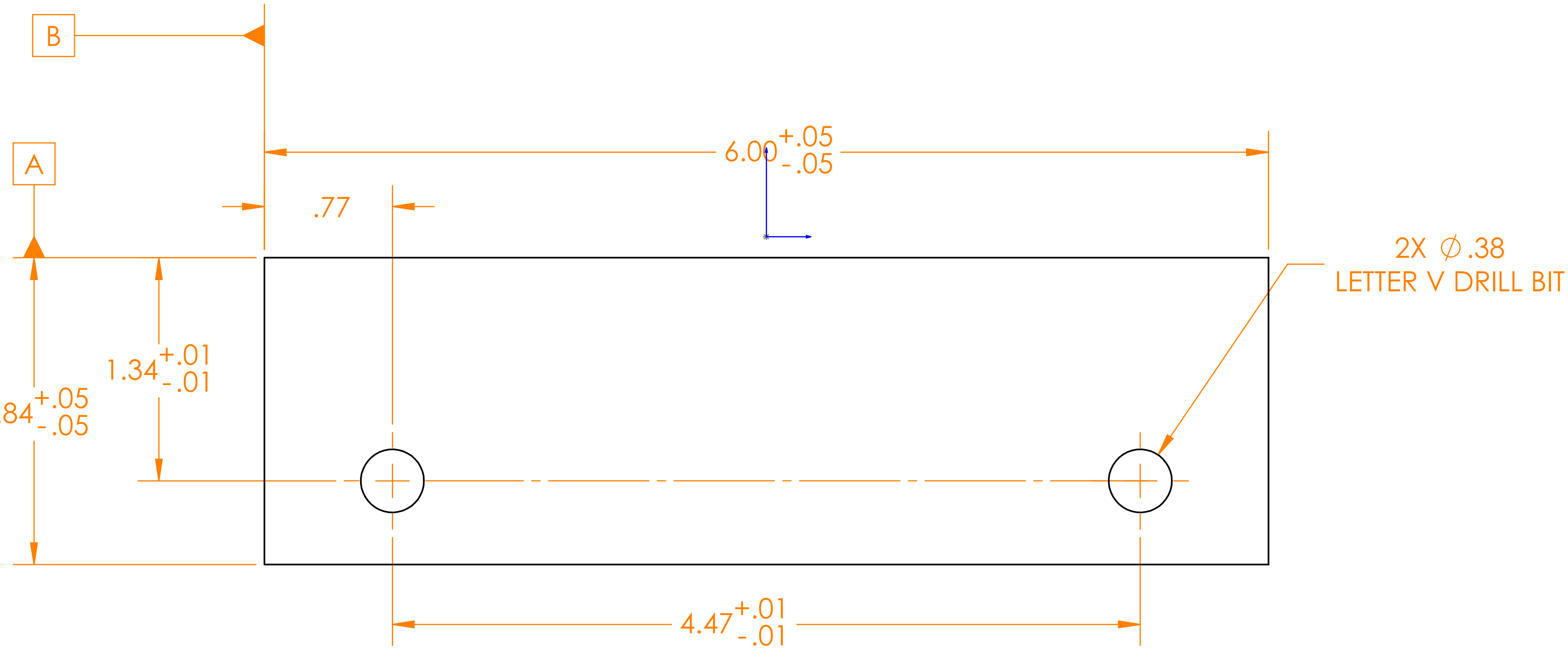

CAL POLY RACING SAN LUIS OBISPO			
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Checked By:	NOT YET CHECKED	Requested End Date:	

QUANTITY TRACKING:

TOTAL QUANTITY NEEDED:	QTY. MADE:	DATE:	INITIALS:
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UNLESS OTHERWISE SPECIFIED:

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ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL: ± 0.05
THREE PLACE DECIMAL: ± 0.005
TOLERANCING PER: MMC

TITLE: LUG PLATE WELD JIG Y

REV AA

SCALE: 1:1 MATERIAL: XXXXXXXX

1 OF 1