MEMORANDUM

TO: DR. JOHN TESTER
FROM: TEAM 01
SUBJECT: SAE MINI BAJA FRAME
DATE: DECEMBER 13, 2013

This is the final proposal for the SAE Baja Frame Team. We compared different sizes and material of tubing and decided to build the frame out of AISI 4130 steel with a 1.250 inch diameter and a 0.650 inch wall thickness. The analysis of the frame proves that the frame can withstand several tests while keeping the driver safe. The drop test analysis determined that after a 10 foot drop it will hold with a yield factor of safety of 5.32 and a max deflection of 0.089 inches. The front collision analysis resulted in a factor of safety of 2.90 and a 0.135 inch maximum deflection. The rear impact analysis showed a yield safety factor of 1.45 and a deflection of 0.263 inches. The side impact analysis showed a yield safety factor of 1.01 and a deflection of 0.363. This may seem low, but this is for yield. 4130 steel as a significant plastic region after yield. A tab shear simulation was done to determine if the tabs that hold various parts of the vehicle such as the suspension and seatbelts would fail. None of the tabs failed after being subjected to large forces that would most likely not be seen during vehicle operation. The team was within the design targets for the constraints and needs of the frame and safety. The projected total cost for the frame team to build and go to competition is. $1994.50. The theoretical production cost of 4000 frames a year is $2,252,146.67. The schedule for next semester is to complete the frame by the end of January, finish the complete vehicle by the end of February, start testing in March, and go to competition April 24th.

SAE Mini Baja Frame

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Project Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

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Nomenclature

F = Force [lbf]

m = Mass [slug]

V_0 = Initial Velocity [ft/s]

t = Impulse Time [s]

E = Young’s modulus [ksi]

I = second moment of area [in^4]

S_y = yield strength [ksi]
c = distance from neutral axis to extreme fiber [in]
g = Acceleration of Gravity [ft/s^2]
h = Drop Height [ft]

Abstract

The frame of the SAE Baja vehicle needs to be lightweight and structurally sound to be competitive but still protect the driver. The vehicle needs to traverse all types of off-road conditions including large rocks, downed logs, mud holes, steep inclines, jumps and off camber turns. During the competition events there is significant risk of rollovers, falling from steep ledges, collisions with stationary objects, or impacts from other vehicles. There are certain needs and constraints that will be defined to create a frame that can be resilient to these conditions. Before testing, the frame tubing diameter and materiel were selected. Several frames were compared against each other to decide which one would best to satisfy the needs. Types of welding were compared to determine the mode of assembling of the frame. The frame design has been analyzed in a variety of different simulations to predict whether it will survive the impact scenarios that may exists at the competition. The results from these simulations indicate that the frame is indeed safe enough in the variety of worst-case scenarios tested. There is a projected cost for building the frame for the competition as well as buying safety equipment. There is a theoretical budget for a general manufacturing of the frame at 4000 units a year. The goal for next semester is to complete the frame by the end of January and have the vehicle assembled by the end of February.

Chapter 1. Introduction

1.1 Project Overview

The Society of Automotive Engineers International (SAE) has contracted the team to design a Mini Baja vehicle. The stakeholders for the project include Dr. John Tester and the Northern Arizona University student chapter of SAE. SAE is a United States based organization that provides international standards for the automotive, aerospace, and commercial vehicle industries. They sponsor a variety of collegiate competitions that simulate the real-world engineering process and challenge students in their area of study. The SAE Mini Baja competition is designed to challenge each team in the design, planning, and manufacturing process as applied to a small off-road vehicle that could be turned into a consumer product. The competition consists of a variety of different events to test speed and maneuverability, and culminates in a final endurance race. The frame team has been assigned the task of designing the frame of the vehicle and ensuring the overall vehicle compliance with the safety regulations.

1.2 Project Need Statement

NAU has not won an event at the SAE Mini Baja competition in many years. During the competition, there will be several events that will test the limits of the vehicle. They include the Presentation, Hill Climb, Endurance, and Acceleration tests. The team must make a sales presentation to a panel of judges on the viability of the design as a consumer product. The maneuverability test consists of a variety of tough obstacles and tight turns, and the hill climb event tests the vehicle's traction and stability while climbing a steep hill. The endurance race is a three hour driving test to test the long-term reliability and average speed of the vehicle. The acceleration event tests the maximum speed of the vehicle. It has been many years since NAU has won an event, and a single event win would satisfy our stakeholders. Therefore, the solution to our need is to win a single event at the 2014 SAE Mini Baja competition.

1.3 Project Goals

The specific goal for our sub-team is to design the lightest possible frame that satisfies all the criteria specified in the 2014 SAE Mini Baja rulebook. This will maximize the Baja Team's chance of winning an event at the completion. To achieve this goal, the team must use lightweight materials and minimize the size of the frame. At the same time, the frame must be designed to meet all the safety requirements. After the frame is completed, the team's goal shifts to the overall safety of the vehicle. The team will ensure that all the sub-teams adhere to the strict safety guidelines throughout the design process and perform safety checks before the competition.

1.4 Objectives

The most important objective for the frame design is safety. The Mini Baja competition focuses heavily on creating a safe environment for the competitors and has strict safety rules. After safety, the next most important objective is to minimize the frame weight. [1, 2] After consulting with Dr. Tester and thoroughly reading the rulebook, the main objectives were generated and are listed below:

- The frame must be safe.
- The frame weight should be minimized.
- The frame should be easy to manufacture.
- The frame should be inexpensive.
- No damage to the safety cell after an impact.
- No significant damage to the overall chassis after an impact.

1.5 Operating Environment

The Mini Baja vehicle will be tested in the Cinders Off Highway Vehicle Area in Flagstaff, Arizona shown below in Figure 1. There the team can evaluate vehicles hill climb performance. Top speed and braking tests will also be conducted in the Cinders OHV Area. The vehicle will also be tested on the El Paso Gas Pipeline service road. This road simulates obstacles that are similar to what the vehicle could encounter during the competition such as large rocks, uneven ground, and jumps. This will test the strength and durability of the vehicle. Tests such as the driver vehicle exit test will be conducted at the Northern Arizona University Fabrication Shop, Building 98C, and parking lot P64.

Figure 1. Cinders OHV Area Flagstaff, AZ [3]

1.6 Constraints

All of the constraints for this project come directly from the SAE Mini Baja rulebook. While the team is limited by the school manufacturing facilities, everything in this project is within the capabilities of the NAU fabrication shop. The primary design constraints are:

- Must be constructed from steel tubing.
- Tubing must have a bending strength of at least 395 N-m.
- Tubing must have a bending stiffness of at least 2790 N-m^2.
- Tubing must have a minimum wall thickness of 0.062 inches.
- Frame length must be below 108 inches.
- Frame width must be below 40 inches.
- Height must be at least 41 inches above the seat bottom.
- Frame geometry must conform to the specifications.
- Vehicle must satisfy all the safety regulations in the rulebook.

1.7 Design Problem

The purpose of the frame is to protect the driver in the event of a collision or rollover, and to provide a chassis to mount the other subsystems. A minimum spacing between the driver and the frame must be maintained to ensure driver safety, and minimum strength requirements must be met. There are also specific requirements for the geometry of the frame as shown in Figure 2. There must be a gap of at least 6 inches in all directions between the driver's head and the frame, and there must be at least 3 inches between the frame and the driver's body. The frame must be constructed of an SAE standardized tubing size or tubing having equivalent bend strength and stiffness. A 64 inch tall driver weighing 250 pounds must be able to sit comfortably in the vehicle with all the proper safety devices. The vehicle must be no wider than 64 inches and no longer than 108 inches.

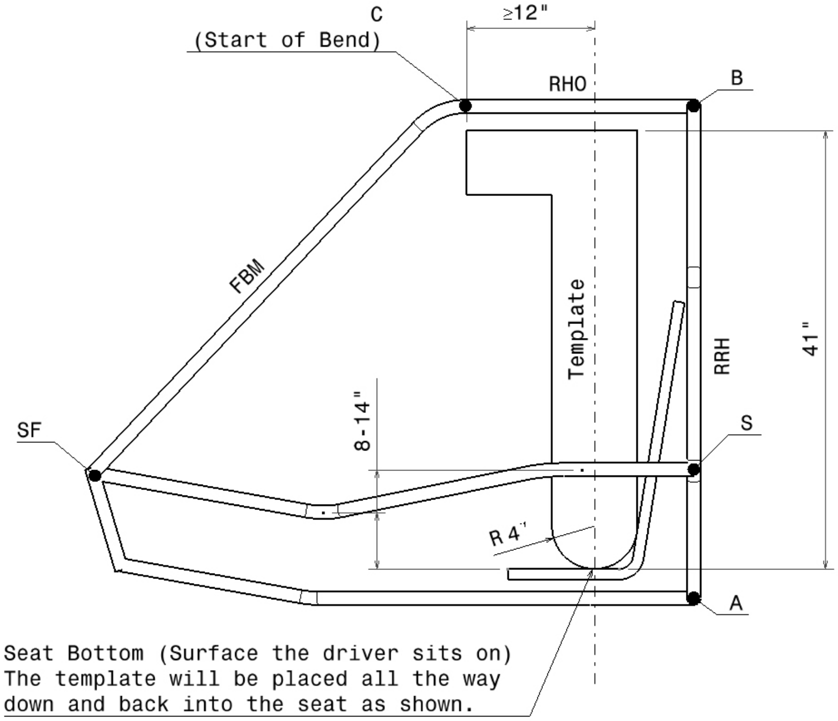
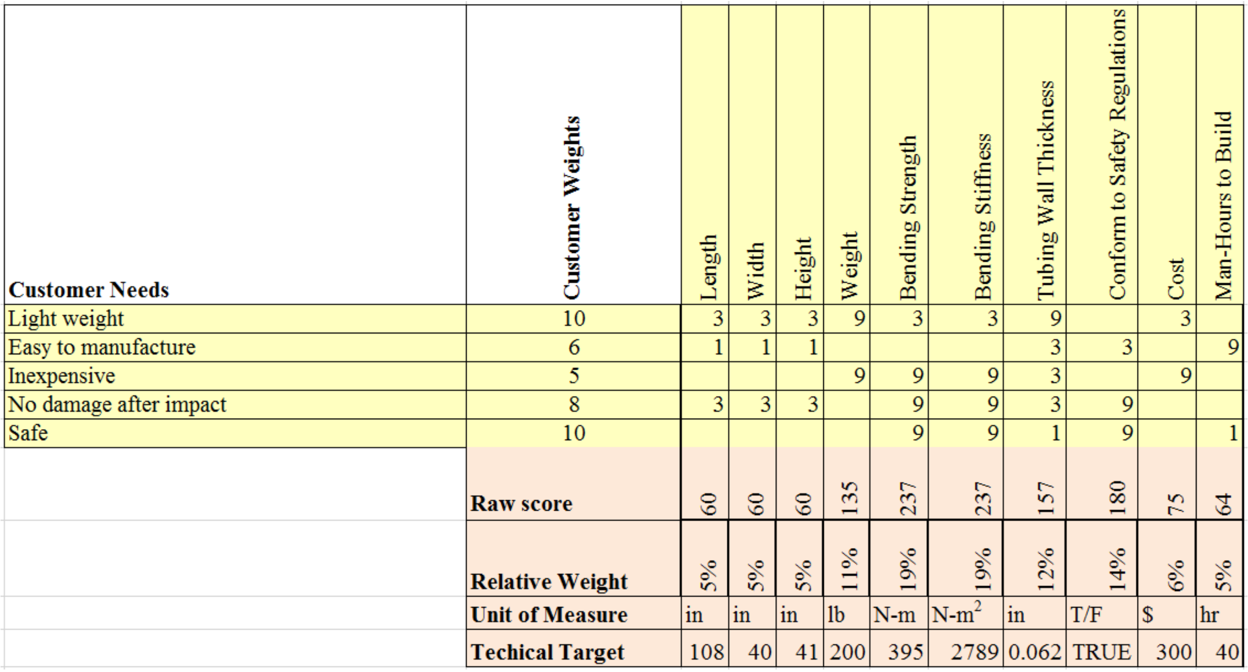


Figure 2. Clearance for the Driver [1]

1.8 Quality Function Deployment

The objectives and constraints have been compiled into the QFD chart below. Each customer need has been given a correlation score of 1, 3, or 9 with the corresponding engineering requirement. The relative weight indicates how important a specific requirements is compared to the others. The most important requirements are related to the safety and overall weight of the frame.



Customer Needs	**Customer Weights**	Length	Width	Height	Weight	Bending Strength	Bending Stiffness	Tubing Wall Thickness	Conform to Safety Regulations	Cost	Man-Hours to Build
Light weight	10	3	3	3	9	3	3	9		3	
Easy to manufacture	6	1	1	1				3	3		9
Inexpensive	5				9	9	9	3		9	
No damage after impact	8	3	3	3		9	9	3	9		
Safe	10					9	9	1	9		1
	Raw score	60	60	60	135	237	237	157	180	75	64
	Relative Weight	5%	5%	5%	11%	19%	19%	12%	14%	6%	5%
	Unit of Measure	in	in	in	lb	N-m	$N\text{-}m^2$	in	T/F	$	hr
	Techical Target	108	40	41	200	395	2789	0.062	TRUE	300	40

Figure 3. Quality Function Deployment

Chapter 2. Concept Generation

2.1 Tubing Selection

The 2014 SAE Baja rulebook specifies a standard tubing selection of AISI 1018 steel, with 1-inch outside diameter and a wall thickness of 0.120-inch. However, SAE does allow alternate selections as long as the team uses steel tubing and can prove that their selection has equivalent bending strength and stiffness. The tubing must have a minimum diameter of 0.5-inch and a minimum wall thickness of 0.065-inch. The tubing selection is independent of the frame geometry and thus was a completely separate decision process.

The most common alternate steel choice in the Baja competition is AISI 4130, because it has significantly higher ultimate tensile strength and yield strength than AISI 1018. Both 4130 and 1018 have the same density, but 4130 produces a much stronger frame for the same weight. The equations defining bending stiffness and bending strength are shown below:

$$Stiffness = E \cdot I \tag{1}$$

$$Strength = \frac{S_y \cdot I}{c} \tag{2}$$

Where:

E = Young's modulus [ksi]

I = second moment of area [in^4]

S_y = yield strength [ksi]

c = distance from neutral axis to extreme fiber [in]

[4, 5]Young's modulus is 29,700 ksi for all steels, and the yield strength for AISI 4130 is 63.1 ksi. AISI 1018 has a yield strength of 53.7 ksi. Calculated values for the bending stiffness and strength for the SAE specified tubing as shown in Table 1.

Table 1: Properties of SAE specified AISI 1018 tubing.

Diameter [in]	**Wall Thickness [in]**	**Stiffness [in-lb]**	**Strength [in^2-lb]**
1.000	0.120	971.5	3.513

[6]Calculated properties for a variety of available AISI 4130 tubing sizes and comparisons with the standard tubing's relative stiffness, strength, and weight are shown in Table 2. The relative measures are simply the property of the 4130 tube as a percentage of the property of the SAE specified AISI 1018 tube.

Table 2: Properties of AISI 4130 tubing of various sizes.

Diameter [in]	**Wall Thickness [in]**	**Stiffness [%]**	**Strength [%]**	**Weight [%]**
1.000	0.120	100	118	100
1.125	0.083	113	119	81.9
1.125	0.095	126	131	92.7
1.250	0.065	130	122	72.9
1.375	0.065	176	150	80.6
1.500	0.065	231	181	88.3

The lightest tubing size that exceeds the SAE minimum requirements is AISI 4130 steel, 1.250-inch outside diameter tubing with 0.065-inch wall thickness. This is the tubing selected regardless of the frame design, and is 27.1% lighter than the stock tubing. AISI 1018 tubing of the same size is less expensive and still meets the SAE minimum requirements, but is not as safe. If sufficient funds are not available for the AISI 4130 steel, the AISI 1018 of the same size will be used as a backup selection.

2.2 Frame Geometry

The team came up with four different initial designs for the overall frame geometry. Each design considered conforms to the 2014 SAE Mini Baja Rules. Below, the advantages and disadvantages for each design are discussed.

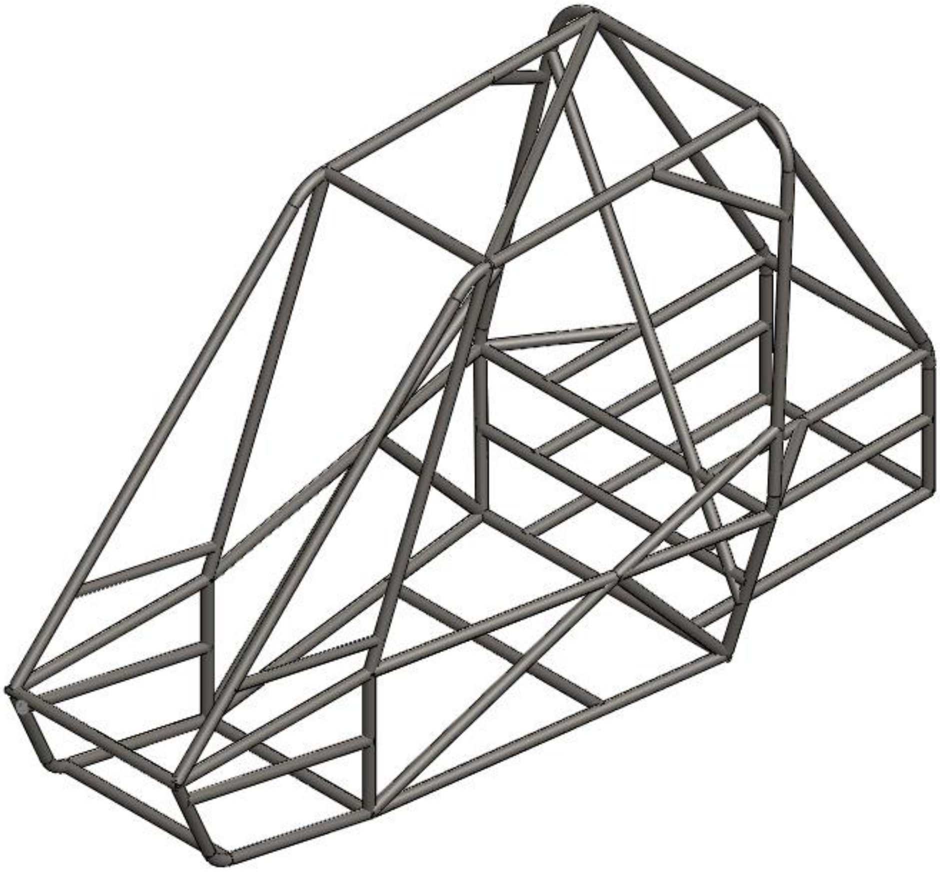


Figure 4: Design 1

Advantages of Design 1:

- Rear roll hoop and cage will provide increased rigidity in frame. There is cross bracing to increase the strength of the roll hoop.
- Wider frame will allow driver to exit vehicle in case of emergency
- Shorter frame length will allow for better handling throughout course

Disadvantages of Design 1:

- Highest amount of tubing will make this the heaviest frame.

- The height of the frame affects the center of gravity potentially causing the vehicle to be less stable.
- Highest number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to complete the frame.

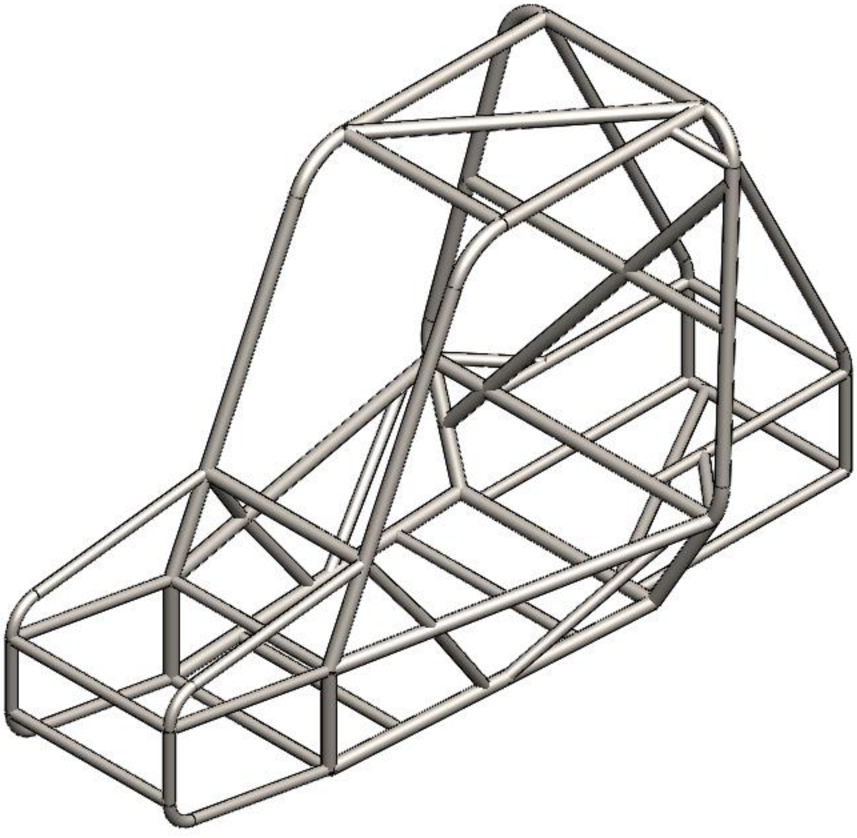


Figure 5: Design 2

Advantages of Design 2:

- Least amount of material used will make for the lightest frame
- Shortest wheelbase will make this the most maneuverable frame because the turning radius will decrease.
- Least number of individual tubes will make this the easiest frame to manufacture as it will require the least cutting and welding of individual tubes.

Disadvantages of Design 2:

- The lack of tubing could affect frame rigidity as there are less members to transfer the loads.

- The height of the frame affects the center of gravity potentially causing the vehicle to be less stable.

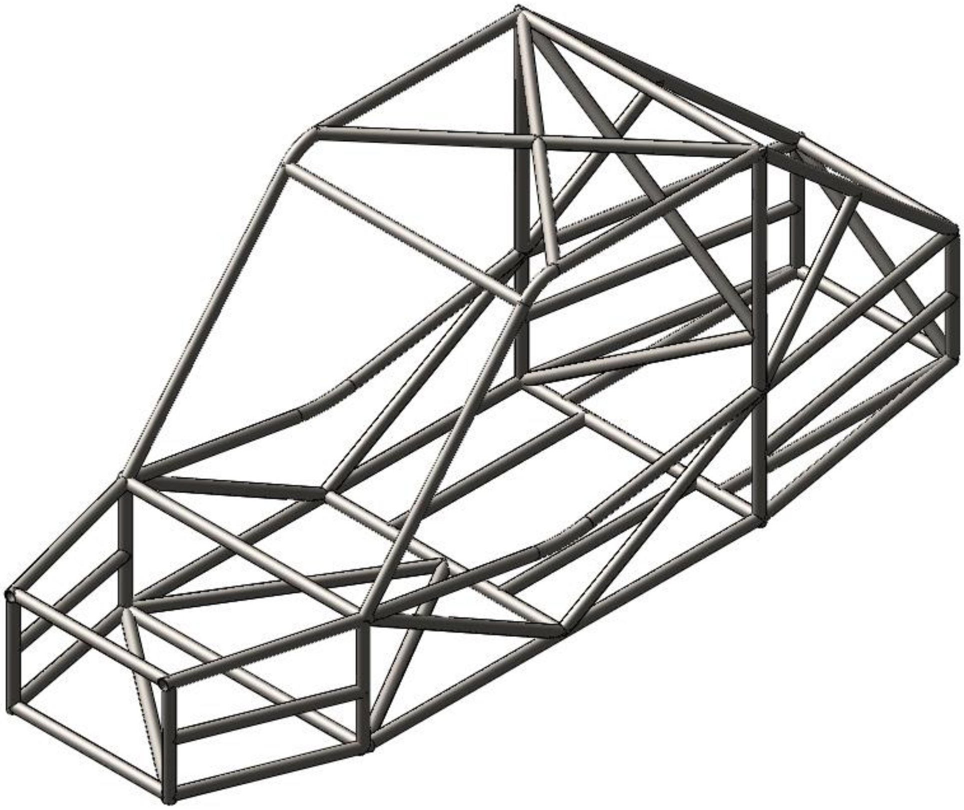


Figure 6: Design 3

Advantages of Design 3:

- Longer frame allows for a longer wheel base increasing the overall stability of the vehicle
- Higher number of individual tubes allows for frame stiffening at specific points increasing the overall rigidity of the frame.
- Low number of bends allows for easier manufacturing because less operations will have to be performed to the pipes saving time.

Disadvantages of Design 3:

- Longer frame decreases maneuverability. The long frame will increase the turning radius
- Large amount of material results in heavy frame which will hinder performance.

- High number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to construct the frame taking up more time and resources.

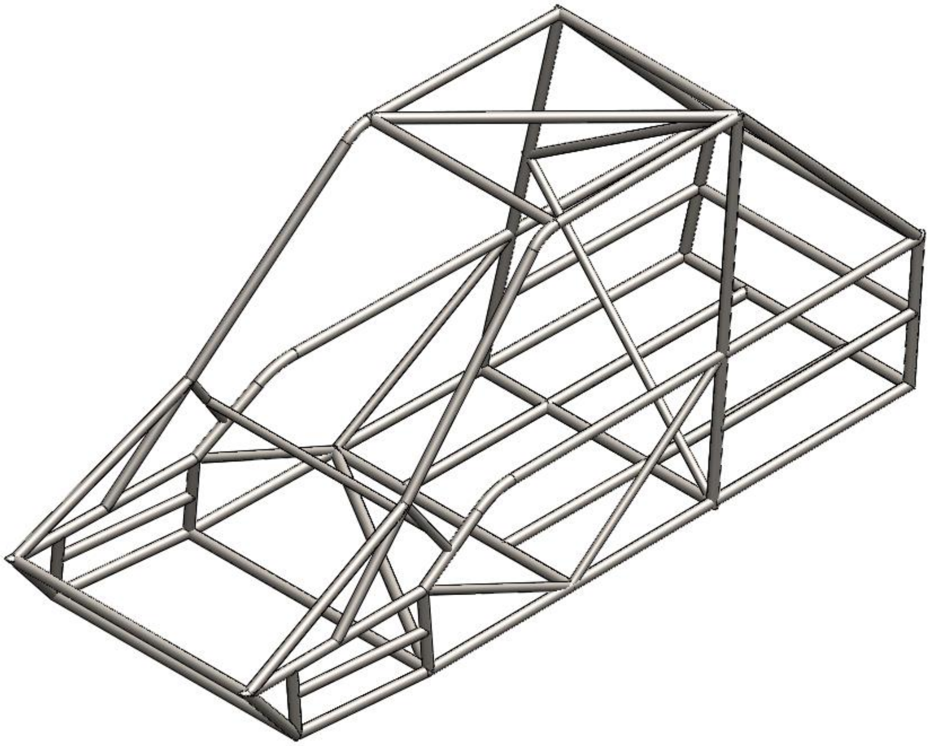


Figure 7: Design 4

Advantages of Design 4:

- Longer frame allows for a longer wheel base increasing the overall stability of the vehicle
- Relatively large interior space will allow taller drivers to operate the vehicle.
- Low number of bends allows for easier construction of the frame.

Disadvantages of Design 4:

- Longer frame increases the turning radius thus decreasing vehicle maneuverability.
- A tall frame will raise the center of gravity. A high center of gravity could cause a vehicle rollover.

High number of individual tubes will decrease ease of manufacturability. More tubes will need to be cut and welded together to construct the frame taking up more time and resources.

2.3 Decision Matrix

The team reviewed the four designs and created a decision matrix shown in Table 3. The relative weight of each criterion indicates its importance in the decision process. The weights were restricted to a nine, five, or one because it is not possible to determine subtle differences at this point in the design process. Raw data was used to populate the design columns for simplicity. The goal was to minimize each of the criteria, thus the lowest overall score is the winner.

Table 3: Decision Matrix

Criterion	Weight	Design 1	Design 2	Design 3	Design 4
Amount of Material [ft]	9	109	94	105	107
Length [in]	5	83	78	100	100
Width [in]	1	32	33	30	31
Height [in]	5	45	44	39	44
Number of Bends	1	10	10	4	4
Number of individual tubes	1	65	43	50	55
Total		1728	1542	1724	1773

The team selected a relative weight of nine for the amount of material needed to build the frame because this directly correlates to the final weight of the frame. Because the tubing selection is independent of the frame design, only the length of tubing required was considered.

The team selected a relative weight of five for the length and height of the frame. The length of the frame affects the maneuverability of the vehicle as well as high speed stability, and the height affects the center of gravity. Although a long length increases the stability, the maneuverability of the vehicle is much more important. The length needs to be minimized to decrease the turning radius and reduce the chance of high-centering on obstacles. A shorter length frame will also make the vehicle easier to transport when not in use. The height also needs to be minimized to reduce rollover risk.

A relative weight of one was assigned to the width, number of bends, and number of tubes. The width of the frame is not the outside width of the vehicle, and does not directly affect clearance or stability. The number of bends and the number of tubes were used to quantify the manufacturability of the frame. The more bends and individual tubes required, the more operations there are to construct the frame.

The decision matrix indicates that design 2, shown in Figure 5, is the best fit for our objectives with the lowest score of 1542. This design has the least amount of material needed and has smaller overall dimensions than the others. It requires more bends than other designs given, but the light weight and small dimensions make up for this minor disadvantage.

2.4 Welding Type Selection

The NAU Machine Shop has three types of welding equipment availbe to use: Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), and Gas Tungsten Arc Welding (GTAW).

SMAW (commonly known as stick welding) requires an electrode, an electrode holder and a ground to the metal to be able to weld the tubing together as shown in Figure 8. Stick welding requires no prep-work whatsoever and the workpiece can be very dirty without any loss in weld strength. However, this process would be very difficult for welding the frame because it is difficult in tight spaces and requires a special type of electrode for AISI 4130. This type of welding also creates a lot of spatter and left over welding material which must be removed afterward. SMAW requires no prep-work but is time consuming and difficult at awkward angles and in tight spaces.

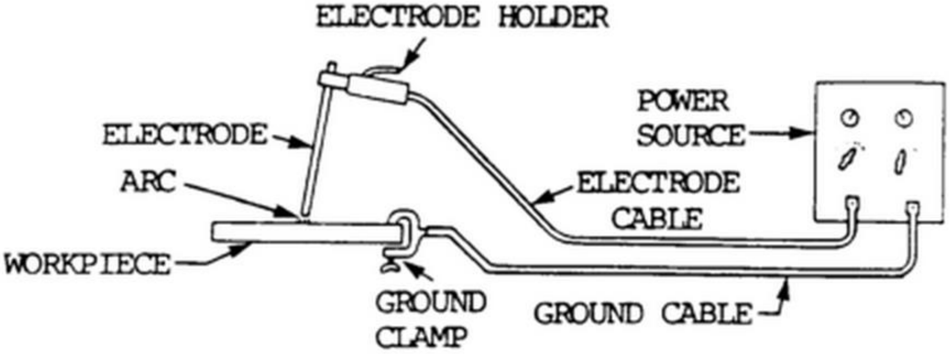


Figure 8: Shielded Metal Arc Welding [7]

GTAW (also known as tungsten inert gas, or TIG) would be the most time consuming type of welding process. This type of process uses an electrode, a torch, a ground and a foot pedal for controling the amperage of the torch current while welding [Figure 9]. The welder must simultaneously control the torch and the foot pedal while manually feeding filler rod into the weld. This process will create no spatter or slag and is the cleanest type of welding process because it requires no clean up. However, it requires a lot of pre-weld prepping and meticulous cleaning of the material, or a weak weld will result. When there are tight or hard to reach spots this welding process becomes very difficult because of the coordination it requires to perform correctly.

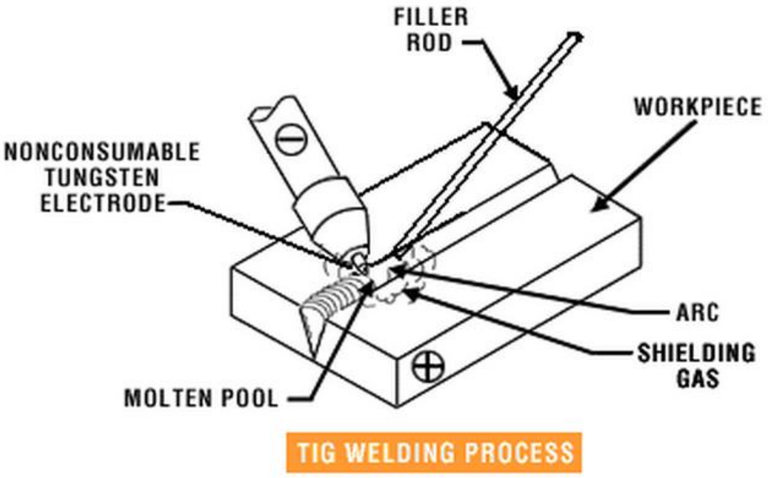


Figure 9: Gas Tungsten Arc Welding [8]

GMAW (also known as metal intert gas, or MIG) welding is process that uses an electrode holder and a ground with a constant wire fed through the electrode holder, as shown in Figure 10. A wire continously feeds through the electrode holder, eliminating the need for the welder to add filler by hand. The electrode holder itself is also small and easy to fit in tight spaces. This type of welding requires little or no prep-work, only produces minimal spatter, and requires very little cleaning after welding. This is the easiest process to use in joining the different parts of the frame together because no special rod is needed and it is easy to weld at odd angles and in tight spaces. The process the team choose to weld this frame is the GMAW or MIG process because it will be easier than the other processes and one process does not produce a stronger weld than the other. This is the process the team chose for the construction of the frame because of its simplicity and user-friendliness.

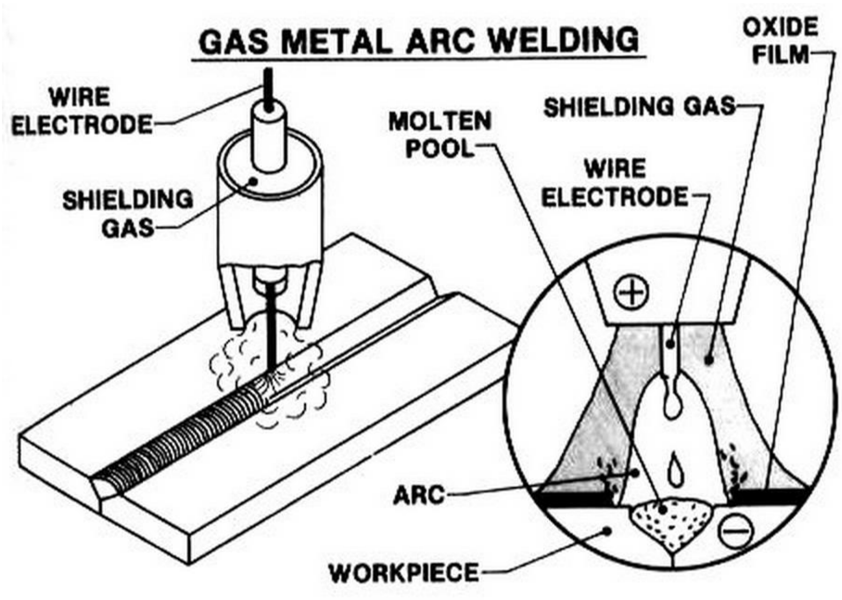


Figure 10: Gas Metal Arc Welding [9]

Chapter 3. Engineering Analysis

3.1 SolidWorks Simulation

In order to determine a frame design which satisfies the engineering design targets, each of the frame iterations was put through SolidWorks simulations. Each simulation was run on a Dell Precision with an Intel Xeon processor, 16 gigabytes of memory, and an Nvidia Quadro graphics card. Because the frame consists of both hollow tubing and solid metal tabs, two separate types of analyses were conducted. Beam elements were used in the frame simulations as shown in Figure 11. *Frame Analysis* For the analysis of the solid frame components, tetrahedral elements were used, as shown in Figure 12. *Tab Analysis* All of the simulations are static stress analyses. For the dynamic impact simulations, a static analysis at the moment of maximum acceleration was performed.

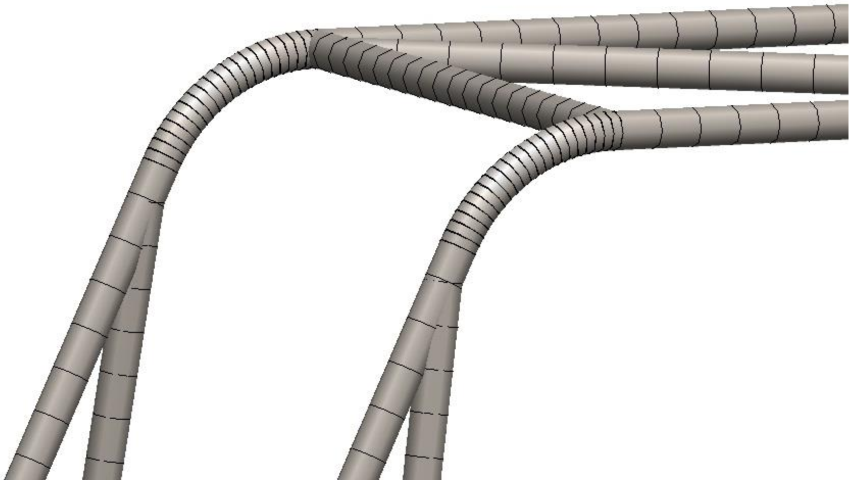


Figure 11. Frame Analysis

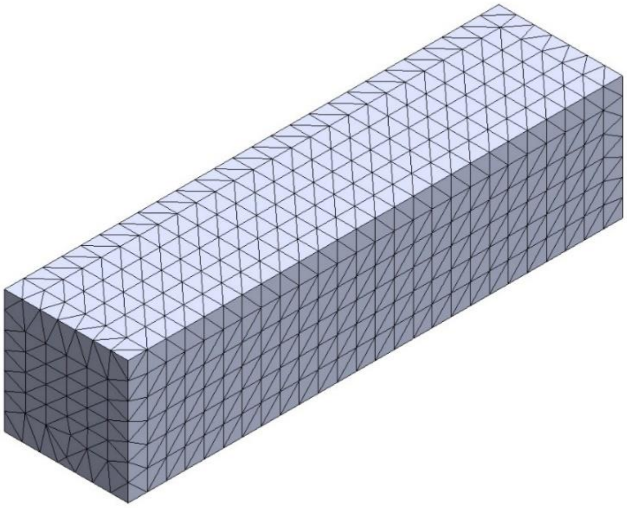


Figure 12. Tab Analysis

3.2 Refined Frame Designs

The four versions of the frame analyzed in this report are shown below. Design 6 retained the majority of the platform from design 5, with the exception of additional bracing in the roll hoop and the rotation of the front roll bar supports from a 45° angle to a 90° angle to increase the rigidity of the roof structure.

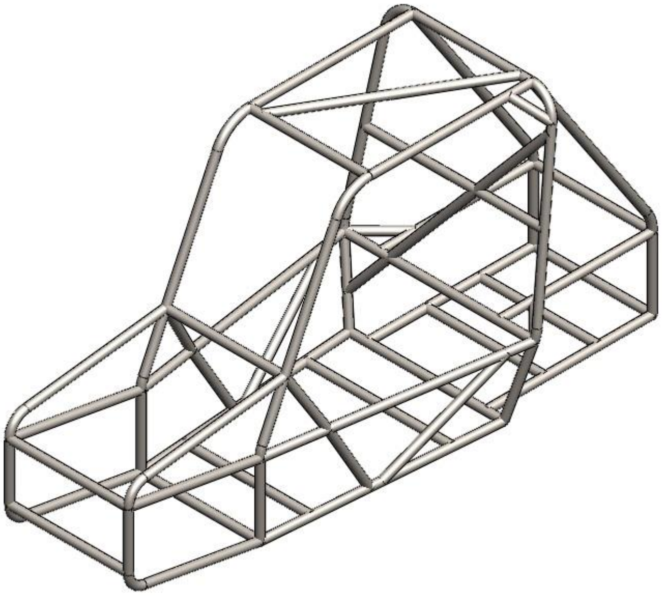


Figure 13. Design 5

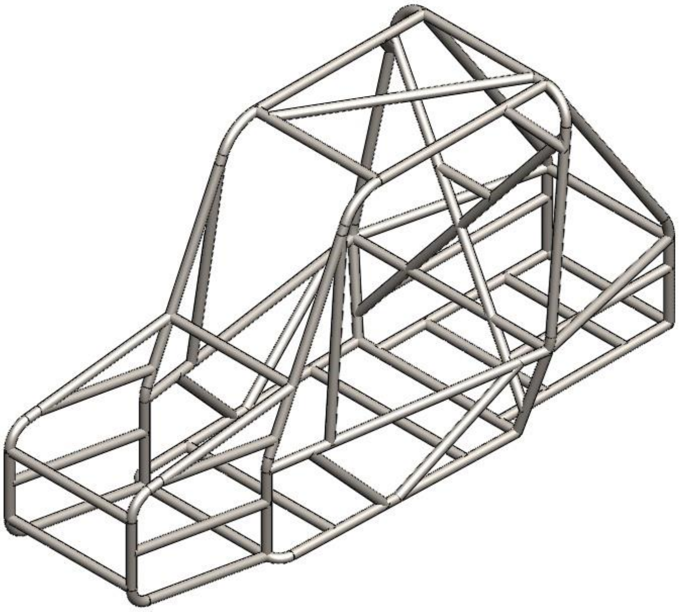


Figure 14. Design 6

Design 7 is an updated version of design 6, but with a focus on manufacturability. Because the Baja vehicle is intended to be a production off-road vehicle, the ease of manufacturability is important and must be taken into consideration. Alterations were made to the rear roll hoop and roll cage to lower the number of bends needed. The current frame, design 8, took the manufacturability of design 7 a bit further by altering the tubing geometry in the base of the frame, at suspension mounting points, and in the drivetrain compartment.

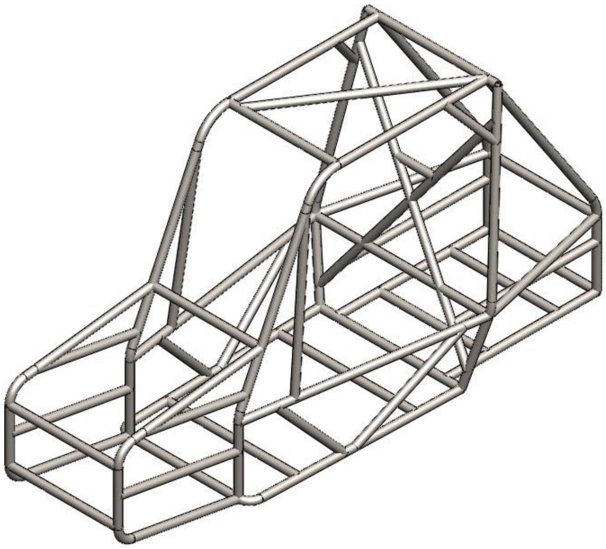


Figure 15. Design 7

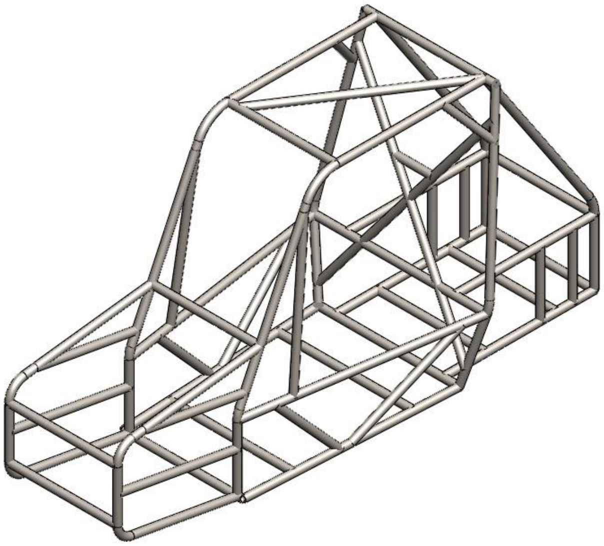


Figure 16. Design 8

To validate that design 8 is indeed stronger than the previous versions, a simple test was simulated to show the stress distribution and yield safety factor of each of the four frames. An arbitrary load of 6000 pounds was evenly applied to the top bars of the roll cage and a static stress simulation was performed in SolidWorks. The frame with the lowest maximum stress has the most even stress distribution, and the highest minimum safety factor. The results of these tests are shown in

Table 4.

Table 4. Simple Loading Results

Design	Max Stress (ksi)	Max Deflection (in)	Yield Safety Factor
5	61.61	0.256	1.08
6	61.20	0.210	1.09
7	60.16	0.202	1.11
8	56.89	0.206	1.17

Based upon these results, Design 8 is the optimal design and the alterations did improve the frame. The removal of the bends from the base of the frame increased manufacturability and allow for better distribution of stresses throughout the frame. The alterations made to the suspension mounting points improved rigidity and allow for easy adjustment of the design based upon changes in the suspension geometry. Design 8 was chosen for all of the more advanced simulations.

3.3 Frame Impact Tests

Each impact test is a worst case scenario that could potentially occur at the competition. There are four tests: a drop test, front collision test, rear impact test, and side impact test. The drop test consists of the vehicle being dropped upside down onto its roof from a height of 10 feet. The three collision tests simulate different 35 mph impacts with stationary objects or other vehicles.

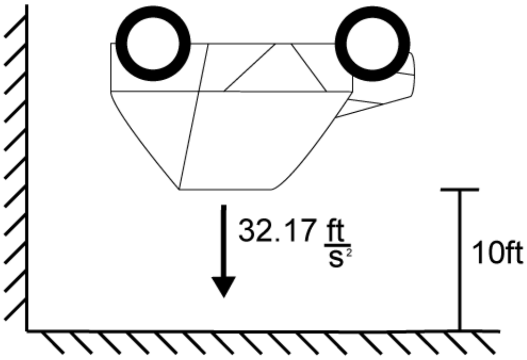


Figure 17: Drop Test

The team selected 10 feet for the drop height because it is sufficiently greater than anything expected at the competition. Equation 1 shows the calculation for the force on the vehicle during the impact. [11] An impulse time of 0.1 seconds was used for the drop test.

$$F = m \cdot \frac{\sqrt{gh}}{t} \tag{1}$$

Where:
F = Force
m = Mass
g = Acceleration of Gravity
h = Drop Height
t = Impulse Time

The front collision test simulates the vehicle hitting a solid, immovable object at a speed of 35 mph as shown in Figure 18. This is the maximum top speed the vehicle is expected to reach. The rear impact test simulates the vehicle being rear-ended by another 500 lb Baja vehicle, again at a speed of 35 mph (Figure 19). To make this test as hard as possible, the front of the vehicle is resting against a solid wall. The side impact test is identical to the rear impact, but the vehicle is oriented sideways relative to the motion of the incoming 500 lb vehicle (Figure 20). In reality the wheels and suspension of the vehicle would absorb some of the energy in the side impact test, but these were removed from the simulation to make it an absolute worst-case scenario.

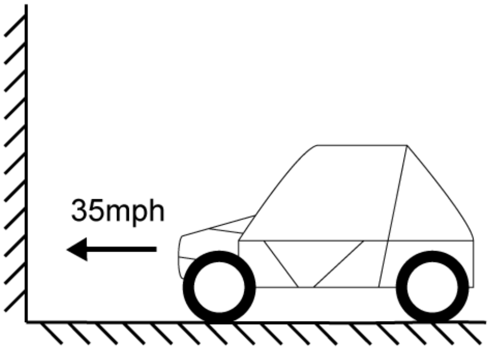


Figure 18: Front collision Test

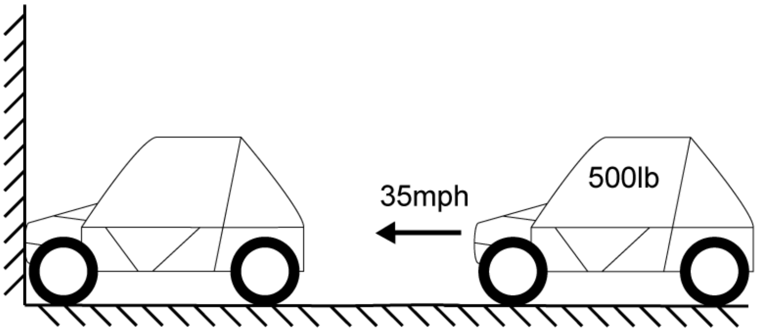


Figure 19: Rear Collision Test

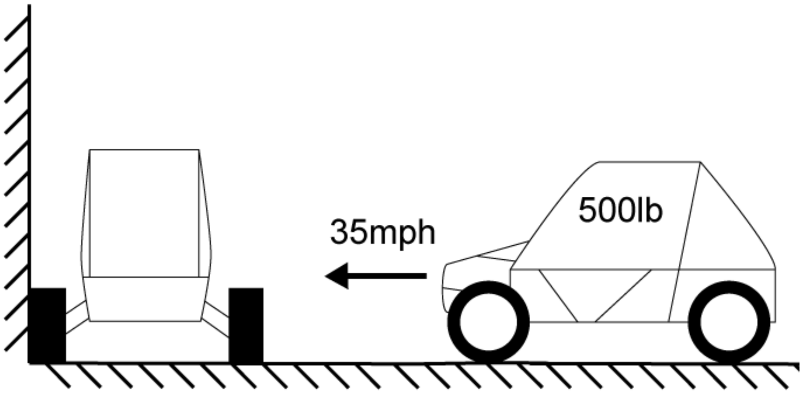


Figure 20: Side Collision Test

For the impact tests, Equation 2 is used to calculate the force on the vehicle. [11] An impulse time of 0.2 seconds was used.

$$F = m \cdot \frac{V_0}{t} \tag{2}$$

Where:
F = Force
m = Mass
V_0 = Initial Velocity
t = Impulse Time

3.4 Analysis Assumptions

For the simulations a few simple assumptions were made. The drivetrain was assumed to be a total weight of 120 pounds, including the engine, transmission, sprockets, and chains. The suspension load was assumed to be a total weight of 50 pounds per corner which includes the A-arms, shocks, and tires. The driver weight was assumed to be 250 pounds because the SAE Baja rules requires a minimum design driver weight of 250 pounds. The frame weight was evaluated to be 100.29 pounds using the SolidWorks model. The tubing used in the simulation was AISI 4130 steel with a 1.25 inch diameter and 0.065 wall thickness. The force equations stated in the test descriptions were applied to each load to simulate the acceleration experienced during the impact.

All the loads were applied at appropriately corresponding to their actual mounting locations in the frame. The suspension evenly on the correct members in each corner. The driver weight was distributed evenly between the 3 pieces of tubing used to secure the safety harness. The drivetrain load is applied on the two tubes in the bottom of the engine compartment that will be used to secure the drivetrain components. Figure 21 shows an example loading condition with the various loads applied in the correct locations.

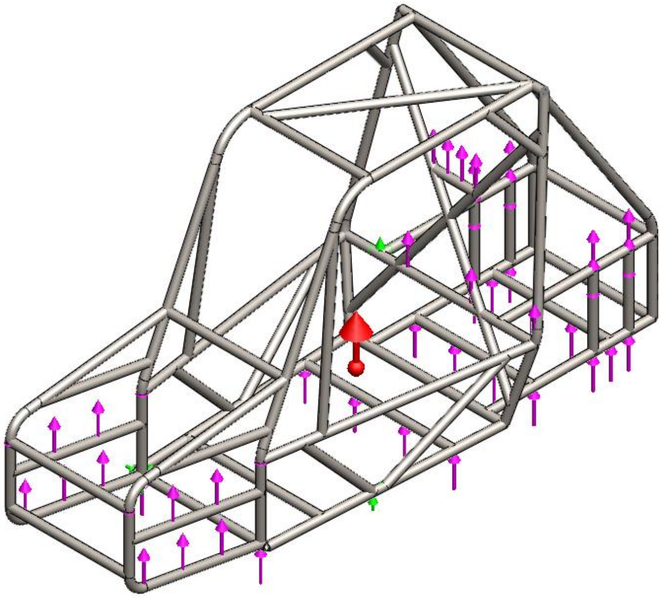


Figure 21. Example Frame Loading

3.5 Simulation Results

The results for the four advanced frame tests are discussed below. Table 5 shows the maximum displacements and the minimum factor of safety for each test.

Table 5. Impact Results Summary

Test	**Max Deflection [in]**	**Yield Safety Factor**
Drop	0.089	5.32
Front Collision	0.135	2.90
Rear Impact	0.263	1.45
Side Impact	0.363	1.01

Keep in mind that the maximum displacement is not necessarily the location of maximum stress. The colors in the deflected shape figures simply indicate the displacement of the element relative to its original position, not bending deflection. In the case of the drop test, the maximum stresses are in the vertical members supporting the roof, but the maximum displacement occurs in the front suspension area of the frame. As the roof crushes, the deformation pulls the front with it. Even though some of the lowest stresses are in the front members, the maximum displacement occurs there because of the effect of the members they're attached to.

In the tests the maximum stresses are expected at the location of impact, which is often the location restrained by the boundary conditions. In SolidWorks these restraints effectively make the point of impact the origin of the displacement measurements. This can make the displacement figures misleading if care is not taken to correctly interpret the results. It may be wise to ignore the color gradients of the deflected shapes and simply examine the geometry alone. For all of the impact analysis, the deflected shapes agree with the results one would expect in a real world scenario.

For each individual test, the figures for the stress distribution and the safety factors produced by SolidWorks are identical. The safety factor figure is simply the stress distribution divided by the yield stress, so the color gradients are the same. SolidWorks simply changes the units and the magnitude of the scale. Because these figures are identical, only the safety factor is included, but the results are equally valid for the stress distribution. Results are shown below in *Figure 22*-*Figure 29*.

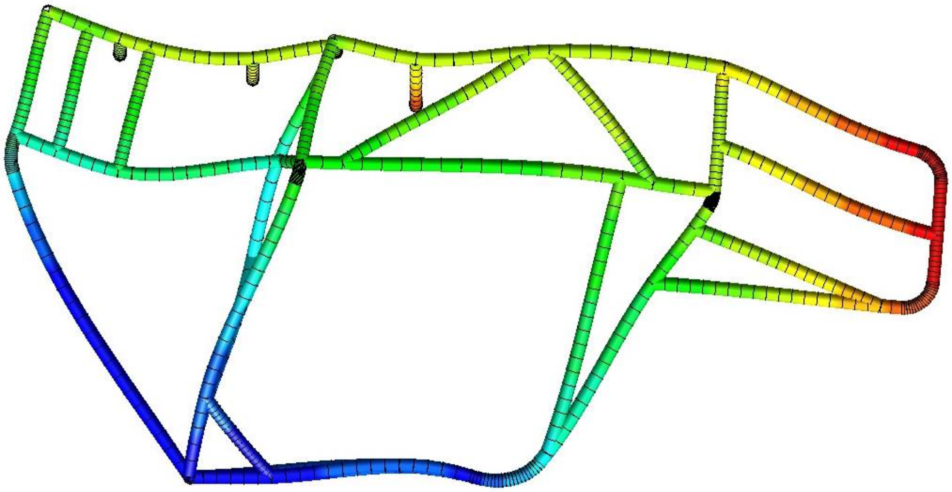


Figure 22. Drop Test Deflected Shape

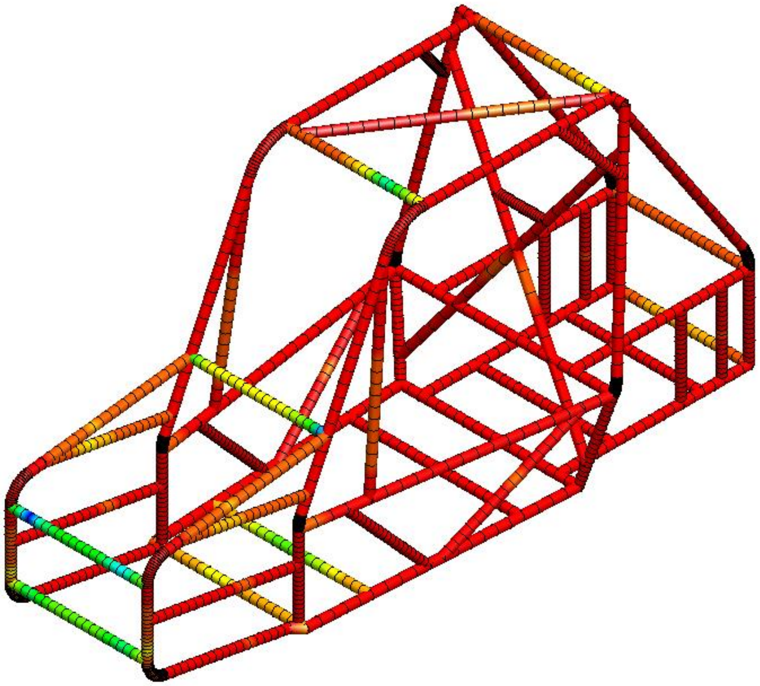


Figure 23. Drop Test Stress Distribution / Safety Factor

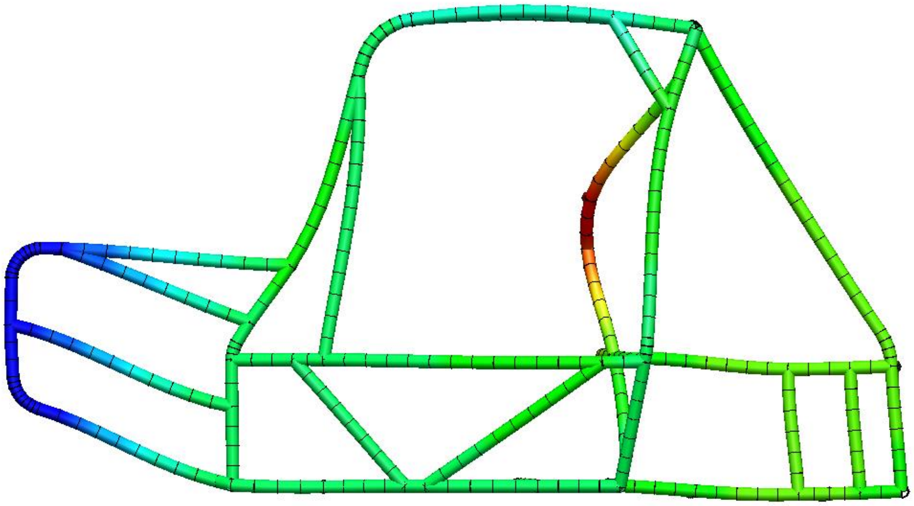


Figure 24. Front Collision Deflected Shape

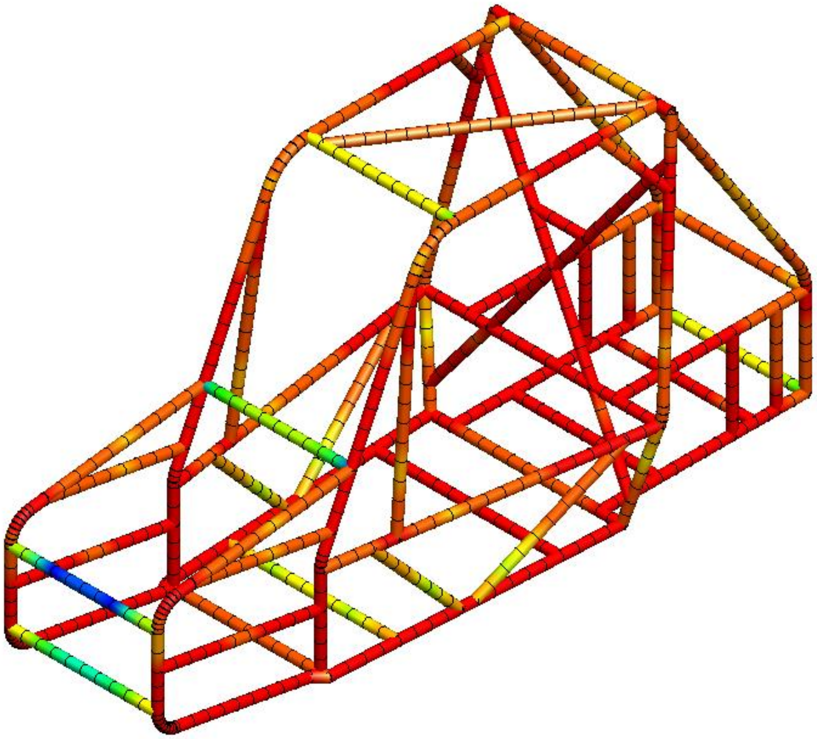


Figure 25. Front Collision Stress Distribution / Safety Factor

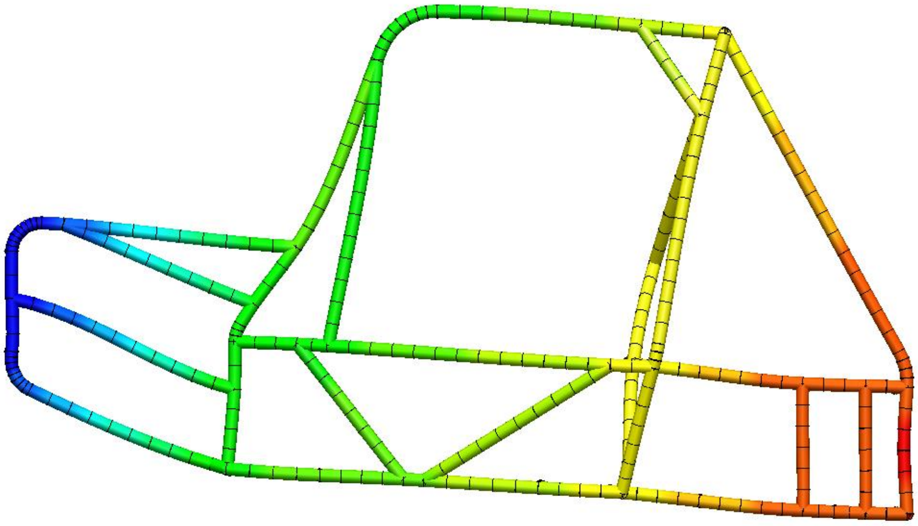


Figure 26. Rear Impact Deflected Shape

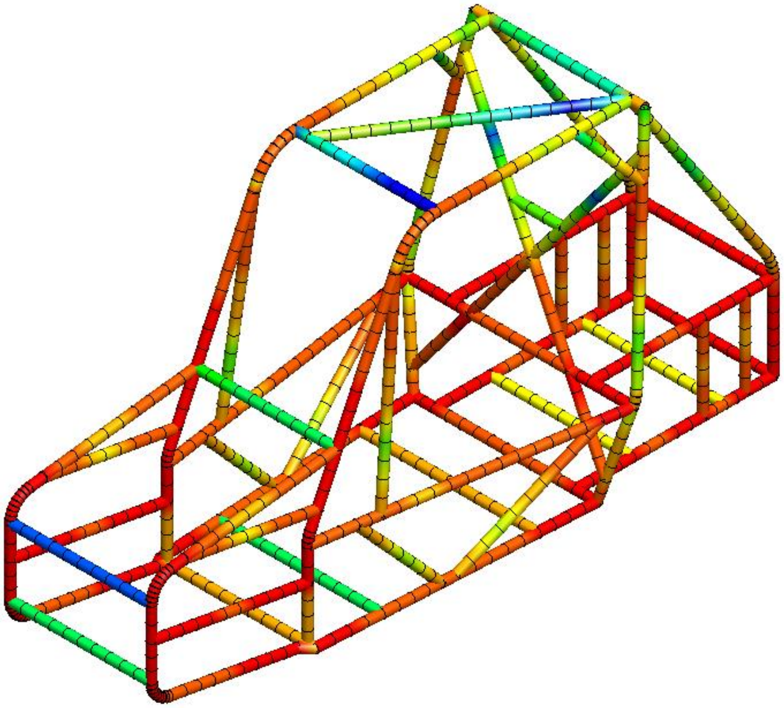


Figure 27. Rear Impact Stress Distribution / Safety Factor

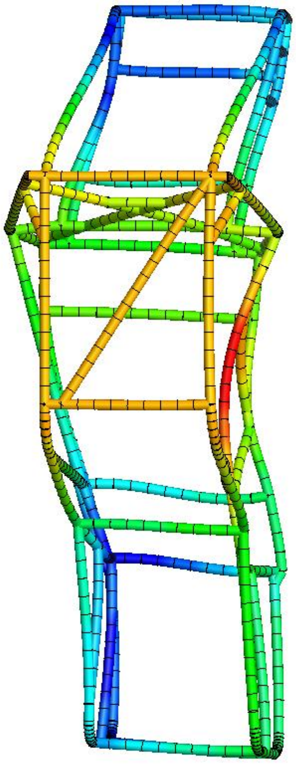


Figure 28. Side Impact Deflected Shape

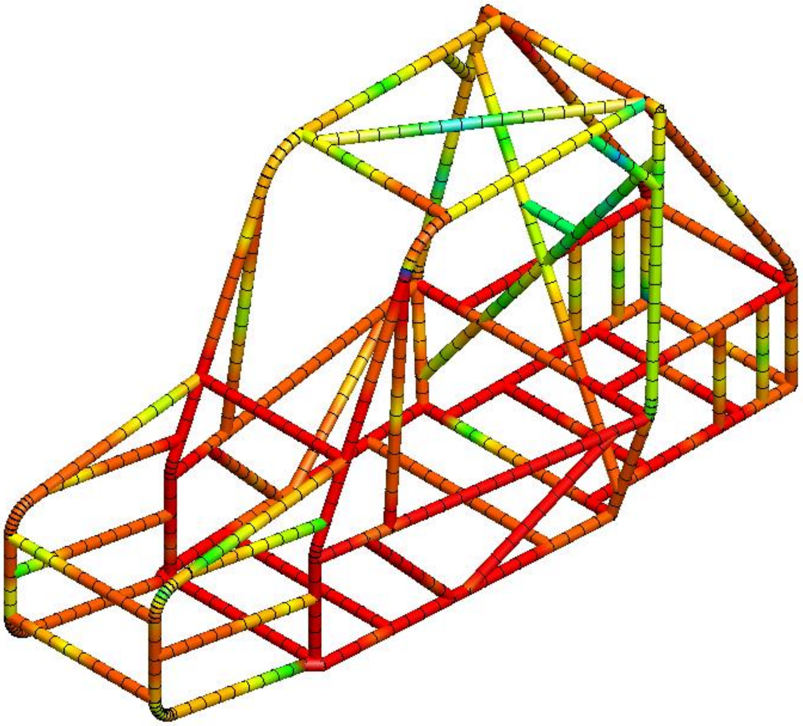


Figure 29. Side Impact Stress Distribution / Safety Factor

In the drop test, the roof structure begins to crush, and the members supporting the driver and the drivetrain show significant stresses. In the front collision test, the momentum from the driver produces high stresses on the shoulder harness mounts, and the momentum of the drivetrain makes the rear end deflect towards the front of the vehicle. The front of the frame has the smallest indicated displacements because it is pushed against the wall, but careful examination of the deflected shape shows significant deformation relative to the rest of the frame. The rear impact test is very similar to the front collision test, but the momentum effects of the driver, drivetrain, and suspension are removed because the vehicle is at rest and pinned against a wall. The frame has sufficiently high safety factors in all three of these tests.

The side impact test is the toughest frame test, and our vehicle barely passes with a 1.01 safety factor. This seems low at first, but it must be noted that the safety factor is for yield stress, not ultimate tensile stress. AISI 4130 steel has a very high ultimate tensile strength, and there is a large plastic deformation region present before the deflection of the frame begins to endanger the driver. Our current frame design passes all of the impact tests within the yield limits of the material, thus there will be no permanent damage from the scenarios analyzed here.

3.6 Tab Shear Tests

While analyzing the frame we spoke with our client and he informed the team that most frames do not fail while at the competition. Rather, the most common structural failure is of the mounting tabs welded onto the frame. These tabs are used to attach almost everything, including the drivetrain, suspension elements, and the driver restraints. To reduce the risk of such a failure in the design, the mounting tabs were intentionally overdesigned using extreme loading cases. Such excess is acceptable because increasing the strength of the tabs adds very little material to the overall frame design and does not greatly affect the weight. Two cases were analyzed: the tabs for the safety harness mounts and the tabs for the suspension mounts. These two were selected because they are the most significant and experience the highest stresses. The force values used in the analysis correspond to the maximum forces calculated for the frame impact tests. 322 pounds was applied to each safety harness tab, and 250 pounds was applied to each of the suspension tabs.

The SolidWorks figures for the tab shear tests are shown below in *Figure 30Figure 33*. The maximum deflections are extremely small and the factor of safety for the driver harness is very high. The safety factor for the frame tabs is lower at 1.5, but 250 pounds per tab is an absolutely ridiculous load. As stated earlier, overdesigning these two components is perfectly acceptable and minimizes the risk for the most common structural failure at the competition. The results are summarized in

Table *6*.

Table 6. Tab Shear Results

Test	**Max Deflection [in]**	**Yield Safety Factor**
Driver Harness	0.001	4.70
Frame Tab	0.024	1.50

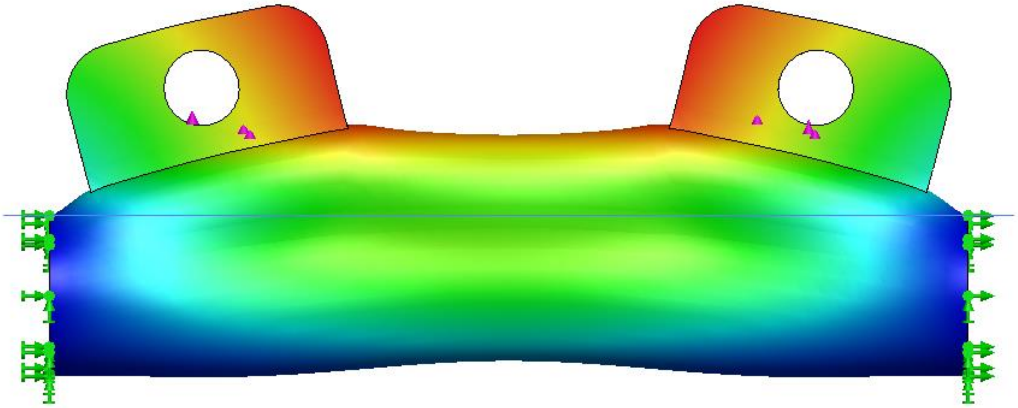


Figure 30. Seatbelt harness tab deflection

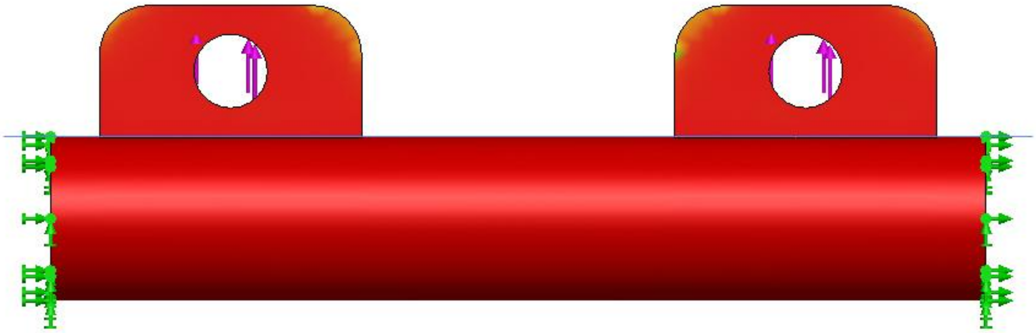


Figure 31. Seatbelt harness tabs factor of safety

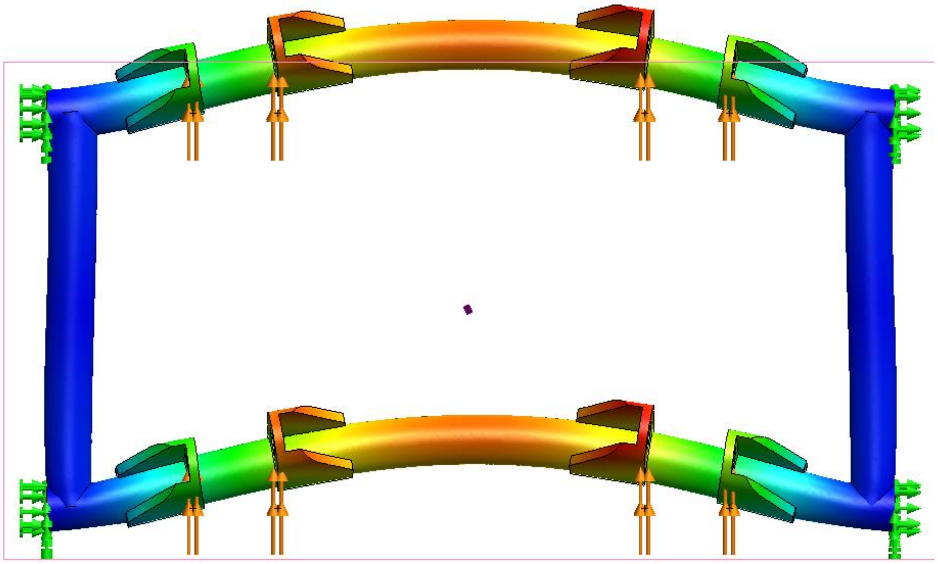


Figure 32: Tab deflection

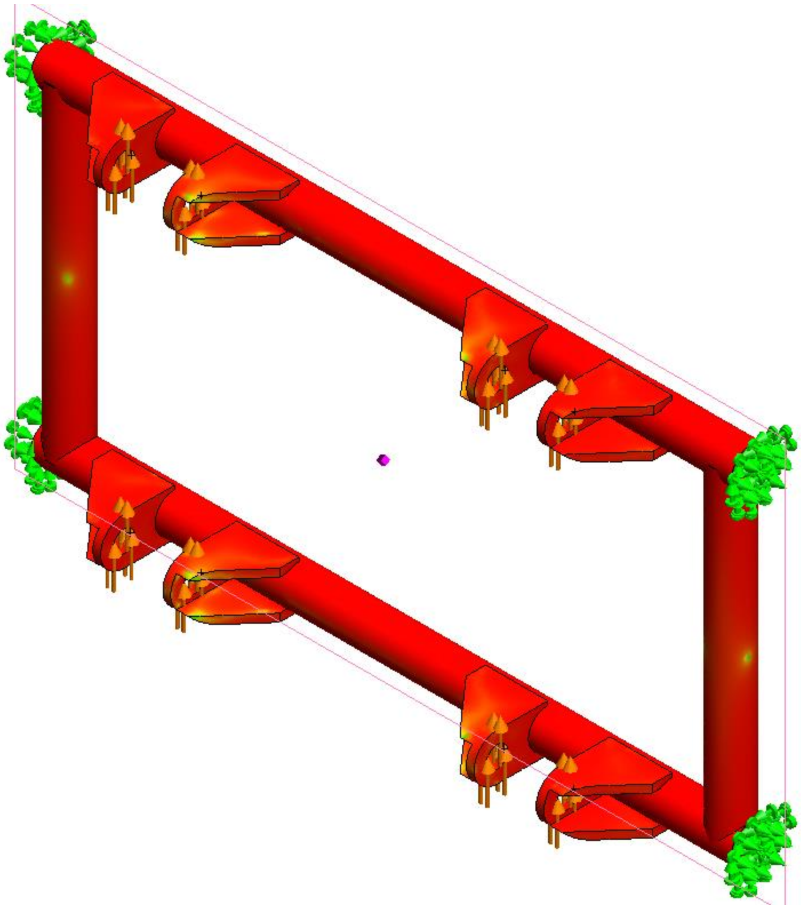


Figure 33. Tab factor of safety

3.7 Engineering Design Targets

The following table lists our engineering design targets from the QFD matrix and compares them to the actual values of our current frame design. All of the targets have been met with the exception of the frame height. The original requirement was unrealistic because of the required empty space between the driver's helmet and the top of the frame. This consideration was overlooked or miscalculated in the original target generation. The current design is as short as possible while still satisfying the safety regulations.

Table 7. Engineering Design Targets

Requirement	Target	Actual
Length [in]	108	88.175
Width [in]	40	32
Height [in]	41	44.679
Bending Strength [N-m]	395	486
Bending Stiffness [N-m^2]	2789	3631
Wall Thickness [in]	0.062	0.065
Pass Safety Rules	TRUE	TRUE

Chapter 4. Cost Analysis

4.1 Team Budget

The cost analysis for this project was broken up into two different budgets; the total cost for the team to build and go to competition and a theoretical production cost for a run of 4000 units annually. The team budget was broken into main categories: raw materials, safety, and miscellaneous. The Raw Materials category contained all the materials needed to construct the bare frame. A total of 120 feet of 1.25” x 0.065” AISI 4130 Chromoly tubing will be purchased to construct the main structural supports of the frame. A total of 60 feet of 1.00” x 0.035” AISI 4130 Chromoly tubing will be purchased for all of the secondary supports in the frame. A 0.375” x 6” x 6’ section of AISI 4130 Chromoly plate will be ordered to create all mounting tabs for suspension, drivetrain, and safety components. The next main category is Safety, in which, all components are outlined and required under the SAE Baja rulebook. A 5-point safety harness, fire extinguisher, and one Ski-Doo kill switch are already provided by previous year’s teams. A Corbeau Baja RS seat, one Ski-Doo kill switch, and a SAE certified brake light still need to be purchased to qualify under the safety guidelines. The last category in the team budget is miscellaneous which contains all costs needed to go to competition. The entry fee of $1,100.00 will be evenly divided between the three Baja teams. Food costs are budgeted for $20.00 per person per day for the four days of competition. The team will split up into two hotel rooms for four nights through the competition. The total cost of the frame, all safety components, and the cost to go to competition is $1,994.50. A detailed list is shown below in Table 8.

Table 8. Team Budget

Category	**Item**	**Quantity**	**Price**
Raw Materials	1.25” x 0.065” AISI 4130	120’ x ($1.67 per foot)	$200.00
	1.00” x 0.095” AISI 4130	60’ x ($1.67 per foot)	$100.00
	0.375” x 6” AISI 1018	1 x (6’ Sections @ $111.86)	$111.86
Safety	Corbeau Baja RS Seat	1 x ($249.99)	$249.99
	5-point Safety Harness	1 x ($73.99)	$0.00
	Ski-Doo Kill Switch	2 x ($19.99) – 1 x (Provided)	$19.99
	Fire Extinguisher/Mount	1 x ($25.46) – 1 x (Provided)	$0.00
	Brake Light	1 x ($33.99)	$33.99
Miscellaneous	Entry Fee	1/3 x ($1100.00)	$366.67
	Food	5 x (4 Days) x ($20.00 per day)	$400.00
	Hotel	2 x (4 Days) x ($64.00 per night)	$512.00
Total			1994.50

4.2 Theoretical Production Budget

The theoretical production cost is a projected budget analysis for a manufacturing company to produce 4,000 units per year. produce 4,000 units per year. This budget is broken down even further into the categories of raw materials, marginal costs, materials, marginal costs, labor, and fixed costs.

Table 9 shows the cost of the required raw materials. Because this is modeled to be an efficient manufacturing process, there will be significantly less waste material and a total of only 80 feet of 1.25” x 0.065” tubing and 45 feet of 1.00” x 0.095” tubing will be needed for this process. Due to the high volume of material this production will go through, it is calculated that all raw materials will be purchased for half the of the retail price resulting in the total cost of raw materials being $317.79 per frame.

Table 9. Raw Material Budget

Category	**Item**	**Quantity**	**Price**
Raw Materials:	1.25” x 0.065” AISI 4130	80’ x ($0.83 per foot)	$66.67
	1.00” x 0.095” AISI 4130	45’ x ($0.83 per foot)	$37.50
	0.375” x 6” AISI 4130	1 x (6’ Sections @ $55.93)	$55.93
	Corbeau Baja RS Seat	1 x ($124.99)	$124.99
	5-point Safety Harness	1 x ($36.99)	$36.99
	Ski-Doo Kill Switch	2 x ($9.99)	$19.99
	Fire Extinguisher/Mount	1 x ($12.73)	$12.73
	Brake Light	1 x ($16.99)	$16.99
Total			$371.79

Table 10 shows the annual labor and marginal cost. Marginal cost consists of the raw materials costs spread over the 4,000 units projected to be produced. Because an average of 16 frames will need to be produced per day, labor for the frame will be spread between fabricators, welders, and installers. With four working fabricators, each fabricator will have two hours per frame to produce all the necessary cuts, bends, and notches. Eight working welders will each have four hours to assemble and weld each frame. Two installers each will have one hour each to install the necessary safety components once the completely welded. Four fabricators at $10.00/hour, eight welders at $15.00/hour, and two installers at $10.00/hour brings the total annual labor cost to $360,000.

Table 10. Labor Costs.

Category	**Item**	**Quantity**	**Price**
Marginal Costs:	Raw Materials	4000 units x ($371.79)	$1,487,146.67
Labor:	Fabricators	4 x (2000 hours x $10.00 per hour)	$80,000.00
	Welders	8 x (2000 hours x $15.00 per hour)	$240,000.00
	Installers	2 x (2000 hours x $10.00 per hour)	$40,000.00
Total			$1,847,146.67

Table 11 shows the final production cost of each frame. This includes the price of the facilities and other costs. [12] Rent is calculated with 10,000 square foot facility at $1.26 per square foot totaling to $150,000 annually. Utilities are calculated at 50% of rent which totals to $75,000 per year. Overhead includes all tooling, insurance, and any unforeseen costs and is calculated at 50% of total Labor costs. The total Production Costs including raw materials, marginal costs, labor, and fixed costs totals to $2,252,146.67, which breaks down to $563.04 per frame.

Table 11. Final Production Budget

Category	**Item**	**Quantity**	**Price**
Fixed Costs:	Marginal Costs		$1,847,146.67
	Rent/Utilities	$150,000 + $75,000	$225,000
	Overhead	Labor Cost x (0.5)	$180,000
Total			$2,252,146.67

Chapter 5. Conclusion

The team was contracted to build a Mini Baja vehicle that can compete in a various competitions and win. The constraints and needs the Baja must meet to compete were defined. We compared different sizes and material of tubing and decided to build the frame out of AISI 4130 steel with a 1.250 inch diameter and a 0.650 inch wall thickness. A variety of frames were compared using a decision matrix and Design 2 was the best choice due to the lightweight and simplicity of the frame. The analysis of the frame was designed to confirm that the frame can withstand several tests while keeping the driver safe. The drop test analysis determined that after a 10 foot drop it will hold with a yield factor of safety of 5.32 and a max deflection of 0.089 inches. The front collision analysis resulted in a 2.90 factor of safety and a 0.135 inch deflection. The rear impact analysis showed a yield safety factor of 1.45 and a deflection of 0.263 inches. The side impact analysis showed a yield safety factor of 1.01 and a deflection of 0.363. A tab shear test was used to determine if the tabs that hold various parts of the vehicle will fail under certain tests which confirmed that they will not fail under a large amount of force. The team was within the design targets for the constraints and needs of the frame and safety. The projected total cost for the frame and safety equipment for the frame used in competition was $1994.50. The theoretical total cost for the frame and safety equipment to be manufactured was $2,252,146.67. The schedule for next semester is to complete the frame by the end of January, finish the complete vehicle by the end of February, start testing in March, and go to competition April 24th to the 27th. A more detailed project plan is shown in Appendix B.

References

[1] SAE International, “2014 Collegiate Design Series Baja SAE Rules,” 2014. Print

[2] Tester, John, Northern Arizona University, personal communication, Nov. 2013.

[3] Olsen, Stu, “Cinders Recreation Area” 2009, Photograph

[4] MatWeb, “AISI 4130 chromoly properties,” http://www.matweb.com/search/DataSheet.aspx?MatGUID=7eb7e2c6eab3433c9fb96eaa9f0312fb&ckck=1, Oct. 2013.

[5] AZOM.com, “AISI 1018 Mild/Low Carbon Steel properties,” http://www.azom.com/article.aspx?ArticleID=6115, Oct. 2013

[6] Industrial Metal Supply Co., “Chromoly (4130) / DOM Tubing,” http://www.industrialmetalsupply.com/Products/chromoly-4130-dom-tubing, Oct. 2013.

[7] Department of the Army, “Welding Theory and application,” Manual TC 9-237, Section 10-8, May 7, 1993.

[8] Advantage Fabricated Metals, “TIG Welding,” http://www.advantagefabricatedmetals.com/tig-welding.html, Oct. 2013.

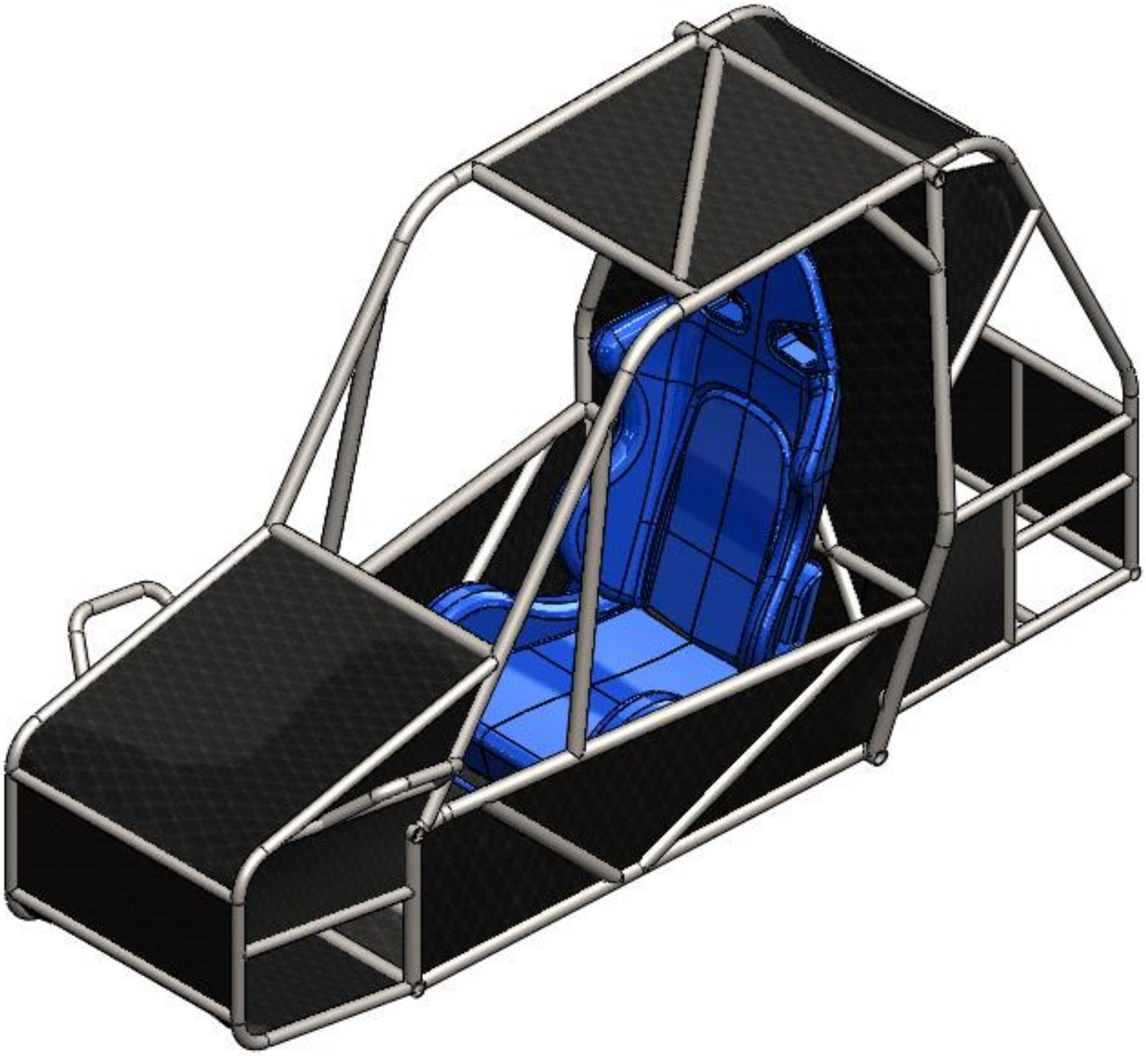
[9] Everlast, “Arc Welding Pros and Cons,” http://www.everlastgenerators.com/arc-welding-process.php, Oct. 2013.

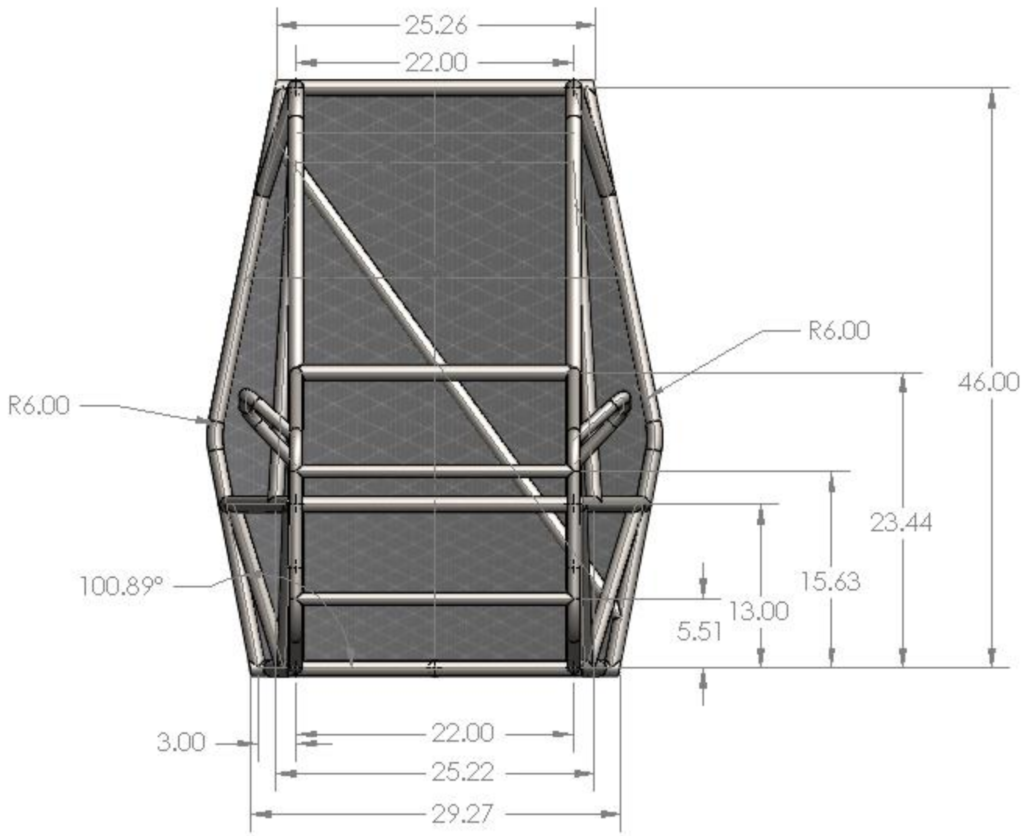
[10] V.M. Radhakrishnan. *Welding Technology & Design*. Noida: New Age International, 2005. Print.

[11] Owens, T., Anthony, Jarmulowicz, D., Marc, Jones, Peter “Structural Considerations of a Baja SAE Frame,” SAE Technical Paper 2006-01-3626, 2006.

[12] CITYFEET, “Industrial For Lease,” http://www.cityfeet.com/cont/ForLease/LN18467902/575-Snowy-Range-Road-Laramie-WY-82072, Dec. 2013.

Appendix A: Engineering Drawings





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APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/8
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.625
THREE PLACE DECIMAL ± .010

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: AISI 4130

FINISH: Powder Coated

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Chris Bennett	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

Frame Front View

SIZE	DWG. NO.	REV
A	Frame V11	11

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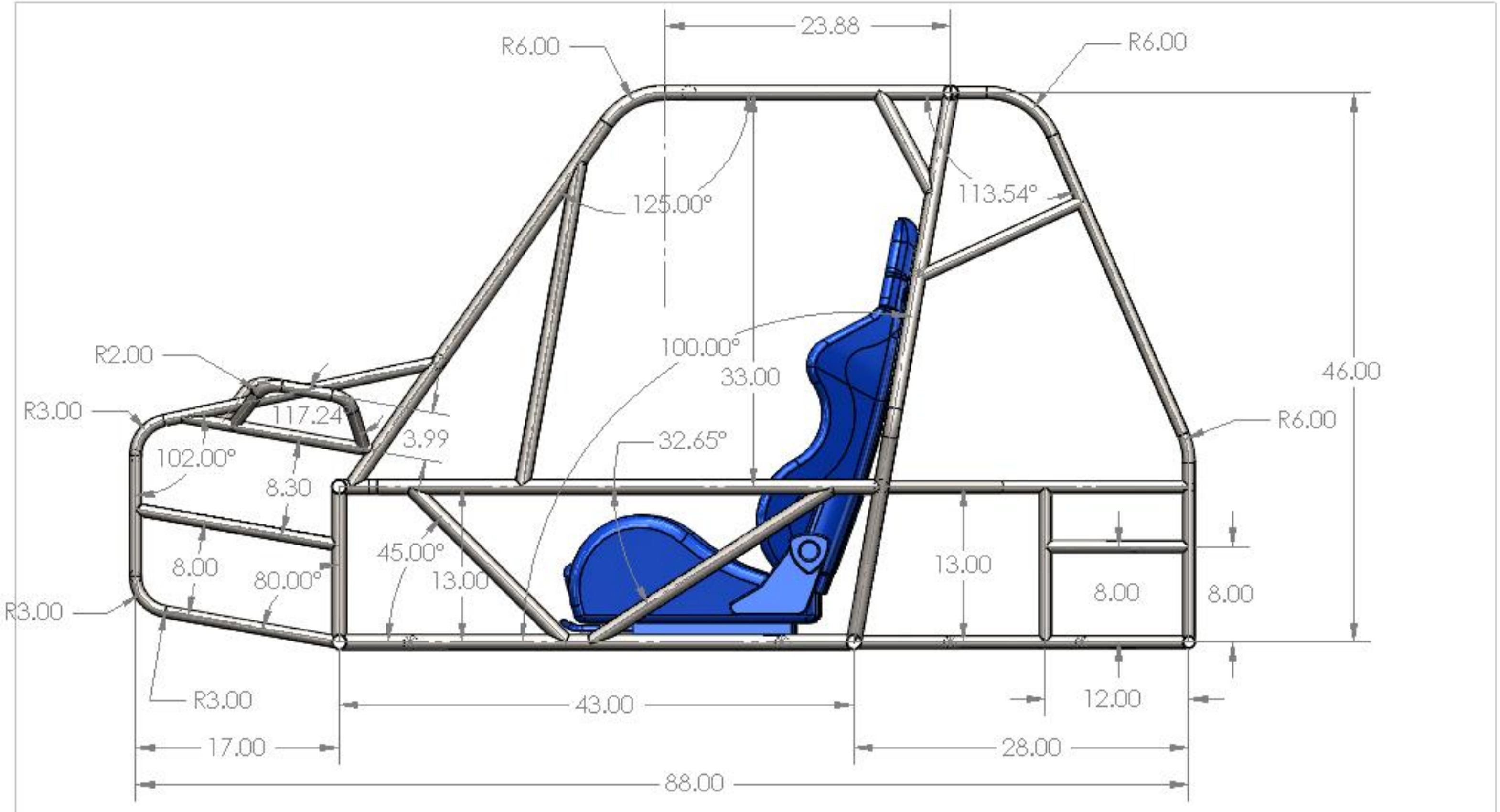

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TWO PLACE DECIMAL ± 0.625
THREE PLACE DECIMAL ± 0.10

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL AISI 4130

FINISH Powder Coat

DO NOT SCALE DRAWING

	NAME
DRAWN	Chris Bennett
CHECKED	
ENG APPR.	
MFG APPR.	
Q.A.	
COMMENTS:	

TITLE:

SAE Baja Frame
Side View

SIZE A DWG. NO. Frame V11 REV 11

SCALE:1:12 WEIGHT: SHEET 2 OF 5

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APPLICATION

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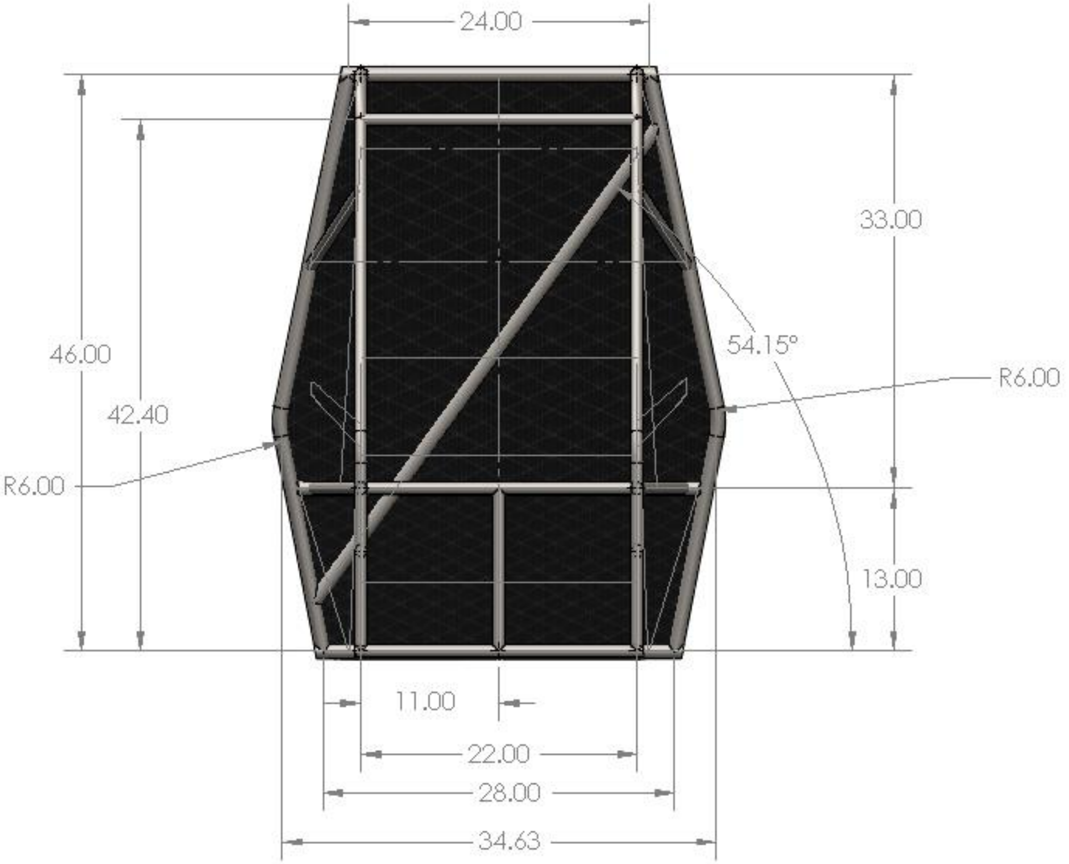

		UNLESS OTHERWISE SPECIFIED:		NAME	
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			CHECKED		Frame Rear
			ENG APPR.		
			MFG APPR.		
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		MATERIAL AISI 4130	COMMENTS:		SIZE A
NEXT ASSY	USED ON	FINISH Powder Coated			DWG. NO. Frame V11
APPLICATION		DO NOT SCALE DRAWING			REV 11
					SCALE: 1:32 WEIGHT: SHEET 3 OF 5

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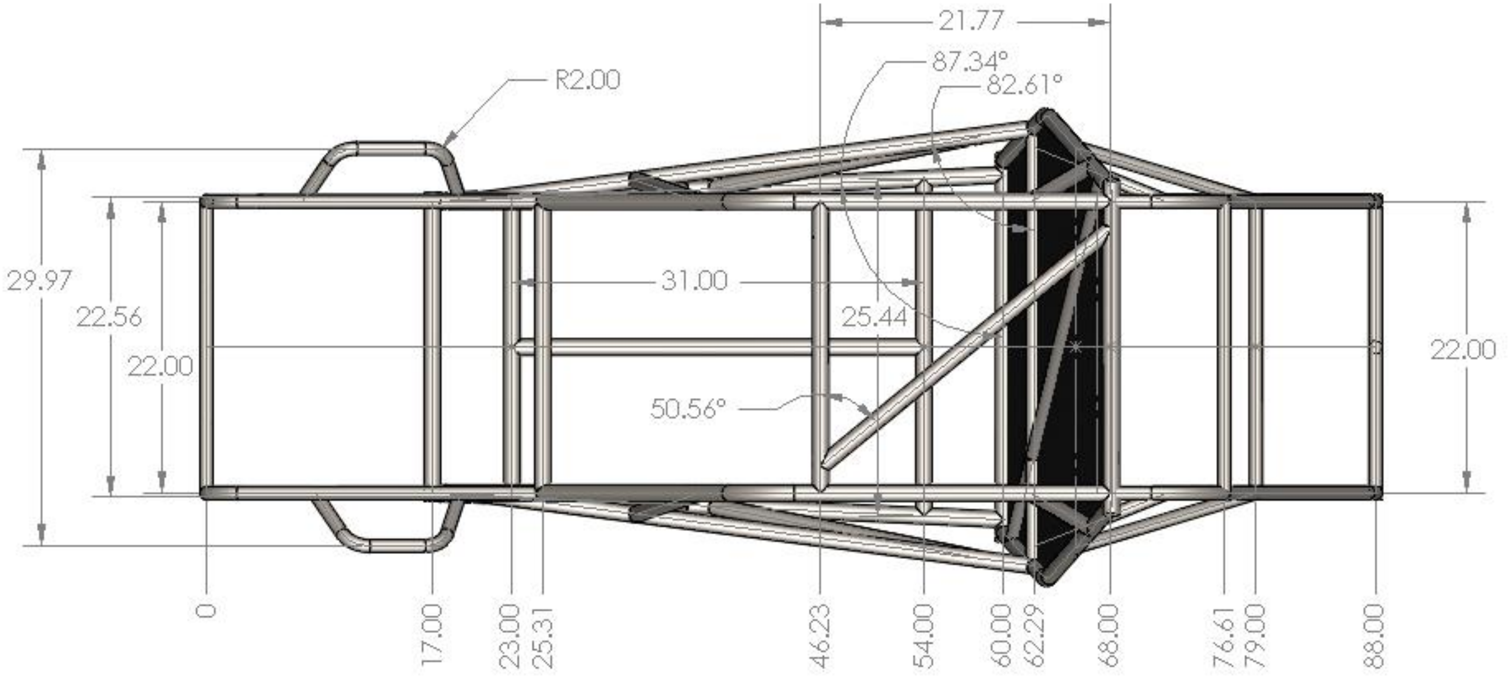

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APPLICATION	

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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL AISI 4130
FINISH Powder Coat
DO NOT SCALE DRAWING

	NAME
DRAWN	Chris Bennett
CHECKED	
ENG APPR.	
MFG APPR.	
Q.A.	
COMMENTS:	

TITLE:

Frame Top

SIZE A
DWG. NO. Frame V11
REV 11
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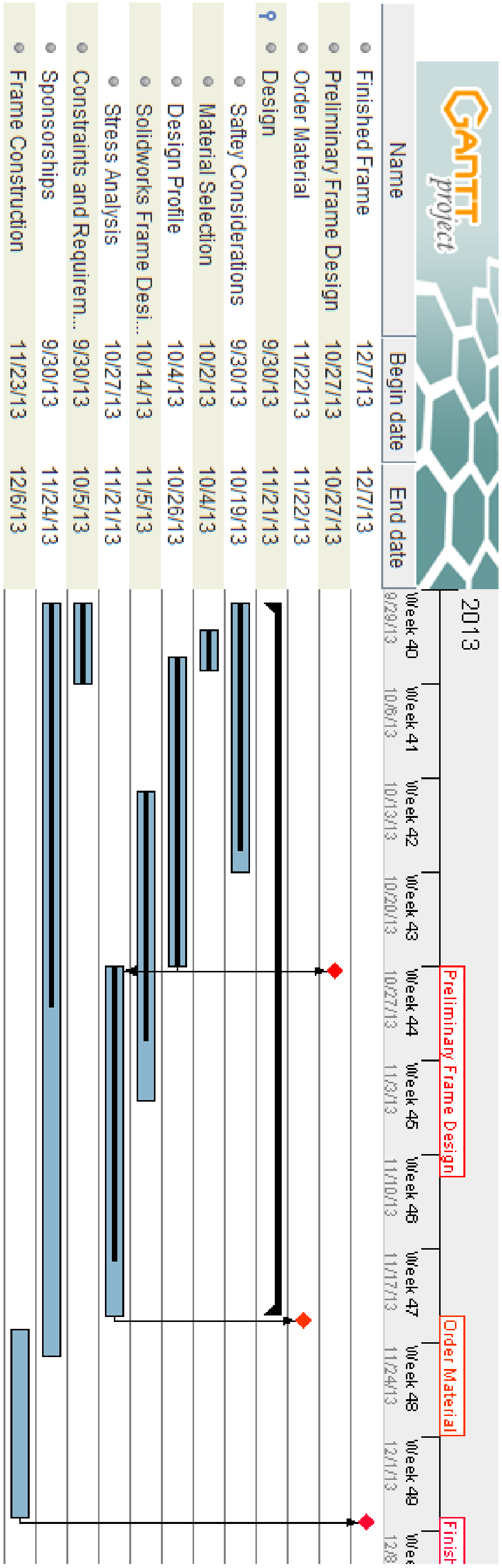
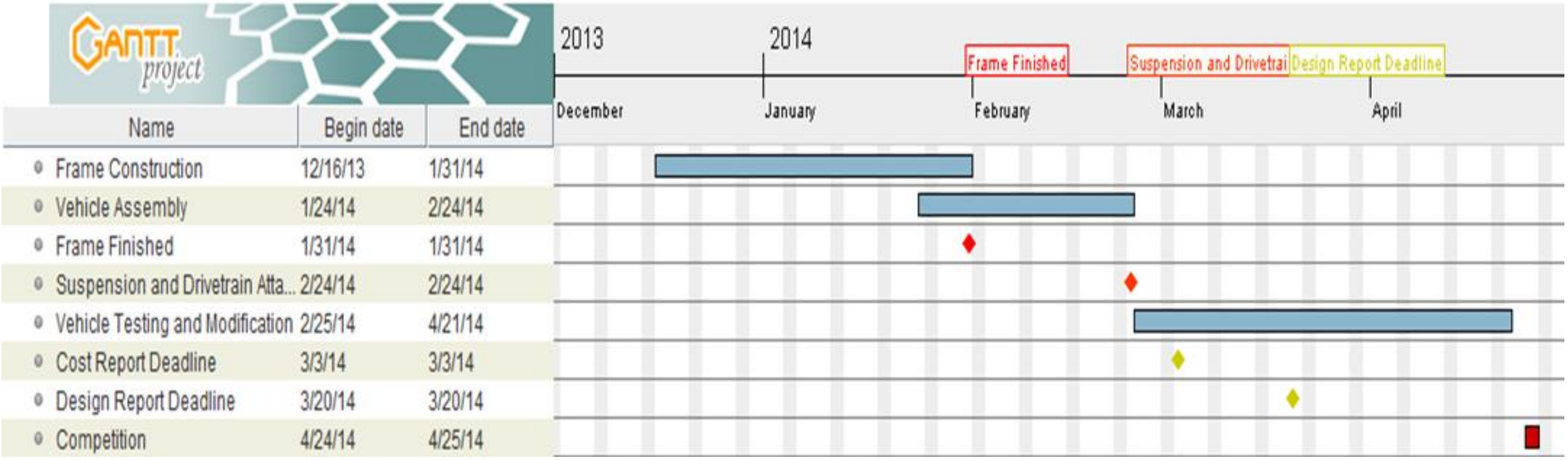
Appendix B: Project Planning



Name	Begin date	End date
Finished Frame	12/7/13	12/7/13
Preliminary Frame Design	10/27/13	10/27/13
Order Material	11/22/13	11/22/13
Design	9/30/13	11/21/13
Saftey Considerations	9/30/13	10/19/13
Material Selection	10/2/13	10/4/13
Design Profile	10/4/13	10/26/13
Solidworks Frame Desi...	10/14/13	11/5/13
Stress Analysis	10/27/13	11/21/13
Constraints and Requirem...	9/30/13	10/5/13
Sponsorships	9/30/13	11/24/13
Frame Construction	11/23/13	12/6/13



Name	Begin date	End date
Frame Construction	12/16/13	1/31/14
Vehicle Assembly	1/24/14	2/24/14
Frame Finished	1/31/14	1/31/14
Suspension and Drivetrain Atta...	2/24/14	2/24/14
Vehicle Testing and Modification	2/25/14	4/21/14
Cost Report Deadline	3/3/14	3/3/14
Design Report Deadline	3/20/14	3/20/14
Competition	4/24/14	4/25/14