ASME HUMAN-POWERED VEHICLE CHALLENGE:

SPEED CLASS

By

DAVID ANDREW COPP

A Thesis Submitted to The Honors College

In Partial Fulfillment of the Bachelors degree
With Honors in

Mechanical Engineering

THE UNIVERSITY OF ARIZONA

MAY 2011

Approved by:

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UNIVERSITY OF ARIZONA ASME HUMAN-POWERED VEHICLE CHALLENGE: SPEED CLASS

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Abstract

Human-powered transport is often the only type available in underdeveloped or inaccessible parts of the world, and if well designed, can be an increasingly viable form of sustainable transportation. ASME's International Human Powered Vehicle Challenge (HPVC) provides an opportunity for undergraduate engineering students to demonstrate the application of sound engineering design principles in the development of sustainable and practical transportation alternatives. In the HPVC, students work in teams to design and build efficient, highly engineered vehicles for everyday use—from commuting to work, to carrying goods to market.

Though some Speed Class vehicles have topped 60 mph, the competition assigns greater value to the elegance and ingenuity of the design, including presentation, practicality, safety and functionality. The recently-introduced Unrestricted Class presents new opportunities for creativity and innovation, allowing teams to incorporate regenerative energy storage devices in their designs.

For this thesis and senior capstone project, the senior design team will design and manufacture a human-powered vehicle by the 2011 Human Powered Vehicle Challenge date.

Statement of Roles and Responsibilities of Team Members:

David Copp

- Project Management
- Development Plan
- RPS and Harness Subsystem Assemblies and Analysis
- Summary of Risk Analysis and Mitigation
- Stability Analysis
- Manufacturing and testing
- Primary vehicle rider

Danielle Craig

- Drivetrain Subsystem Assembly and Analysis
- Requirements Review and Acceptance Test Plans
- System Requirements

Avi DuBois

- Introduction
- Scope of Project
- Fairing description

Ian Geery

- Frame and Fork Assemblies and Analysis

Heather Meacham

- Steering and Braking Assemblies

- Design Overview

Sean Phillips

- Bill of Materials
- Seat Positioning System
- Manufacturing and testing

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1.0 Introduction

1.1 Scope of the Document

This document intends to provide a top level, complete description of the final design selected and serves as a road map for the manufacture, assembly, implementation, and testing of the finished product. It provides results from detailed component analysis and thorough testing.

1.2 Problem Statement & Background

Human-powered transport is often the only type available in underdeveloped or inaccessible parts of the world, and if well designed, can be an increasingly viable form of sustainable transportation. ASME's International Human Powered Vehicle Challenge (HPVC) provides an opportunity for undergraduate engineering students to demonstrate the application of sound engineering design principles in the development of sustainable and practical transportation alternatives. In the HPVC, students work in teams to design and build efficient, highly engineered vehicles for everyday use—from commuting to work, to carrying goods to market.

Though some Speed Class vehicles have topped 60 mph, the competition assigns greater value to the elegance and ingenuity of the design, including presentation, practicality, safety and functionality. The recently-introduced Unrestricted Class presents new opportunities for creativity and innovation, allowing teams to incorporate regenerative energy storage devices in their designs.

1.3 Scope of the Project

For the 2011 Human Powered Vehicle Competition, the senior design team will design and manufacture a human powered vehicle by the competition date. This design's major components consist of three distinct parts which must be fully integrated into a complete vehicle. Those parts are as follows: a frame, a drive train, and a full-body fairing. The frame must meet or exceed appropriate factors of safety for the design. The frame must also be light weight and reasonably low-cost. It should be completed first, as it will determine the critical loading points needed to integrate the drive train and fairing components. The drive train should be designed to allow the minimum power input from the rider to achieve the maximum power output from the system. This can be done in several ways with different gearing methods. The final component is the fairing, which must be sufficiently light weight so as not to exceed the customer's desired maximum weight of 60 lbs. There are no material restrictions; however, the Rollover Protection System requirements will most likely assist in material selection. A design report required for competition should not exceed 30 pages and should include all tests and summaries of each method of analysis used. The club would like all major design, testing and construction to be completed by the design team.

1.4 Project Expectations

The team is expected to compete in the 2011 American Society of Mechanical Engineers' Human Powered Vehicle Challenge in Bozeman, Montana at the end of April. This team is also expected to provide sufficient documentation to allow subsequent teams the ability to build upon their data and research. The completed vehicle and documentation will remain in the possession of the UA|ASME club.

1.5 Customer

The sponsor for the 2010-2011 ASME Human Powered Vehicle Challenge- Speed Class is the UA|ASME student club. This chapter exists as a support network for students majoring in engineering and provides an introduction to the mechanical engineering industry. The club was last active in 2006 and participated in the HPVC with a tandem vehicle that placed second in its division. As there has been a large span of inactivity, all documents from the previous competitions are missing. The club would like to use this project to help in reestablishing the UA student chapter and provide a basis for all subsequent teams.

2.0 Project Progress and Background

The University of Arizona has not participated in the Human Powered Vehicle Challenge since a tandem vehicle entry in 2006. While the lack of legacy information proved frustrating in that there was a lack of pre-defined direction for the team, the end result was a design process that was devoid of emotion or loyalty to a particular vehicle style, allowing for the team to be more objective in the design process. This provided an incredible opportunity to begin fresh and develop what is hoped to be a successful design.

While the prototype afforded the team experience building and assimilating concepts pulled from several recumbent racers, there was a significant amount of time spent modifying it to make it work for all of our riders. Upon the completion of the prototype frame and evaluation of the vehicle, the decision was made to deviate sharply from the original path and to design and build a second bicycle. This new design had to be completed in three weeks time from start to finish allowing the team to remain on track with the build schedule and ensuring enough time to modify and build the fairing.

While the *Gila Monster* is unproven in the field of competition, the design, analysis and testing indicate a strong likelihood of competitiveness. The new design incorporates a more commercial look and feel to the final product, from the aluminum frame to the ergonomic adjustability. Although the general goals of the team would have been met by the prototype frame, the final frame is far superior with respect to rider comfort and safety as well as being more aesthetically pleasant and practical with its modularity.

Figure 2.1: Chromoly Prototype

Figure 2.2: New aluminum frame in jig

Figure 2.3: Gila Monster: Final Vehicle

3.0 Design and Innovation

As the UA|ASME student club has been dormant for several years, this year's team had no access to the previous competition submissions either in report format or in previously completed vehicles. A decision was made last spring to attend the 2010 HPVC West Coast at California State University – Northridge, providing a basic idea of which designs had the best chances of success and those which did not. Several conclusions were arrived upon early in the design process, such as ruling out tandem vehicles and rear-wheel steering designs. The bikes and trikes that fared the best for either the speed or unrestricted classes were simplistic in design and of solid construction. This further narrowed the options with which the team was faced. The decision matrices for the prototype frame and final frame are provided in subsections 3.1.1 and 3.3.1.

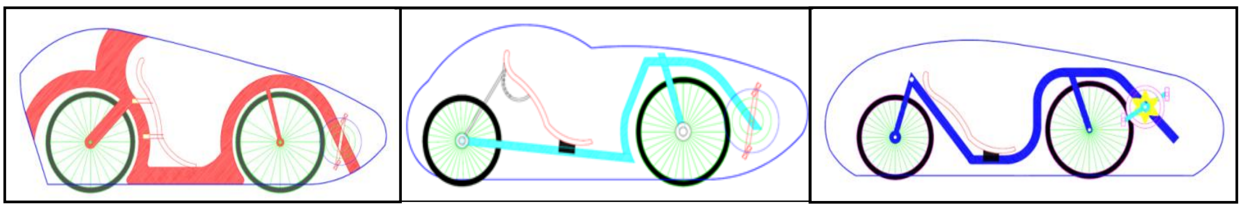


Figure 3.1 Three preliminary design concepts, from right to left: NOCOM frame, C-Bend, S-Bend.

3.1 Research

Beyond viewing last year's competition, a substantial amount of time was spent researching successful recumbent bicycles. The team's original definition of a successful vehicle was one that simply went 'fast', providing a glimpse into our naïveté, the existence of which will be demonstrated further in several of the team's prototype design choices. Recumbent racing bicycles that were researched included the *Varna Diablo* series as well as the *Mephisto* and *Blue Yonder*, and additional research was performed on commercial non-competitive recumbent bicycles and tricycles.

While this research provided the necessary theoretical background, nothing was as useful as building a prototype would prove. With the intention of the original design being the one used at competition, it quickly became apparent that a major redesign was necessary for the team to be competitive. Major issues with the original design included chain path and tensioning problems, an overly-heavy frame and incorrect rider positioning for the wide range of rider heights.

3.1.1 Prototype

The best prototype design was determined using a weighted grading scale. The following design categories were considered for each vehicle concept: cost, safety, reliability, expected life, frontal area and weight. Table 3.1 shows the weights assigned to each criterion and how they were evaluated for each design.

Criterion	Weight	Concept 1 Score	Concept 2 Score	Concept 3 Score
Cost	0.3	3	7	7
Weight	0.1	7	5	8
Reliability	0.2	4	8	4
Expected Life	0.1	4	8	4
Frontal Area	0.1	2	8	8
Safety	0.2	6	9	6
Total	1	4.2	7.6	6.1

Table 3.1: Concept Screening Matrix

The final prototype concept that the team chose to work with was the streamlined vehicle using the C-bend frame. This design was chosen because of the following:

- Least expensive overall
- Chromoly frame provided the best material properties neglecting weight
- Has the lowest profile, potentially the most aerodynamic design
- Greatest manufacturability compared to the other frames, single bend per piece of metal

The team opted to make the prototype frame out of Chromoly steel because it would allow the greatest flexibility in welding the frame together and reduce the risk of the frame breaking while conducting prototype frame tests, which are detailed below. Being able to weld the prototype together ourselves was key because it was necessary to make quick changes to hardware and subcomponent locations to continue testing. We used this frame for trial and error purposes and to ensure that our final vehicle build is manufactured correctly.

The fairing material chosen was fiberglass, as it minimized the cost of the project, would form well with vacuum bagging, could hold a smooth surface and was the easiest of the composite fabrics to work with. Another feature of this design was the more vertical windshield that provided better range of visibility for the rider. As the curvature and angle of viewing through the PETG plastic increases, the view outside becomes distorted. The fairing would have also been manufactured to fit a removable roll cage that could be tested without risking damage to the entire fairing. The roll cage was to have been made of a combination of Nomex Honeycomb core material and carbon fiber to improve stiffness. There were also vertical and horizontal cross members planned that would have been made of lightweight aluminum that would assist in preventing deflection during high loading conditions and allow for the use of a harness with wrap-around ends, eliminating the need for drilling holes in the frame or attaching tabs.

The prototype frame is seen in Figure 2.1 above next to the new aluminum frame, Figure 2.2. Based upon the first round selections and design evaluation, a different method was chosen to validate the results of the process.

3.2 Design Goals

Based off of research conducted during the summer of 2010, the UA|ASME design team was able to come up with certain design requirements deemed necessary for this vehicle. They include the following:

Team Goals	40 mph HPVC Sprint Speed
	Adjustable seat
	Low vehicle weight
	High level of stability and maneuverability
	Redundant braking system
	Fiberglass fairing
Constraints	25 ft. turn radius
	Full stop from 15 mph within 20 feet
	Travel 100 feet in straight line
	Safety harness with at least 3 attachment points
	Fully faired

Table 3.2: Project Requirements

From this list of goals and constraints for our project, we were able to come up with a generalized concept vehicle. This concept was implemented into our prototype vehicle. The project network with task durations is shown in Figure 3.3.

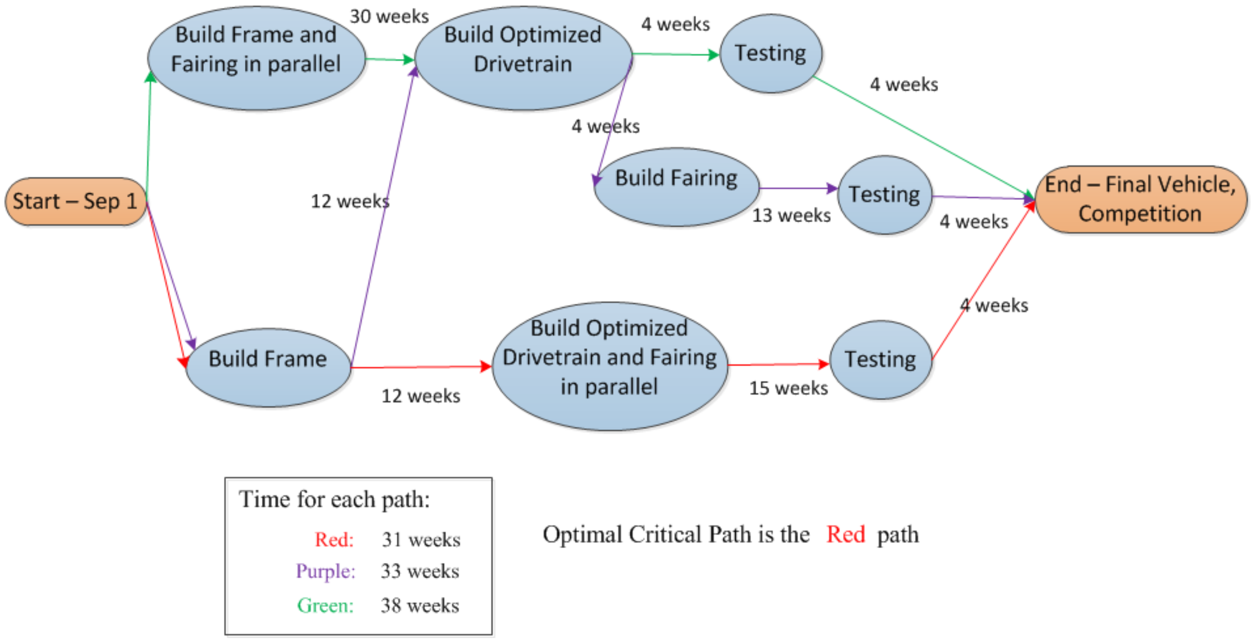


Figure 3.3: Project Network

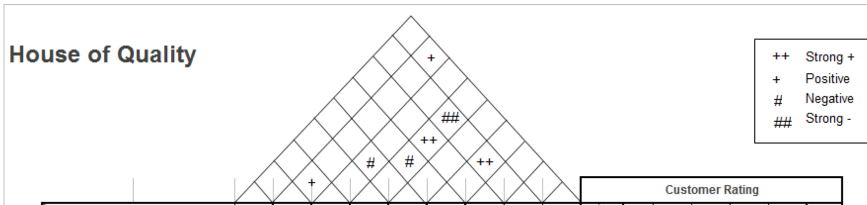
3.3 Design Selection for Competition

The new design was reached using a Quality Function Deployment tool (QFD) after developing a short list of pros and cons based on the prototype frame. This allowed the team to evaluate the prototype by a highly simplified method.

	Pro	**Con**
Prototype	• Built and partially tested • Aerodynamically superior to most other frame styles	• Poor turning • Not suitable for most team members skill level or physical attributes • Dangerous chain path

Table 3.4 Prototype Evaluation

Table 3.4 illustrates the pros and cons that were determined after build and test completion. The competition vehicle was designed to overcome some of the pitfalls of the prototype and includes all design change requirements. Table 3.5 details the design development of the competition vehicle in a House of Quality matrix. This matrix shows that the new design is a significant improvement upon the prototype vehicle and is a more advantageous build for competition.



Customer Requirements (What) / Design Requirements (How)	Importance (1-10)	Weight	Cost	Min. Rider Height	Development Time	Seatback Angle	Crank Length	Field of Vision	Turn Radius	Customer Requirement	Prototype	Planned Vehicle	Improvement Ratio	Sales Points	Relative Improvement	Overall Rating
										Customer Rating						
Fast	4	7	8	6		7	6	3		5	1	5	1.4	1.3	0.15	9.1
Stable	7	8		6		8		3	9	4	1	4	1.3	1.2	0.1	6.24
Safe	10		6			7		10	10	5	1	5	1.4	1.5	0.2	10.5
Durable	3	9	8							3	5	3	0.8	1	0.05	2.4
Lightweight Vehicle	5	9	5							2	1	5	1.4	1.5	0.1	4.2
Repairable	2		7		6					3	5	2	0.7	1	0.05	2.1
Low Cost	8		9		8					4	2	4	1.2	1.5	0.1	7.2
Innovative	6	7	9		4					3	4	4	1	1.4	0.1	4.2
Maneuverable	9						8	8	9	4	1	5	1.4	1.4	0.1	7.84
Time to Deliver	1				9					3	1	2	1.1	1	0.05	3.3
Absolute Importance	6.40	3.90	5.45	1.50	1.95	3.25	1.70	3.55	3.80	31.50	1	2	3	4	5	
Relative Importance	0.2	0.12	0.17	0.05	0.06	0.1	0.05	0.11	0.12	5			1(low) - 5(high)			
Prototype		75	3000	72	900	135	170	180	25	4						
Improvement Direction		↑	↑	↑	↑	↑	↑			3						
Target Value		60	2500	64		150	152	180	25	2						
Units		lbs	$	in	hrs	deg	mm	deg	ft	1						

Table 3.5: House of Quality for Final Design

3.3.1 Final Vehicle

From prototype build and testing, we were able to determine what subcomponent designs worked to meet our requirements and those designs which did not. After the disaster which was the prototype frame, several decisions were made regarding frame material, modularity and overall vehicle design.

The greatest concern for the team was finding a material that could withstand the forces exerted upon it in the course of normal riding as well as be considerably lighter in weight than the Chromoly. As the budget for building a second complete frame was limited, the team decided to look into 6061-T6 Aluminum. The calculations necessary to determine whether or not the new material would be strong enough are as follows.

Equation 1

The selected aluminum tube with a wall thickness of .125 inches provides a yield stress of 13550 psi. The yield for the T6 is generally established at 37000 psi. This provided a factor of safety of 2.73 in normal uniform loading of a simply supported beam. Comparison to load factors in similar applications where weight of the final product plays a critical role, such as aircraft design, the desired factor of safety for this vehicle was any value greater than 2. To further strengthen the frame in locations where the bending stresses are the highest, an aluminum c-channel was placed. This acted not only as reinforcement but also as a seat positioning mechanism. Additional gussets were welded into the frame as well where there were indications of higher load forces such as both of the bottom bracket positions.

Equation 2

The deflection of the beam was also investigated as there was concern that in the switch from steel to aluminum the modulus of elasticity decreased. Equation 2 was used to calculate the anticipated deflection for the simply supported condition, in the case of our tube selection a deflection value of .391 inches was determined. Again, the addition of the c-channel to the top of the seat tube allowed the team to strengthen the frame and help protect not only the rider from possible chain slip or break due to the deflection issues but also provide a firmer ride and minimize unnecessary power losses.

The modular connection for the front and rear of the vehicle was also strengthened by adding a ferrule that was permanently epoxied into the rear fork section of the frame, which will distribute the bending load experienced at this joint. The bolts used in the modular connection cannot withstand high bending loads and therefore the ferrule will also reduce the risk of the bolts failing.

Since the prototype vehicle was not rideable due to physical constraints for several of the team members, it was determined that a much smaller 16 inch diameter wheel in the front would be better suited to meet requirements; the 24 inch wheel that had originally been located in the front of the prototype was instead used as the rear wheel. With this change, it was necessary to shift from a front wheel drive system to a rear wheel drive one as the amount of travel is dependent upon the size of the powered wheel.

The rider also benefitted from this shift in the drive wheel location as the chances of injury to the rider's ankles and legs decreased. By removing one chain path from between the rider's legs, the required rider stance decreased. Originally, the rider was forced to pedal in a bow-legged fashion with not only a full cassette but also a disc brake located on the front wheel.

To aide in the welding of this new aluminum frame a jig stand was built to ensure that all welds were made at the correct angles and that the frame remained planar. The design was also simplified by creating a frame that would need fewer welded pieces and contained no bent tubes allowing for most of the welded joints to be mitered versus fish mouthed.

The final fairing schedule consists of three different weights of fiberglass and Lantor Soric XF as the core material as well as reinforcement of the roll cage area with .125 inch Nomex Honeycomb . This enables easy modification of the layers to fit the needs of the design. As there are no severe or compound curves involved, the weave of the fiberglass is not the primary concern. Instead, rigidity is the team's top priority.

The schedule for the fairing build is detailed in Table 3.6. The lighter layers of fiberglass will prevent print through from the core fabric during vacuum bagging and produce a better finish than the use of a coarser weave fabric as the top layer. A final gel coat will also ensure that the finish is of higher quality. Epoxy resin will be used in the composite build and will be mixed with 120 minute hardener as the team has a significant amount of surface area that will need to be covered. This, in addition to the number of layers used, will guarantee a better final cure as none of the courses will have time to set before the vacuum bagging of the mold is complete. A black pigment will also be added to the epoxy before being applied so that the color difference will in determining whether or not the resin has fully saturated through the fabric. This also offers the best color durability as it is embedded in the fairing and not applied as a top coat that can be damaged.

Weight (oz)	Fabric and Weave Type	Orientation
.73	Fiberglass, Plain	0˚,90˚
3	Fiberglass, Plain	0˚,90˚
3	Fiberglass, Plain	0˚,90˚
6	Fiberglass, Tight	±45˚
6	Fiberglass, Tight	±45˚
Core	Lantor Soric XF	
6	Fiberglass, Tight	0˚,90˚
6	Fiberglass, Tight	0˚,90˚
3	Fiberglass, Plain	±45˚
3	Fiberglass, Plain	±45˚

Table 3.6: Composite Schedule

Seaming of the fairing will be done by using 2 inch carbon fiber tape and the same epoxy resin as used in the regular layup. While reinforcement of the openings for the wheels and the windshield area will be done with the use of additional layers or patches of the 6 ounce fiberglass. Attachment points and fixtures will be installed with All-Purpose Amazing Goop versus other epoxy systems as the flexibility and elasticity of the adhesive as well as the heat and moisture resistance properties are favorable in our vehicle application.

The windshield will be constructed from clear Acrylic sheeting of either .06 or .08 inches in thickness. The determination of which sheet thickness will be done based on heating methods available to the team as the size of the windshield eliminates the possibility of using a standard oven for even heating of the material.

4.0 Design Analysis

The team created a work breakdown structure which allowed us to divide the design of the subcomponents between team members. Analysis was focused primarily on the fairing, frame, drivetrain, and the vehicle stability which will be detailed in the sections below.

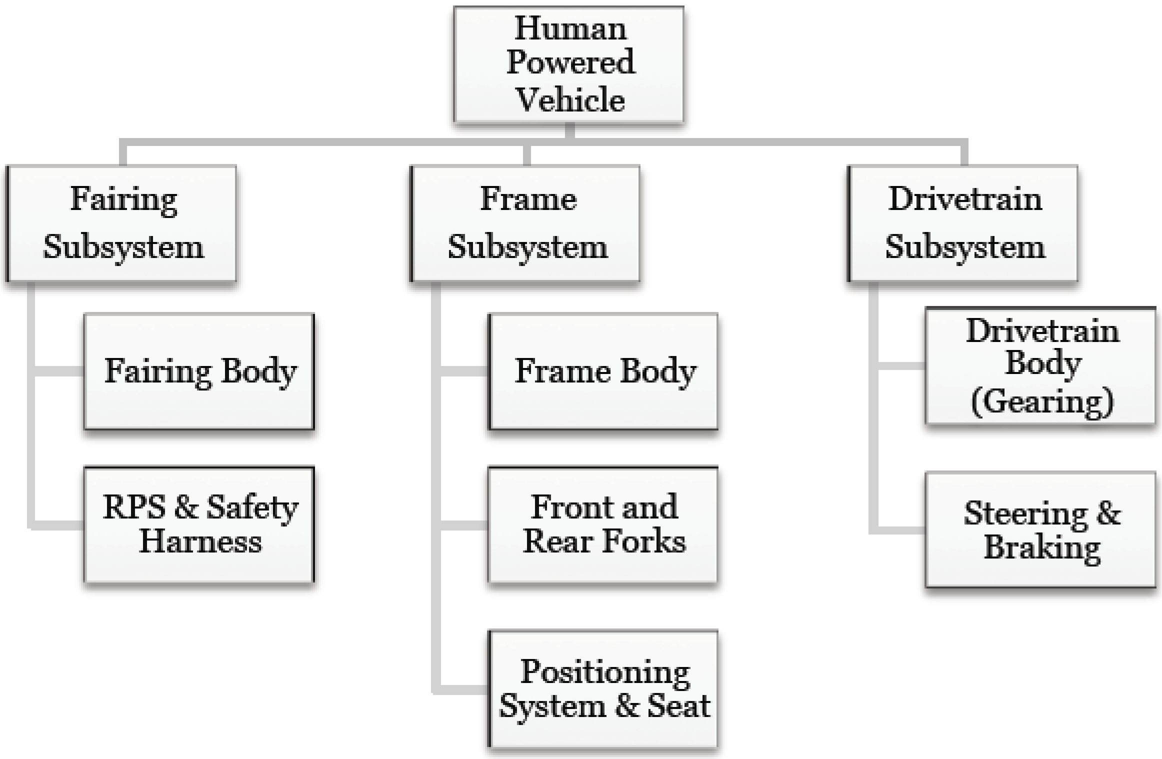


Figure 4.1: Work Breakdown Structure Diagram

4.1 Aerodynamics Analysis

Drag force values are dependent upon the weather and geographical conditions in Indianapolis where the competition will be held. These values include the average temperature, elevation, air pressure and air density in Indianapolis at the end of April, where averages of these values have been obtained through research on weather information websites. The frontal area of the fairing has been estimated and drag coefficient values have been obtained from Sighard Hoerner's book *Fluid-Dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance.*

As can be seen in Table 4.2, riding the vehicle in Indianapolis will induce slightly more drag force onto the vehicle because of the fact that Indianapolis has a much lower average elevation to that at the University of Arizona in Tucson, Arizona. The lower elevation in Indianapolis also increases the power required of the rider to pedal the vehicle. This will not cause a very drastic difference for the rider, but this analysis does show that the fairing must be as aerodynamic as possible so that it does not increase the drag force that the rider must overcome in order to power the vehicle.

	Indianapolis, IN			Tucson, AZ		
	D1 (717ft)	D2 (717ft)	D3 (717ft)	D1 (2000ft)	D2 (2000ft)	D3 (2000ft)
	0	0	0	0	0	0
	0.161	0.215	0.268	0.1543	0.205	0.257
	0.645	0.860	1.075	0.617	0.823	1.028
	1.452	1.936	2.420	1.388	1.851	2.314
	2.581	3.442	4.303	2.469	3.292	4.115
	4.034	5.378	6.723	3.858	5.144	6.430
	5.809	7.745	9.681	5.555	7.407	9.259
	7.906	10.542	13.177	7.562	10.082	12.603
	10.327	13.769	17.212	9.876	13.169	16.461
Velocity (mph)	**HP Required**			**HP Required**		
0	0	0	0	0	0	0
10	0.004	0.005	0.007	0.0041	0.005	0.0069
20	0.035	0.046	0.058	0.033	0.044	0.055
30	0.118	0.158	0.197	0.113	0.151	0.188
40	0.281	0.374	0.468	0.268	0.358	0.447
50	0.548	0.731	0.914	0.524	0.699	0.874
60	0.948	1.264	1.580	0.907	1.209	1.511
70	1.506	2.008	2.510	1.440	1.920	2.400
80	2.248	2.997	3.746	2.150	2.866	3.583

Table 4.2: Drag Force and Horsepower Required Calculated Data

4.1.1 Fairing

Aerodynamics plays a large role in the efficiency of the power conversion from rider to vehicle velocity. The smaller the frontal area, more streamlined the shape and smoother the finish, the better the vehicle will perform. This is due to a reduction in drag forces created by the wind. The best aerodynamic conditions occur when all of the above criteria are maximized and the flow over the bicycle is kept in the laminar flow regime. This means that the vehicle's fairing, or enclosure, must be less than ten feet as a general rule for speed races. The UA|ASME team's fairing is 96 inches in length, translating to 8 feet, which will keep the fairing within the critical length. While there will still be a transition from the laminar to turbulent flow regime greatly increasing the drag at higher velocities, the streamline shape of the bike and high gloss finish applied to the fairing will again help negate these effects.

Figure 4.3: Measuring Tolerance Points for Fairing

Using CFDesign 2010, a computational fluid dynamics (CFD) model was created to determine the optimal fairing design. A mock windtunnel was generated in CFDesign 2010 to analysis the fairing designs. Figure 4.4 shows the model of the new fairing built in SolidWorks 2011 inside the mock windtunnel.

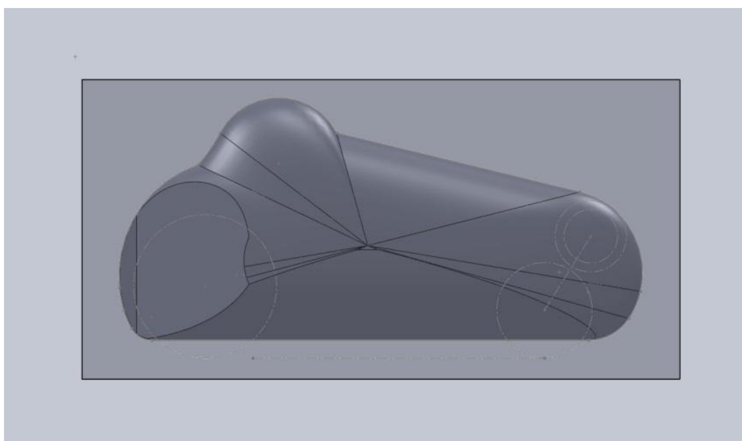


Figure 4.4: SolidWorks model of the design to be simulated in CFDesign 2010.

The great advantage of CFDesign is the iteration convergence plot which graphs several critical values with respect to the numerical iteration index so that one can visually see the solutions converge to the final answer in real time. Figure 4.5 shows the convergence plot of critical values for a simulation at index number 102 in CFDesign. This particular simulation ran for 1.5 hours with 111 iterations.

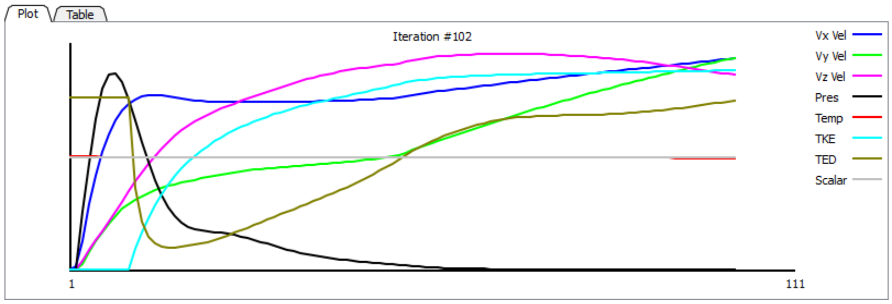


Figure 4.5: Convergence Plot

The aerodynamic force was calculated using Equation 3 after the simulation was completed.

– **Equation 3**

Where ρ is the density of the fluid, C_d is the drag Coefficient, A is the project area, and V is the velocity. More aerodynamic fairings will have a lower C_dA value and for the vehicle fairing it is, therefore, desirable to have the lowest C_dA value. The program specifies the force of air that is exerting on the body as well as the velocity and pressure profile along the body of the vehicle. Assuming the density is constant and the velocity is 40 mph you can massage Equation 3 to give the C_dA.

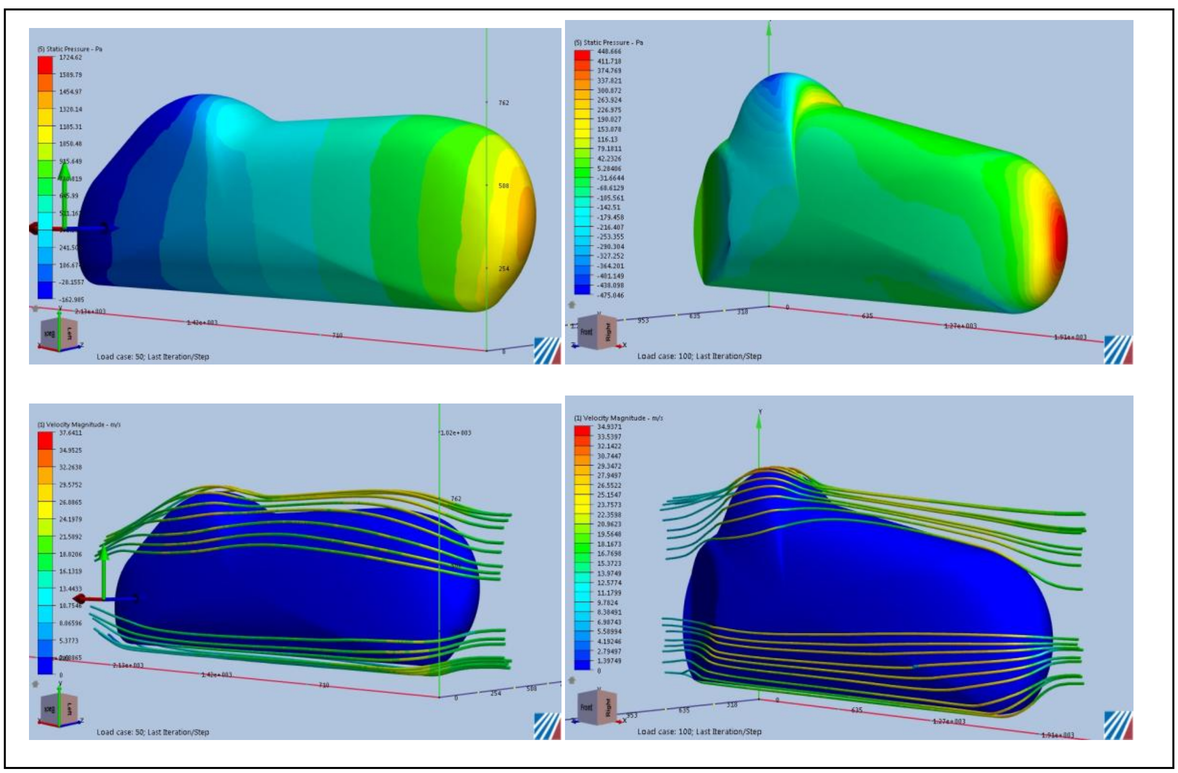


Figure 4.6: The outputs of the CFD simulations. Static Pressure (top row), Velocity Particle Tracing (bottom row)

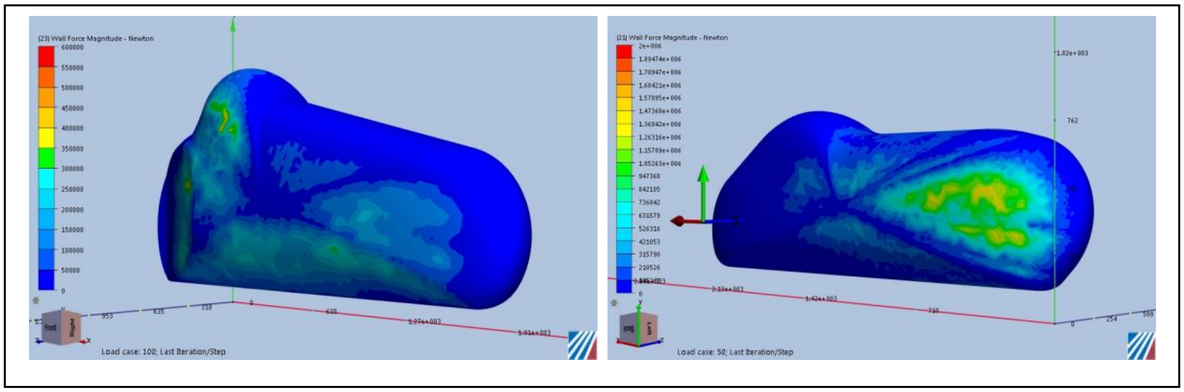


Figure 4.7: Force Magnitude Profile

	Force (N)	Scalar	Density (kg/m^3)	Velocity (m/s)	Cd
New Fairing	5.4396	0.5	0.1	17.88	0.3403
Old Fairing	3.21	0.5	0.1	17.88	0.200817

Table 4.8: Aerodynamic Drag Calculation

Table 4.8 shows the difference in fairing designs of the prototype and the new iteration vehicle designs. The new fairing is not as aerodynamic as the prototype, but this is one of the trade-offs that comes with the new, lighter vehicle design.

4.1.2 Drivetrain Analysis

Considerations accounted for in the analysis of the drivetrain included the elevation, temperature, and air density of the competition location which could affect the drag on the vehicle, the power required and the available power of an average person to power the vehicle, and gear ratios to obtain our required speed of at least 40 miles per hour (MPH).

Using a jackshaft-intermediary gear system, we were able to reduce the amount of power input from the rider and increase our output speed. Figure 4.9 shows the progression of gear changes through the gear cassette at the driving wheel and what maximum output RPM is potentially attainable, assuming that the maximum rider cadence is about 120 RPM.

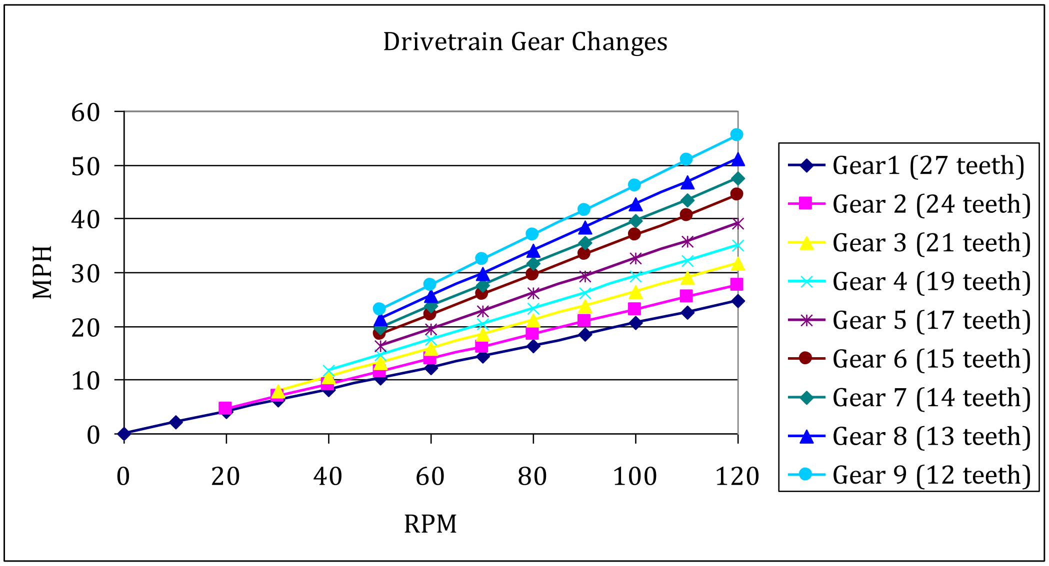


Figure 4.9: Drivetrain Gear Changes

Figure 4.9 shows that the gear changes will be smooth for the rider. This is based off of how close the required RPM is for each gear at a specified MPH. Meaning, that in 4th gear and an input of 70 RPM, the rider will be able to easily switch to 5th gear because the RPM needed to maintain a speed of about 20 MPH is actually less in 5th gear, which means that the rider will not have to increase their power input very much to change gears.

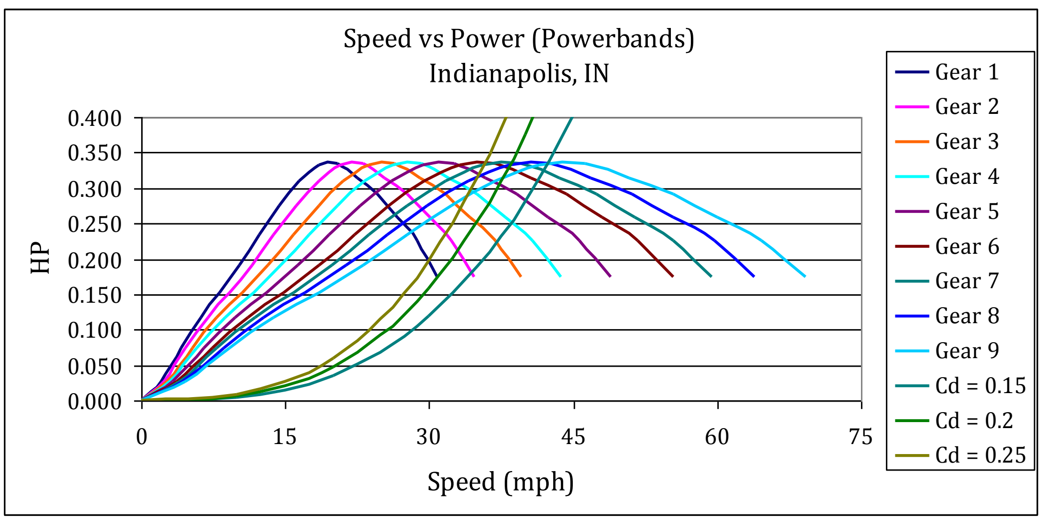


Figure 4.10: Speed vs. Power

In Figure 4.10, the lines labeled "Cd" represent the input power required to pedal the vehicle for three different drag coefficient (Cd) assumptions. And the other lines represent the available human power for each gear. The purpose of this graph was to try different combinations of gear ratios to obtain the best overlap between the power required and power available lines, which would give the best drivetrain design for the vehicle. The best overlap would occur when the line labeled Cd=0.15, which is the lowest assumed drag coefficient value of the fairing, and the Gear 9, which is the highest gear available, line would cross at about 45 MPH, which would mean that the rider should be able to reach the required speed of at least 40 MPH.

4.2 Stability Analysis

The following figures and analysis comes from the textbook *Fundamentals of Vehicle Dynamics* by Gillespie. Figure 4.11 depicts the bicycle as it makes a turn of radius, R where is the steering angle, L is the wheelbase, b and c are the distances from the center of gravity to the front and rear axles respectively, and is the slip angle of the wheel.

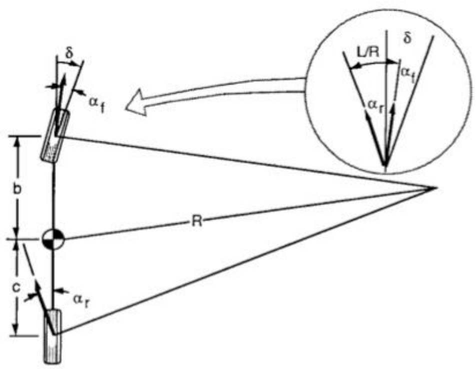


Figure 4.11: Bicycle Stability

The vehicle is stable when the following equation is true:

Equation 4

Equation 4 states that if the sum of the lateral cornering forces from the tires ( ) is equal to the mass of the vehicle ( ) multiplied by the centripetal acceleration (, where V is forward velocity and R is the radius of the turn), then the vehicle is stable and will not experience tire slip or lateral sliding. When the centripetal acceleration gets too large (i.e.), the vehicle becomes unstable.

The plot below shows the relation of lateral force to slip angle of the tires and is useful in performing stability analysis.

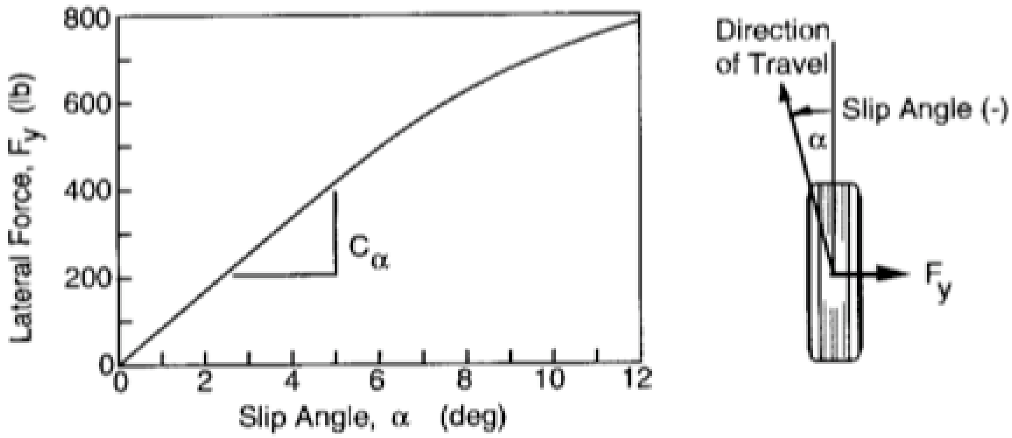


Figure 4.12: Slip Angle Plot

A program was written in MATLAB to analyze the stability of the vehicle given various parameters. The program was specifically used to determine the critical velocity beyond which the vehicle would become unstable for differing steering angles and turning radii. Figure 4.13 below shows the results of this analysis. See Appendix A for the program code.

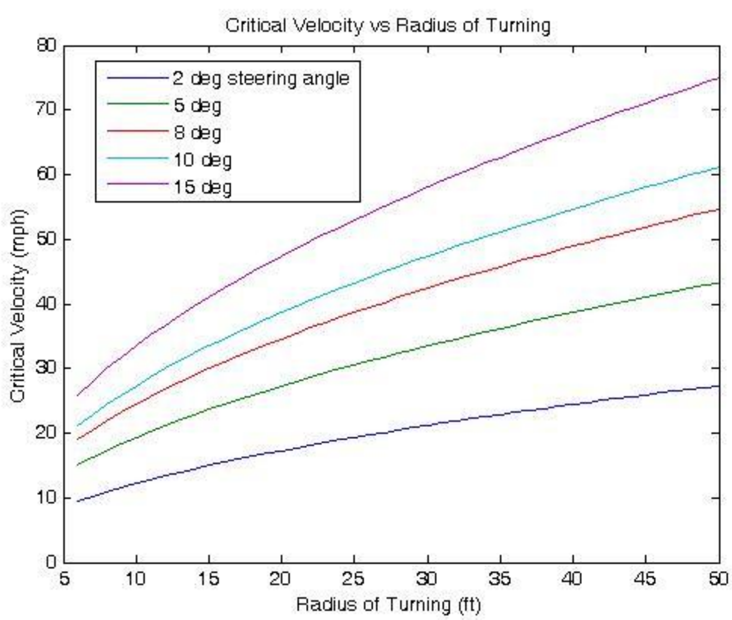


Figure 4.13: Critical Velocity and Turning Angle

Research into the geometry necessary for stability also included a foray into the world of single-track vehicle control. This allowed the team to determine one of the causes for the poor handling of the prototype. Even with the most skilled of our riders, the torque produced by the trail was difficult to overcome. To establish the range of trail required for optimal control of the new vehicle, the following formulas were utilized.

Equation 5

Equation 6

In these equations, the variables are as follows: K5 is the steering responsiveness with lower values leading toward less required input, B is the horizontal distance from the rear wheel point of contact to the occupied vehicle center of gravity, M is the total mass of the vehicle including the rider, h is the vertical distance from the ground to the center of gravity and Kx is the gyration value assigned to a specific seat back angle. In this case, a seat back angle of 30 degrees was chosen to reduce the overall height of the fairing as much as possible without undermining rider comfort, control and safety. For the maximum trail, the wheel flop was calculated as 20mm and then used in combination with the following terms. Rh represents the radius of the handlebars; Nf is the normal force at the front wheel (or approximate front wheel loading) and β is the compliment of the head tube angle. To satisfy conditions for an easy to handle vehicle a flop value of 200 N/rad was chosen. With these equations the range of trail suitable for the new vehicle was anywhere between .849in and 4.52in (21.6 and 114.8 mm respectively). The final trail of the vehicle is 1.34 in (53 mm).

5.0 Testing

Testing of the vehicle largely occurred on a trial and error basis on the prototype vehicle. This vehicle was an extremely useful tool in our build process because we were able to determine what parts of our initial design worked and what needed to be modified. This was a working prototype and adjustments were, therefore, able to be made to the frame and its subcomponents to best suit the requirements for the final vehicle design. After vehicle fabrication is been completed, acceptance testing will be conducted on the final vehicle design and any further performance optimization will be determined and incorporated before the HPVC competition.

5.1 Prototype Frame Test

Testing of the prototype frame was conducted after frame fabrication and hardware installation was completed. The best rider of the team was chosen to test the vehicle first because this person would be able to power the vehicle even if the drivetrain design did not initially meet the requirements of the project. To determine whether the vehicle met the competition requirements, a course around a nearby parking lot was constructed which would allow the rider to get up to a cadence of at least 60 rpm and make the 25 foot radius turn that will be seen at competition. Several tests were conducted on this vehicle as modifications were made to it. These changes and their outcomes in testing are detailed below in Table 4.1.

Test	**Action**
Balance	Drive straight for 100 feet
Steering	Weaving
	90 degree turn, 25 foot radius

	Straight away
Pedaling	Ease of pedaling
Ingress/Egress	Ease of ingress/egress
	Frame loaded and unloaded
Rider Comfort	Seat comfort
	Pedal length & alignment
	Steering wheel alignment
	Long distance comfort

Table 5.1: Prototype Vehicle Test Items

A major requirement of this vehicle was that it has to be usable by all team members, who range in heights from 5'1" to 6'. However, a severe drawback of the prototype frame design was that it was not rideable for most of the team because the front crank was positioned too far forward on the frame and was out of reach for many of the team members. Several options were considered to overcome this design flaw and ultimately, the frame itself was modified to wrap more tightly around the front wheel and shorten the length of the tube so that the crank was closer to the seat. This modification allowed the majority of the team to ride the bike, but still not all members. It was concluded that the next iteration of the frame would need to be redesigned to meet out rider requirement.

During testing, the prototype was prone to chain slip due to lack of proper tensioning in the chain. Idlers were added to the drivetrain subsystem design to manage the risk associated with chain slip. The seat design was also modified throughout the testing phase. The riders that tested the vehicle noticed significant improvement in their ability to power the vehicle with a more structured seat back and bottom with which they could push off of to provide more power with their legs. Modifications were also made to the attachment of the seat back to the seat bottom to increase the rigidity of the seat and reduce torque induced on the screw attachments.

Steering issues arose from using crank arms longer than 152mm, which obstructed the wheel from allowing the vehicle from easily maneuvering around the 25 foot radius turns. Our final vehicle design will, therefore, incorporate 152mm crank arms. From rider feedback, it was suggested to move the steering wheel closer to the rider to allow for better control and rider comfort. However, the extended steering wheel also proved to reduce the ease with which riders could enter and exit from the vehicle and prompted a need for a collapsible configuration. This change also created better rider comfort and usability depending on their seated position.

Overall, the prototype vehicle proved to be extremely invaluable to the design and fabrication of the final vehicle design. All changes made to the prototype vehicle will be incorporated into the final vehicle design and make the production of this vehicle much smoother and with fewer errors.

Figure 5.2: The Prototype Vehicle

5.2 Fairing Test

The final fairing will be tested using samples of composite built by the same schedule and process as the fairing itself. This will allow the team to determine if additional reinforcement is needed especially at the RPS load points. The tests will also include abrasion resistance on blacktop and impact durability using hand weights dropped from several heights to determine the materials tendency to fracture or crack.

Abrasion resistance will be evaluated using a simulated skid scenario. In this test a fairing sample will be towed behind a car across blacktop at 15 mph for a distance of 200 feet with four load situations, spaced evenly at 10 pound intervals from 10 to 50 pounds. The expected outcome of this test is that there will be a significant increase in damage incurred at the higher loads that will eat the gel coat from the surface yet not cause irreparable damage to the underlying composite.

Impact durability testing will comprise of a 10 pound weight being dropped from various heights above a suspended fairing sample that will be reinforced with the Nomex Honeycomb representing the area surrounding the roll cage. Exact forces impacting the sample will be calculated and the damage evaluated on a 10 point scale, one representing no perceived damage and ten a complete fairing failure. The fairing as a whole will then be evaluated for safety based upon the results from both tests.

The roll cage will also be tested externally before being permanently mounted inside the fairing. The tests will simulate the applied load forces and directions established in the competition rules. The final installed system will also be tested with a simple loading scenario prior to the competition. Any deflections in the roll cage will be monitored to ensure that there is no danger of rider interaction with the system. Additional tests may be performed based upon the results of the other tests. If there are any indications that there will be catastrophic failures the fairing schedule will be adjusted to compensate.

6.0 Safety

Safety is a top priority for the team and all actions taken thus far in design and testing reflect that. It is for this reason that all concerns voiced from the prototype testing were addressed. This was the main reason for the change of the drive wheel location and the exchange of the front wheel with the rear due to the hub width. While the prototype was several inches lower to the ground, the bulkiness of the frame made it decidedly less stable than the new one. Even our smallest riders can easily right the vehicle now that it is less than one third of the original frame weight.

In addition to the concerns raised, the competition requirements have also been taken into account. A purchased racing harness has been purchased and installed to protect the rider from ejection in case of a collision. There is also a reinforced roll cage that will be permanently mounted to the inside of the fairing that will meet the maximum deflection requirements set by ASME.

6.1 Safety Harness

The requirements state that the safety harness must have a 95% confidence of ultimate strength in excess of 750lb. The requirements also state that off-the-shelf harnesses are sufficient as long as they meet regular safety standards.

The safety harness selected for our vehicle is a 4-point off-road seat belt from Wesco Performance. This harness features a 2” shoulder strap that is adjustable to 62” and a 2” lap strap that is adjustable to 73”. It has wrap around ends that will be attached to the aluminum cross member of the RPS above the rider.

This is best so that the ends do not have to be bolted into anything that might cause stress concentrations or fatigue leading to fracture or failure. The ends of the lap strap will be attached to the bottom of the seat so that they adjust with the seat and the rider. This harness is SFI, FIA, USAC, SCCA & FMVSS #209 safety approved and will sufficiently fulfill the competition requirements.

6.2 Roll-Protection System

The materials that will be used to make the RPS are fiberglass composite and Nomex, and it will be reinforced with cross-members of 6061 aluminum tubes. Multiple layers of fiberglass and Nomex will be stacked together to form the outer ring of the RPS. In between the layers of fiberglass and Nomex, 6061 aluminum plates will be embedded so that the aluminum tubes can be TIG welded to those 6061 aluminum plates. The aluminum tubes do not interface with each other as there is a gap between the vertical and horizontal cross members preventing higher stress locations caused by welding or bolting the tubes together.

6.3 Protection to the Bystander

To take the safety of the bystander into account of our design, we have implemented redundancy into our braking system; meaning that disc brakes and caliper brakes will be used to ensure that the vehicle stops within a reasonable distance. The vehicle wheels will be almost fully enclosed inside the fairing, exposing only the wheel rims, which will prevent any extremities from getting caught in the spokes or other hardware. This will protect bystanders in the event of a crash during the course of the competition. The team will also have tires with a more aggressive tread on hand for bad road conditions should they be needed.

The fairing will include a thermoformed windshield with a range of visibility of at least 180 degrees. This will provide the riders the ability to view the entire road course and avoid any obstacles. The vehicle fairing will also include reflectors which will guarantee safety for both the rider and the bystander in less than ideal weather conditions and lighting.

7.0 Final Vehicle and Results – Statement of Performance/Success

The final vehicle successfully made the trip to the ASME East Coast Competition in Indianapolis, IN. The final vehicle placed top 3 in the design event, top 10 in both the men's sprint event and endurance event, and number 7 overall in the speed class. This was a tremendous accomplishment for a first year vehicle on a small budget. Unfortunately the fairing did not get completed, so a roll cage was attached last minute in order to be able to still compete and fulfill the safety requirements. The final vehicle and some of its components can be seen in Figures 7.1-7.4 below.

One of the goals of this project was to begin a legacy for future ASME members at the University of Arizona in human-powered vehicles. This project successfully completed that goal. Teams in the future should be able to receive sponsorship easier now that we have completed a vehicle and won awards with it. This final vehicle will also be left to the ASME so that it can be modified or built upon for future competitions. We have documented the whole design and build process, so future teams have documentation to reference and legacy information to build on.

A lot was learned in the designing and building of both the prototype and final vehicles. A key learning point was flexibility in design and manufacturing. For example, a disc brake mount should be bolt-on rather than welded so that the brake caliper can be adjusted and properly biased after it is mounted. Knowledge like this goes a long way in building and tuning a vehicle. It is known that a lot can be learned from failure as well, and that is true in our case. The fairing was not completed because the epoxy/poly-resin combination we used to lay-up the fiberglass did not harden. This could be because of the environment it was drying in, because not enough hardener was used, or several other things. We found out that other teams at the competition had similar experiences when building their own fairings. We learned a lot about composites and how the building of a fairing works and does not work. This knowledge will be passed down to future teams, and if they begin the build process early enough, many issues can be resolved using the things we learned during our experience.

Figure 7.1: Final Vehicle and Team at Indianapolis Motor Speedway

Figure 7.2: The Final Vehicle

Figure 7.3: Front Fork

Figure 7.4: Plug for Incomplete Fairing

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Appendix A: Matlab Code

Stability.m

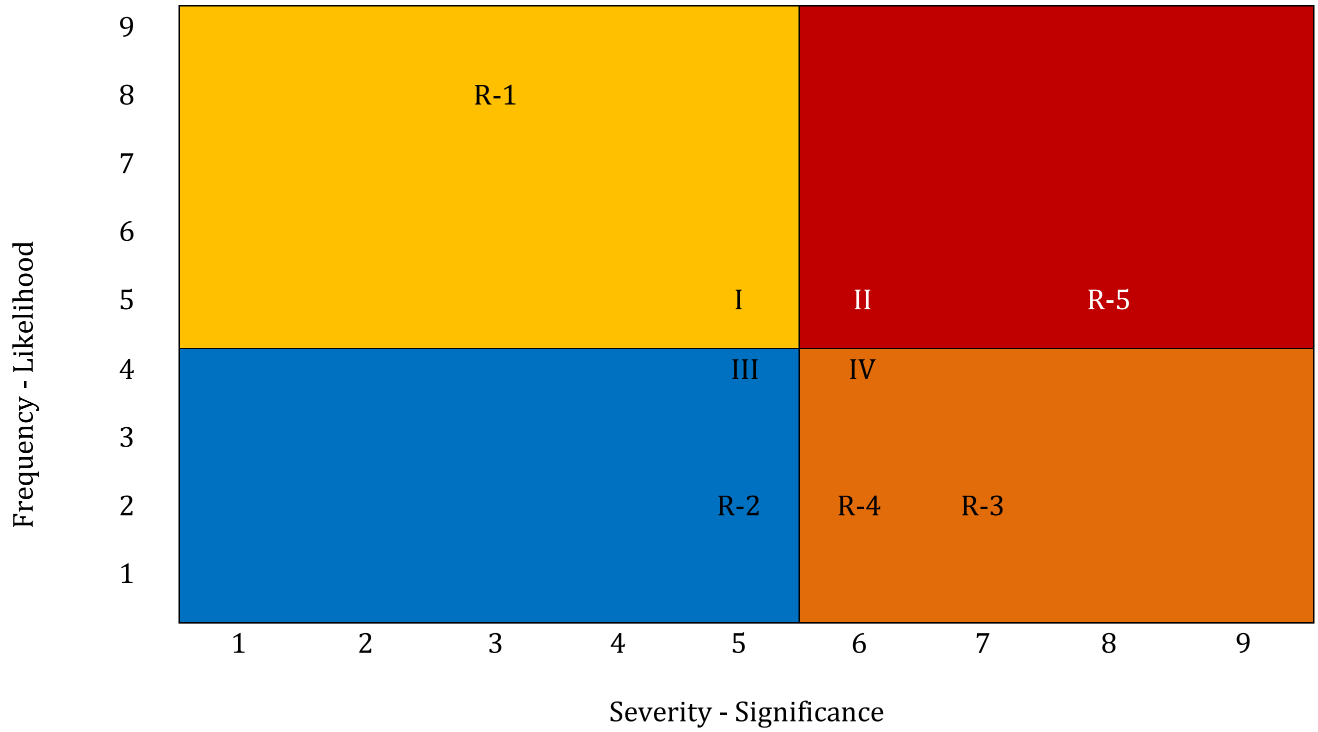
```
%References
%Fundamentals of Vehicle Dynamics: Gillespie

R = 6:1:50; % ft   radius of turn
L = 4.667; % ft = 56 in
b = 2.613; %ft    % CG to front
c = 2.054; %ft    % CG to rear
h = 1.8; %ft    % height of center of gravity
Weight = 225; % lb  toal weight of vehicle + rider
M = 6.2112;  % lb*s^2/ft
g = 32.2; % ft/s^2   gravity
delta = [2 5 8 10 15]; % deg; max steer angle [vector of all steering angles]
V = 7; %ft/sec
gamma = 20; %deg; maximum camber angle
Calpha = 100; %Cornering Stiffness
for i = 1:5
alphar = delta(i)./(c/b+1); %Rear Slip Angle (deg)
alphaf = delta(i)-alphar; % Front Slip Angle

Fyr = Calpha.*alphar;
Fyf = Calpha.*alphaf;

Fy = Fyf + Fyr;         % total lateral cornering force
Vcrit(:,i) = sqrt(Fy.*R./M);  % critical velocity for stability
end
plot(R,Vcrit*0.681818182) % converted ft/s to mph
ylabel('Critical Velocity (mph)')
xlabel('Radius of Turning (ft)')
legend('2 deg steering angle ','5 deg','8 deg','10 deg','15 deg','Location',
'Best')
title('Critical Velocity vs Radius of Turning')
```

Appendix B: Costs

Overall Expenditures	
Employees (Qty)	Cost (USD)
Welder (1)	2,000
Machinists (3)	8,000
Workers (5)	13,750
Engineer (2)	7,000
Capital Costs	
Building Rent	2,750
Utilities	975
Equipment	2,000
Advertising	785
Shipping	1,000
Plug Construction	1,650
Cost per month	$39,910
Additional costs per unit	3,400
Total Cost per unit	$7,467

QTY	ITEM #	DESCRIPTION	UNIT PRICE	TOTAL	VENDOR
2	BB-5500 V1	Shimano 105 Octalink Bottom Bracket	44.99	89.98	Westernbikeworks.com
1		SPRAM APEX Brake Caliper Set	59.99	59.99	
1		Shimano Dura-Ace 7800 Road Brake Cable Set	17.99	17.99	
2	PG-1070	Spram 10-Speed Cassette	89.99	179.98	
2	CN-7901	Shimano Dura-Ace 10-Speed Chain	69.99	139.98	
1	FD-5700-L	Shimano 105 Front Derailleur	49.99	49.99	
1		Ritchey Logic WCS Threadless Headset	74.99	74.99	
1	PD-M520	Shimano SPD Pedals	54.99	54.99	
		Micellaneous Vehicle Components	100.00	100.00	Bicas and Bike Swap Meets
1		Off-Road Roll Bar Mount 4-pt. Harness	49.95	49.95	Wescoperformance.com
6		6061 AL 0.75" OD 0.065" Wall	20.09	20.09	Onlinemetals.com
8		6061 AL 1.75" OD 0.125" Wall	83.32	83.32	
1		6061 AL Round Rod 0.625" D	1.80	1.80	
1		6061 AL Sheet 0.1"T	28.96	28.96	
1		6061 AL Sheet 0.19"T	23.71	23.71	
1		Nomex Honeycomb	80.00	80.00	Acp.composites.com
73		Fiberglass	2.63	192.10	
7	MA-01A	Aeromat	17.00	119.00	
3		Sealant Tape VB	7.95	23.85	Fiberglast.com
4		Strechlon 200 VB plastic	19.95	79.80	
1		Glass Microspheres	11.95	11.95	
25		Bleeder Breather Cloth	4.35	108.75	
10		Peel Ply	8.95	89.50	
2	1041-B	Duratec Surfacing Primer	109.95	219.90	
1	2306-A	Duratec Thinner	54.95	54.95	
1	69-D	MEKP Hardener	49.95	49.95	
2	2000-B	System 2000 Epoxy	104.95	209.90	
2	2120-C	System 2120 Hardener	129.95	259.90	
		TOTAL		$2,475.27	

Appendix C: Risk Analysis



Severe Risk **High Risk** **Elevated Risk** **Guarded Risk**

	Risk	**Frequency - Likelihood**	**Severity - Significance**	**Risk Score**
1	Chain break/slip	0.8	0.3	0.24
2	Brake Failure	0.2	0.5	0.1
3	Wheel Failure	0.2	0.7	0.14
4	Down Tube Bending	0.2	0.6	0.12
5	RPS Failure	0.5	0.8	0.4

Appendix D: Sample G-Code for CNC Machine

```
M03 S2000                    %for seat slider
G00 X-16.2134 Y2.2044 Z0.1
G01 Z-0.0236 F1
X-15.9482 Y1.9392F10
X-16.0366 Y2.0276
G02 X-15.9482 Y2.241 R0.125
G01 X-15.055
```

```
G02 X-14.9666 Y2.2044 R0.125
G01 X-14.7014 Y1.9392
X-14.7898 Y2.0276
G02 X-14.7014 Y2.241 R0.125
G01 X-13.805
G02 X-13.7166 Y2.2044 R0.125
G01 X-13.4514 Y1.9392
X-13.5398 Y2.0276
G02 X-13.4514 Y2.241 R0.125
G01 X-12.555
G02 X-12.4666 Y2.2044 R0.125
G01 X-12.2014 Y1.9392
X-12.2898 Y2.0276
G02 X-12.2014 Y2.241 R0.125
G01 X-11.305
G02 X-11.2166 Y2.2044 R0.125
G01 X-10.9514 Y1.9392
X-11.0398 Y2.0276
G02 X-10.9514 Y2.241 R0.125
G01 X-10.055
G02 X-9.9666 Y2.2044 R0.125
G01 X-9.7014 Y1.9392
X-9.7898 Y2.0276
G02 X-9.7014 Y2.241 R0.125
G01 X-8.805
G02 X-8.7166 Y2.2044 R0.125
G01 X-8.4514 Y1.9392
X-8.5398 Y2.0276
G02 X-8.4514 Y2.241 R0.125
G01 X-7.555
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G01 X-7.2014 Y1.9392
X-7.2898 Y2.0276
G02 X-7.2014 Y2.241 R0.125
G01 X-6.305
G02 X-6.2166 Y2.2044 R0.125
G01 X-5.9514 Y1.9392
X-6.0398 Y2.0276
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G02 X-4.9666 Y2.2044 R0.125
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X-4.7898 Y2.0276
G02 X-4.7014 Y2.241 R0.125
G01 X-3.805
G02 X-3.7166 Y2.2044 R0.125
G01 X-3.4514 Y1.9392
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G00 Z0.1
```
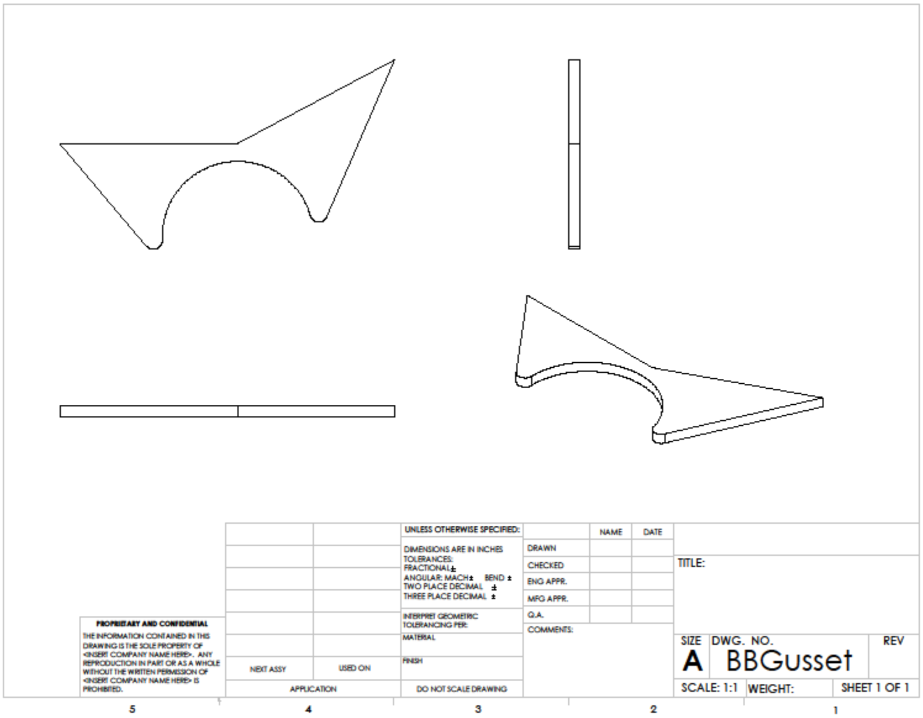
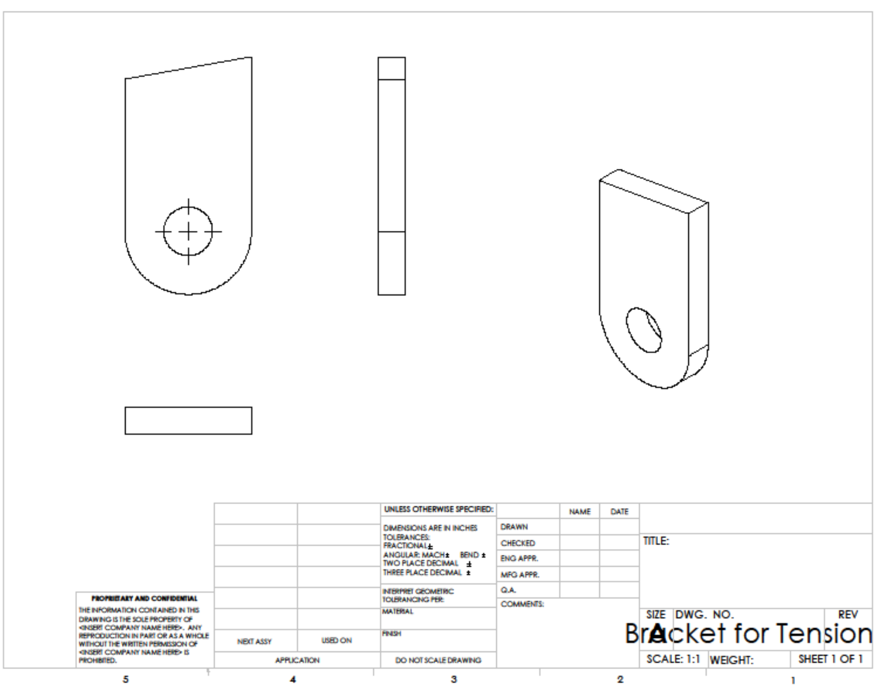
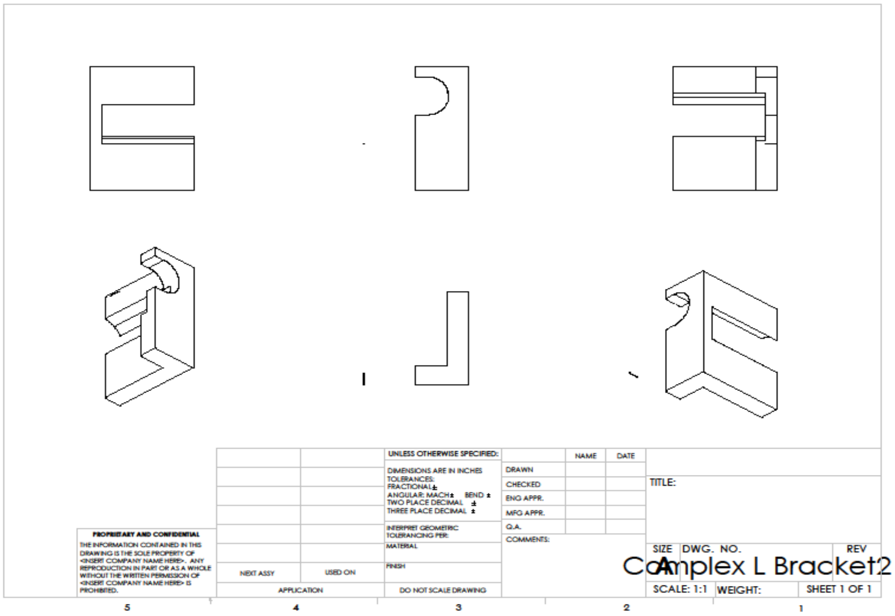

Appendix E: Miscellaneous Part Drawings







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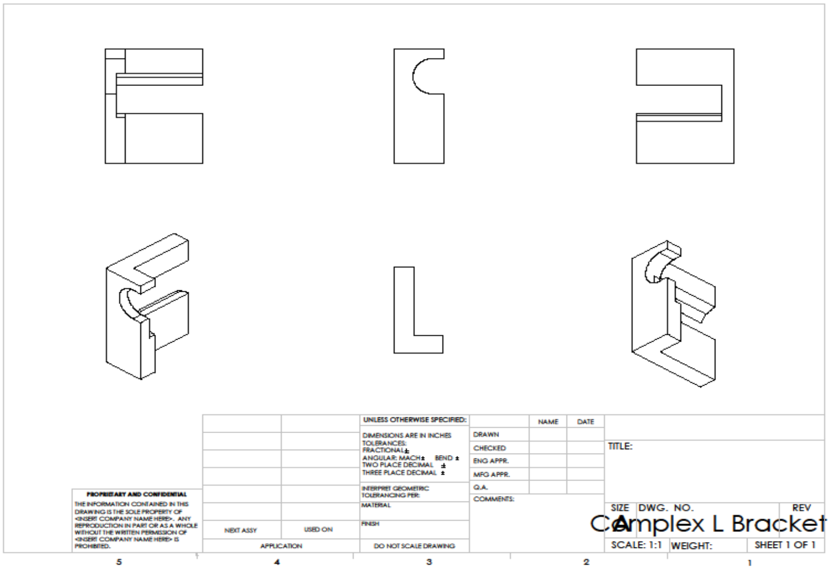
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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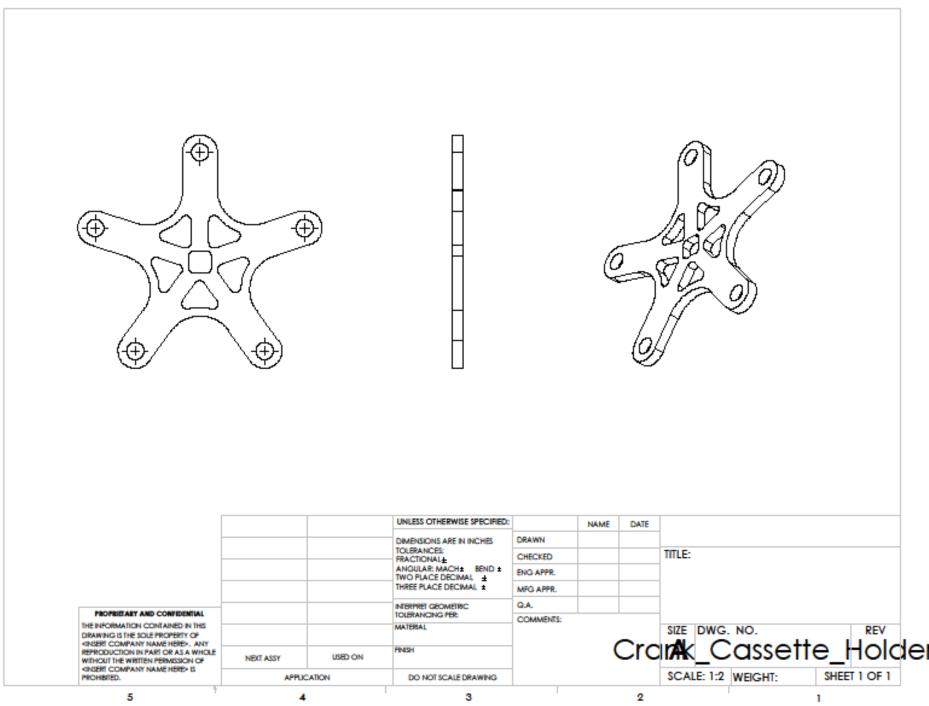
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
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WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
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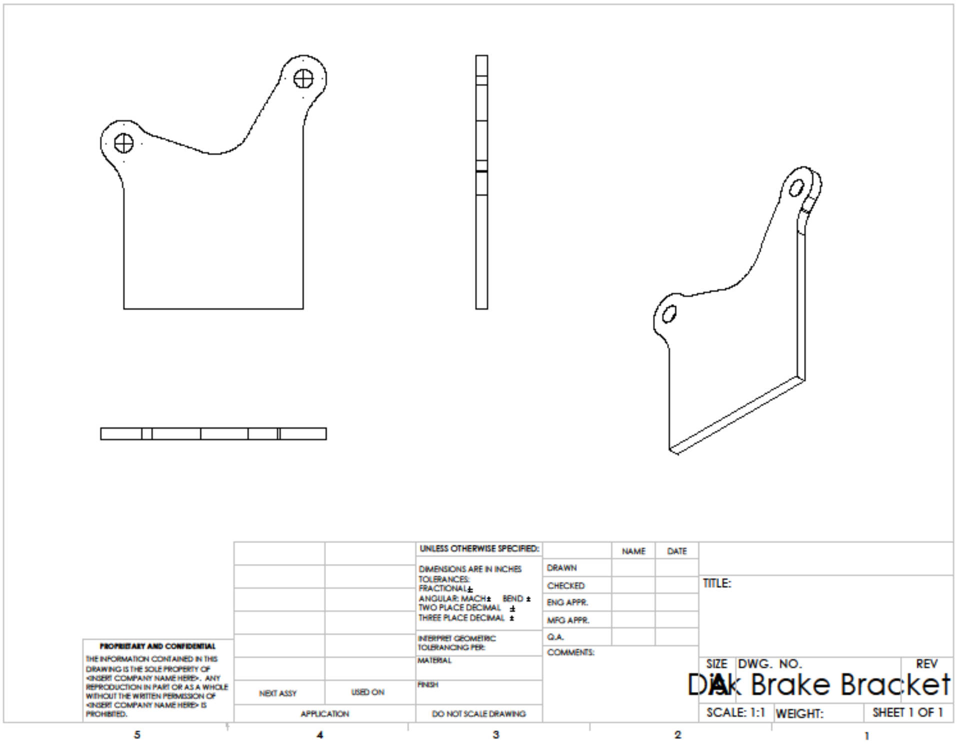

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PROPRIETARY AND CONFIDENTIAL
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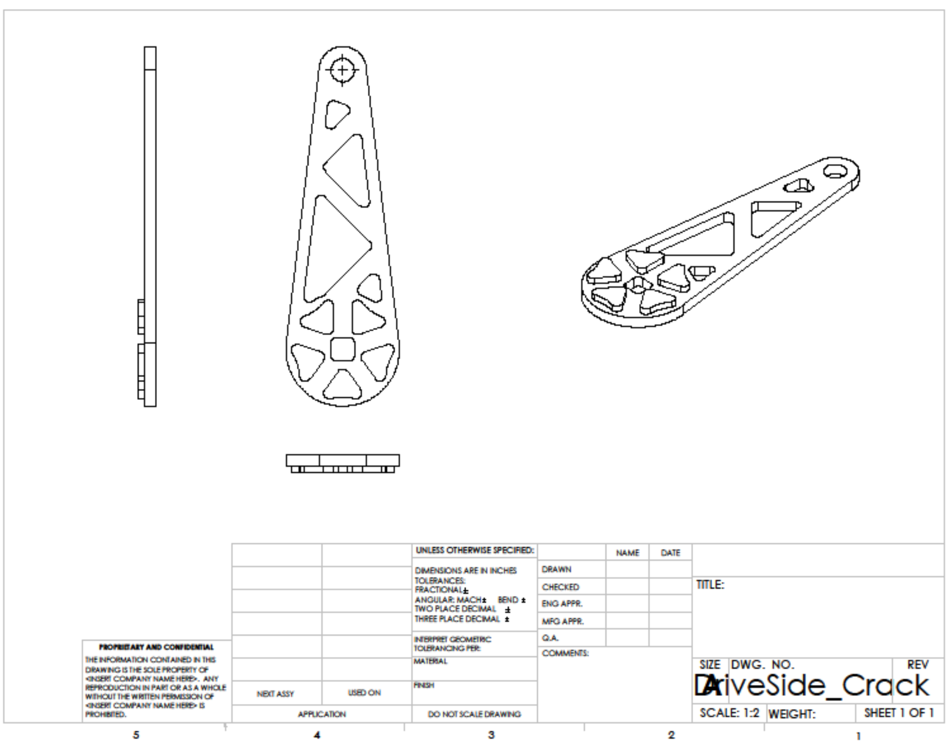

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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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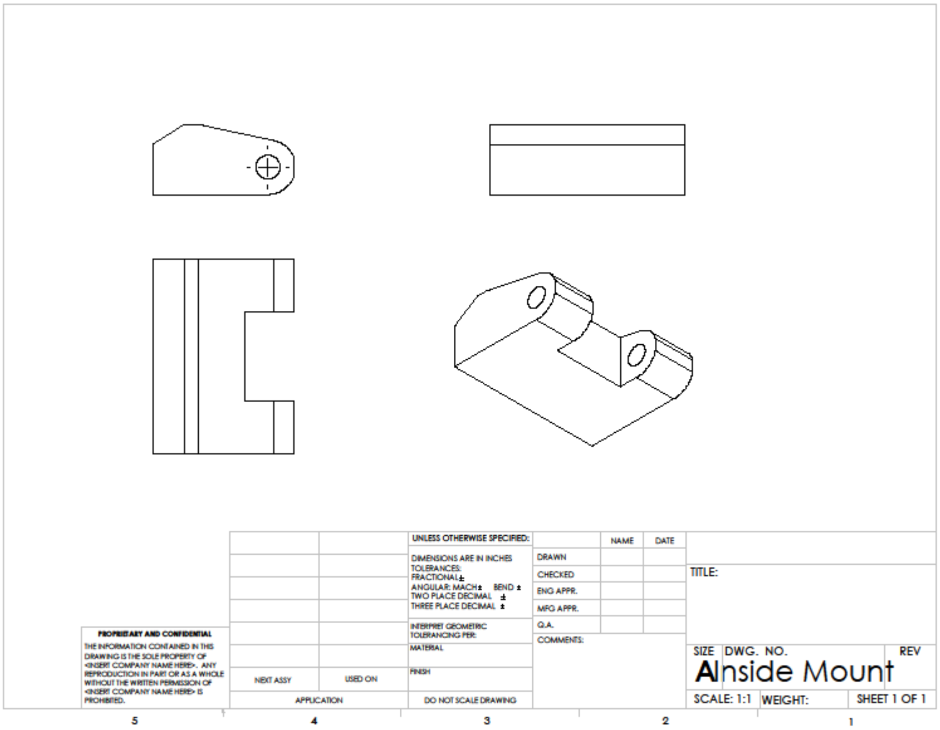
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PROPRIETARY AND CONFIDENTIAL
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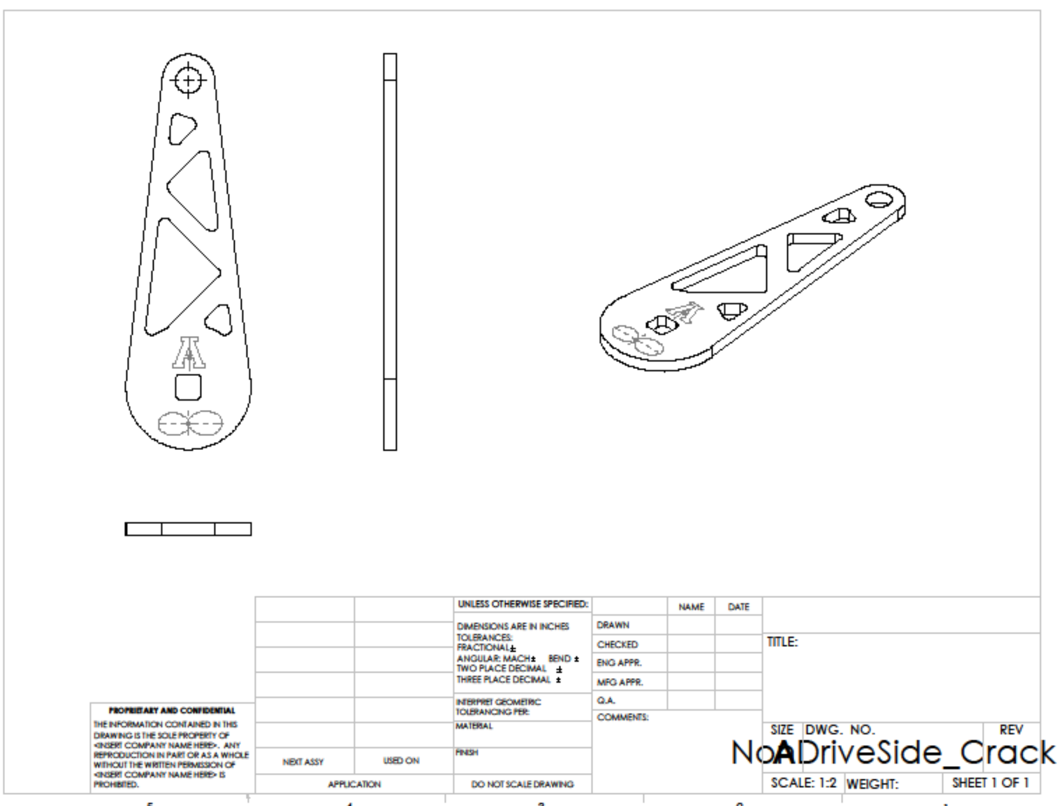
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PROPRIETARY AND CONFIDENTIAL
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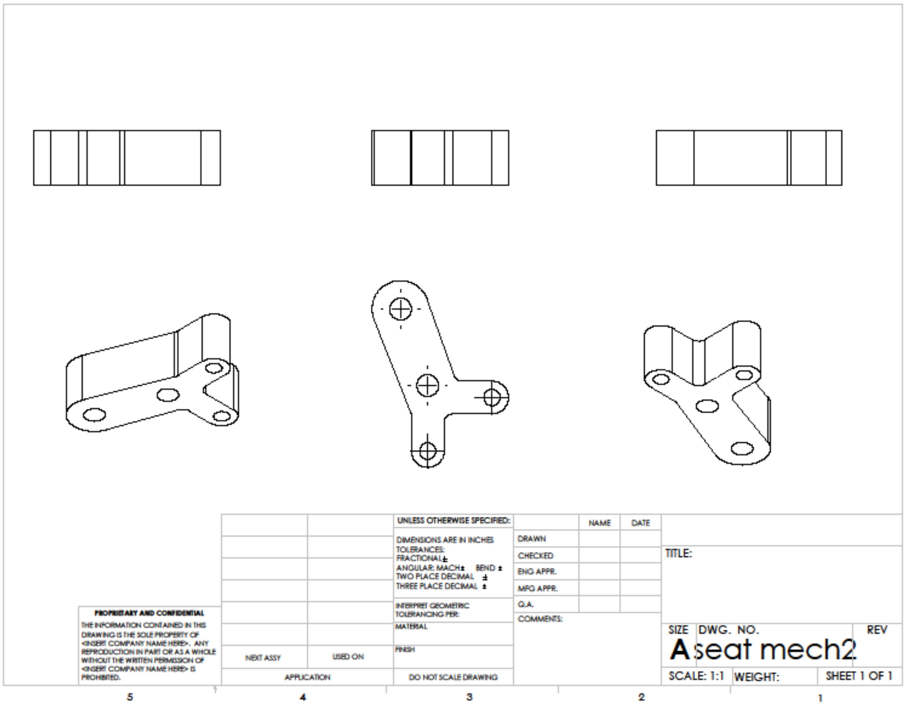
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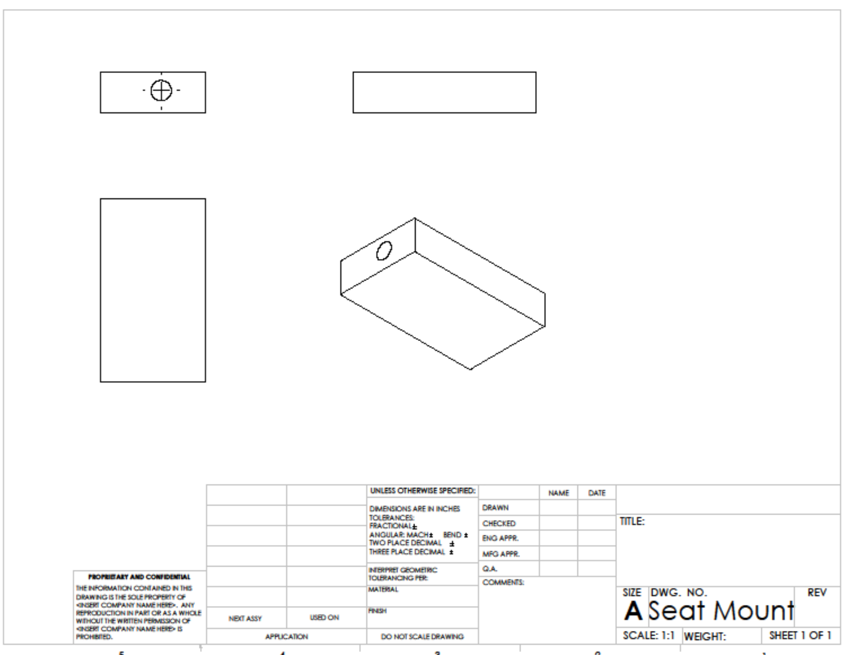
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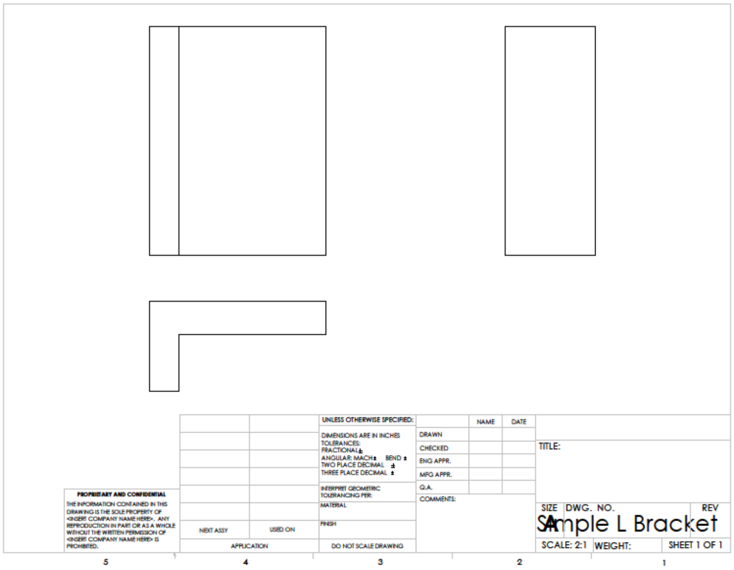
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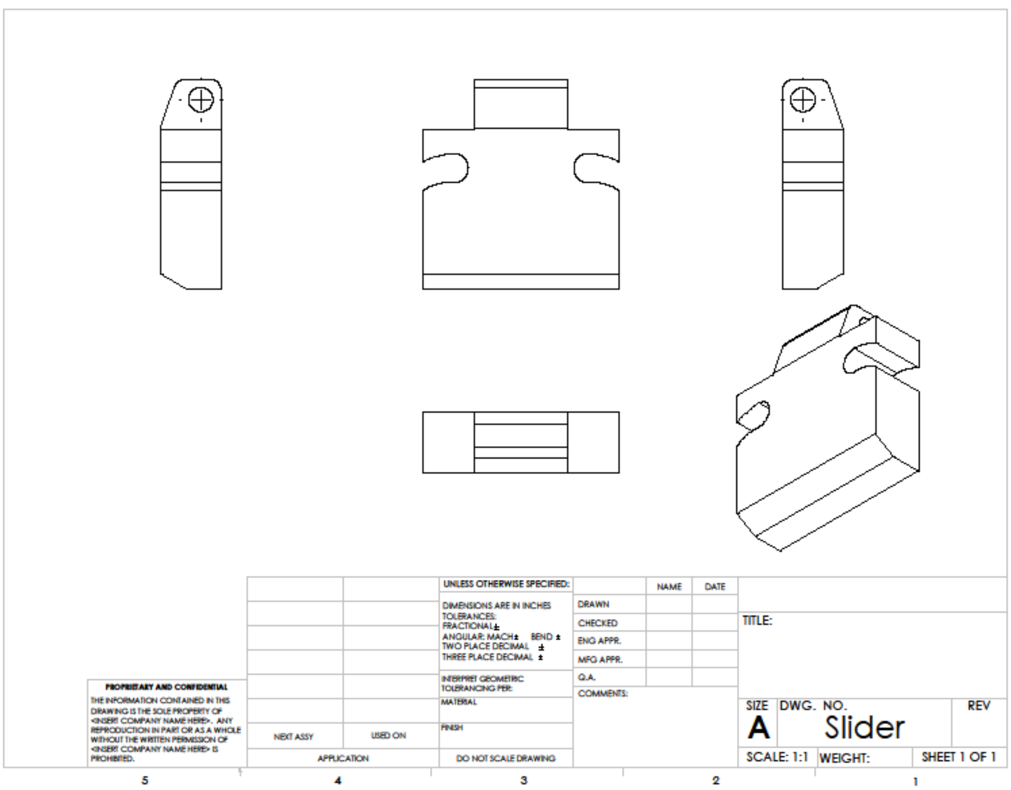
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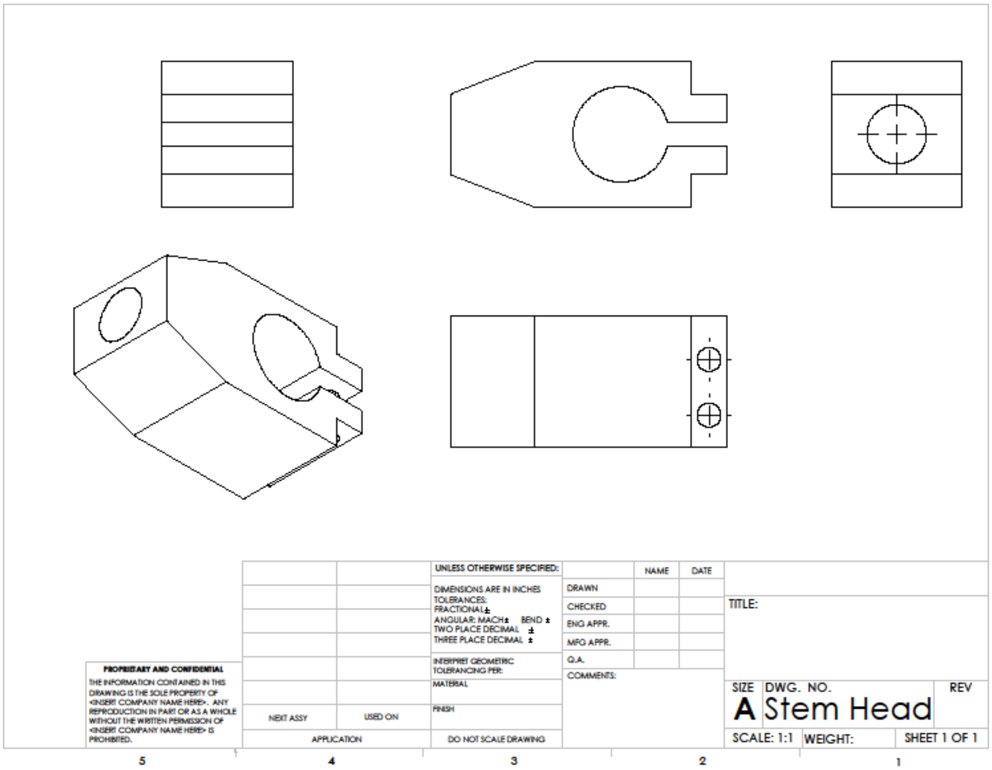
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PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
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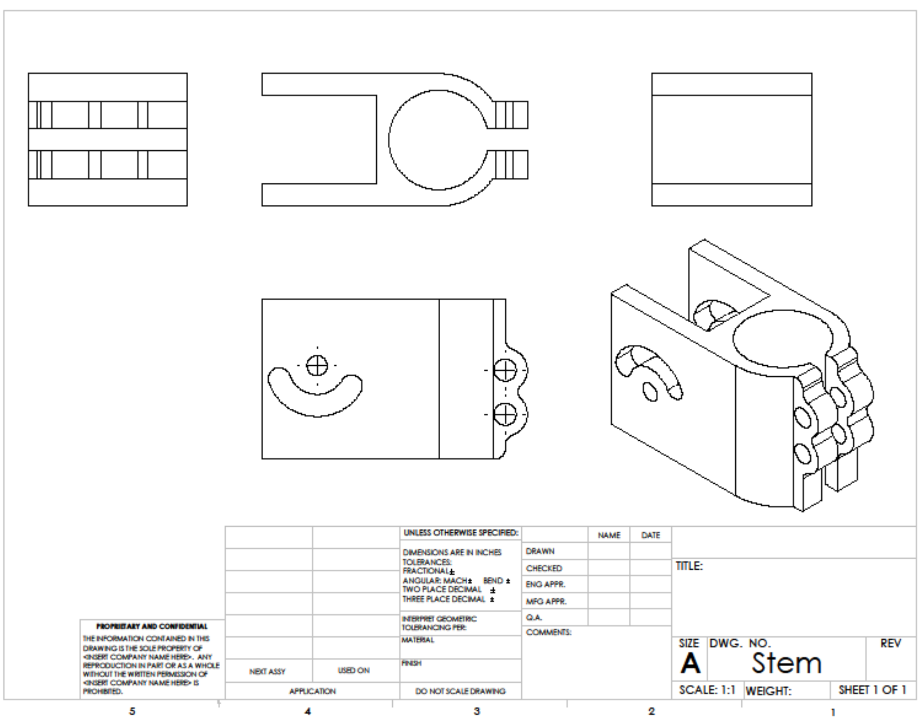
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PROPRIETARY AND CONFIDENTIAL
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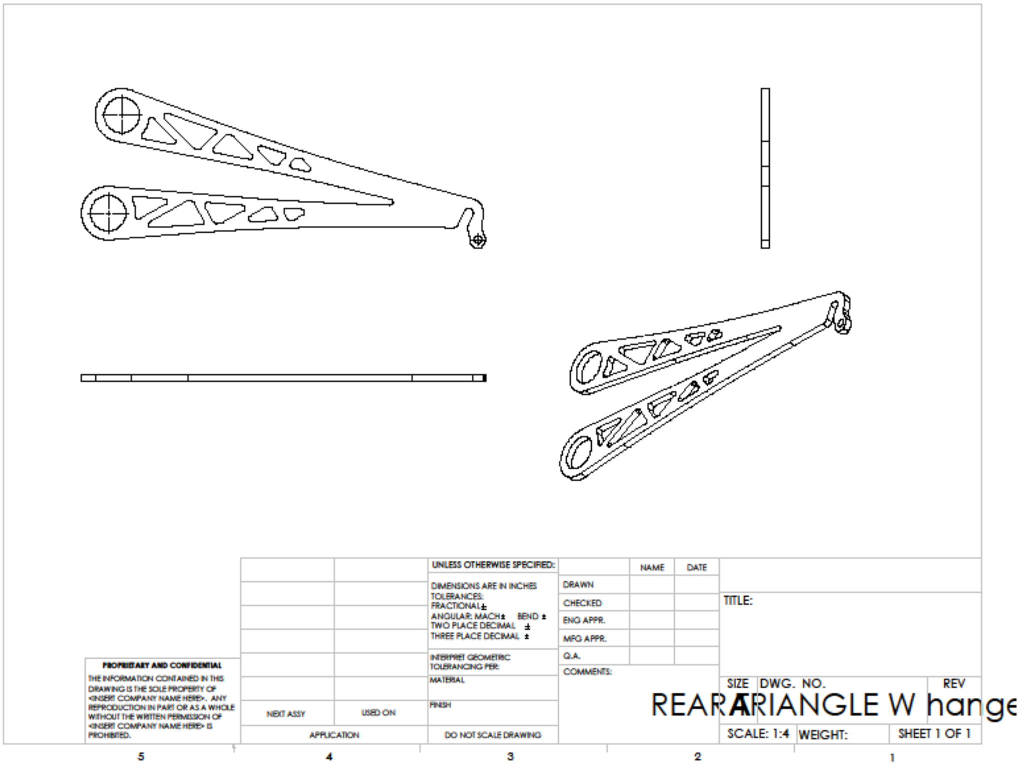
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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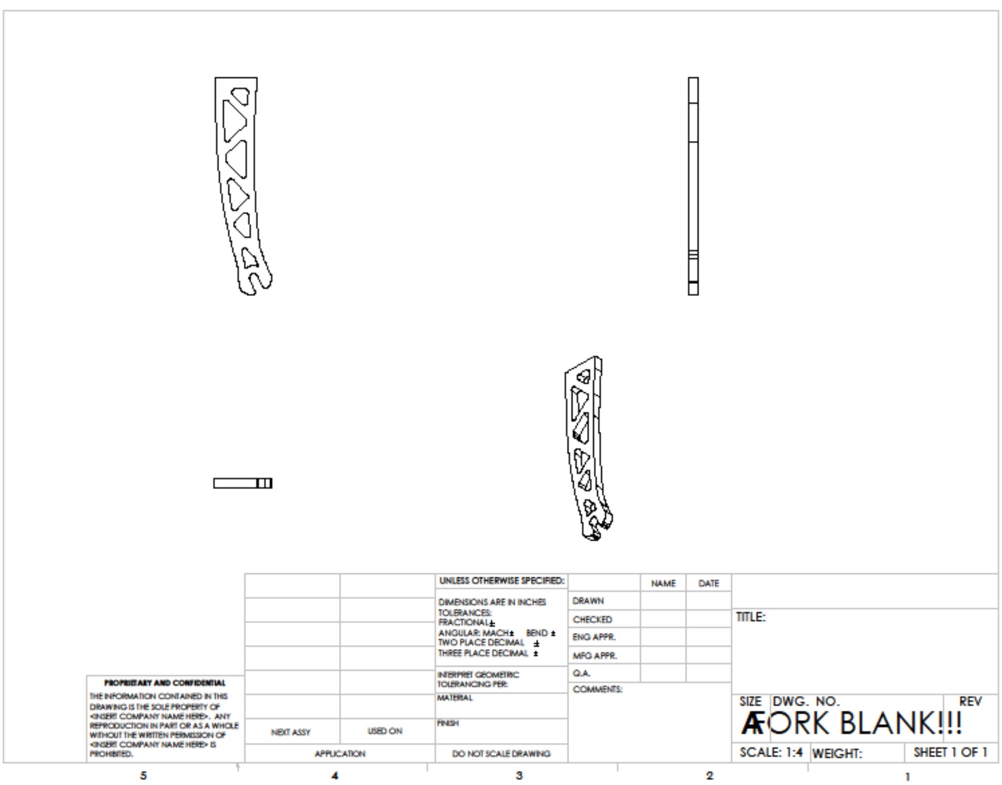
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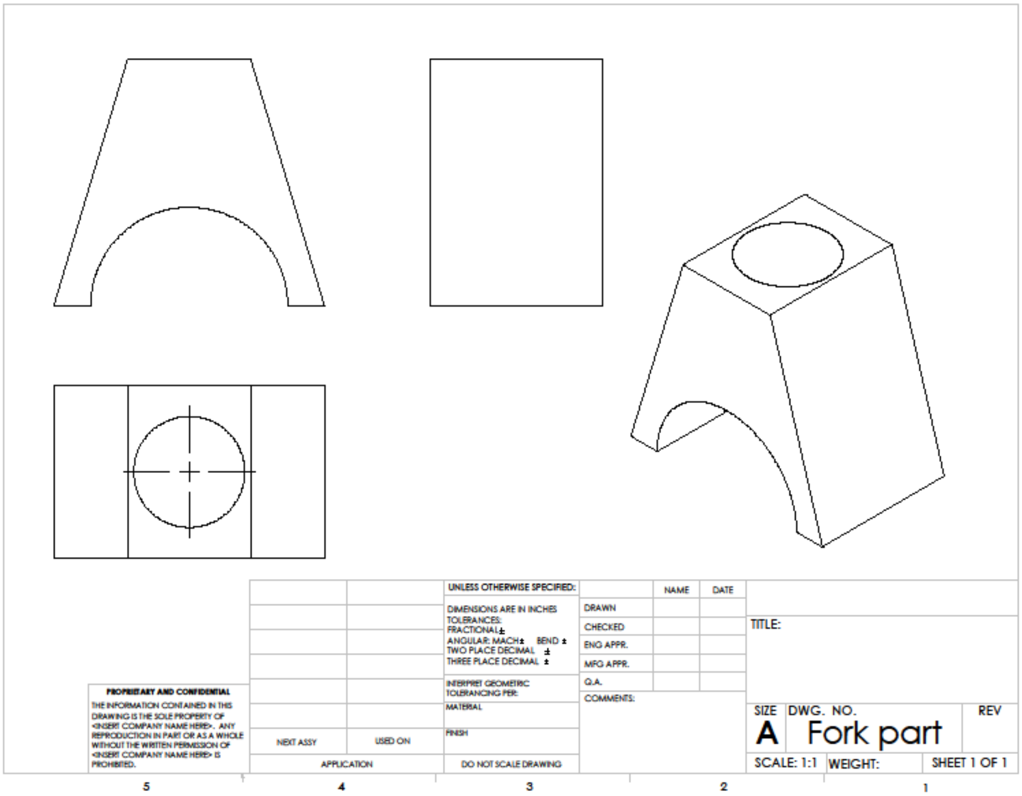
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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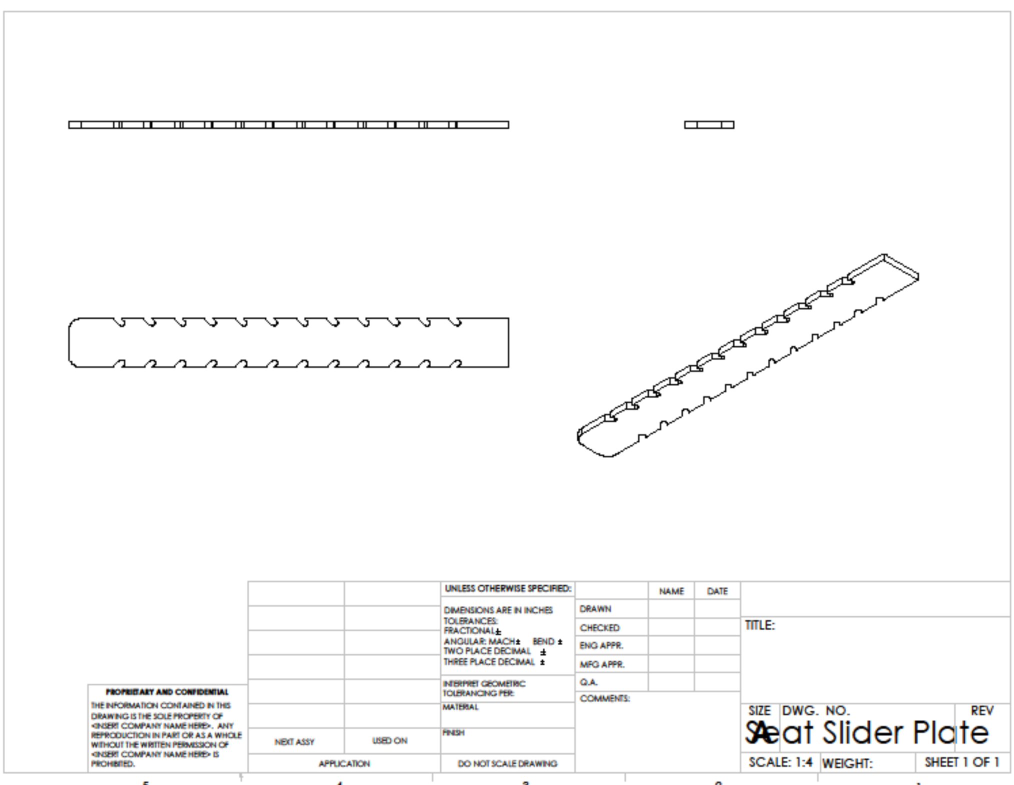
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Seat Slider Plate
SCALE: 1:4
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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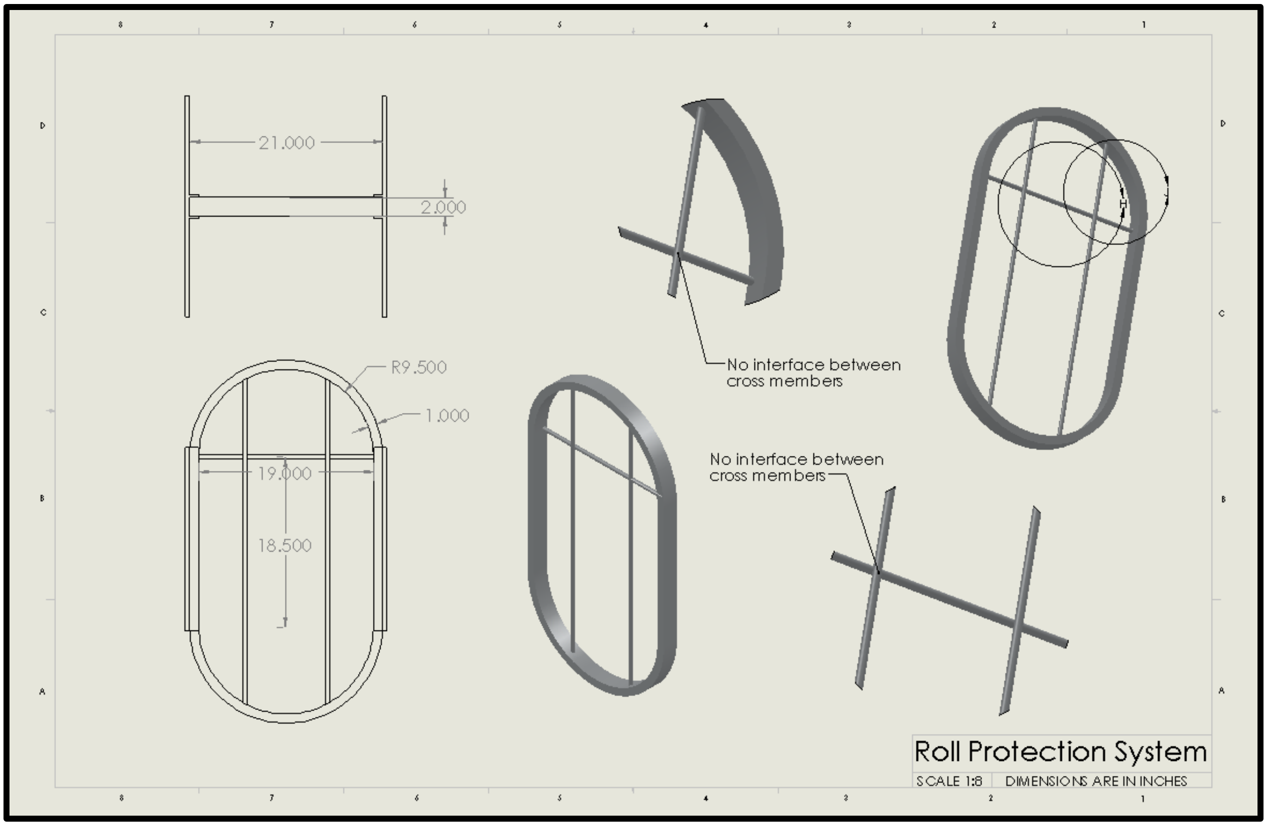
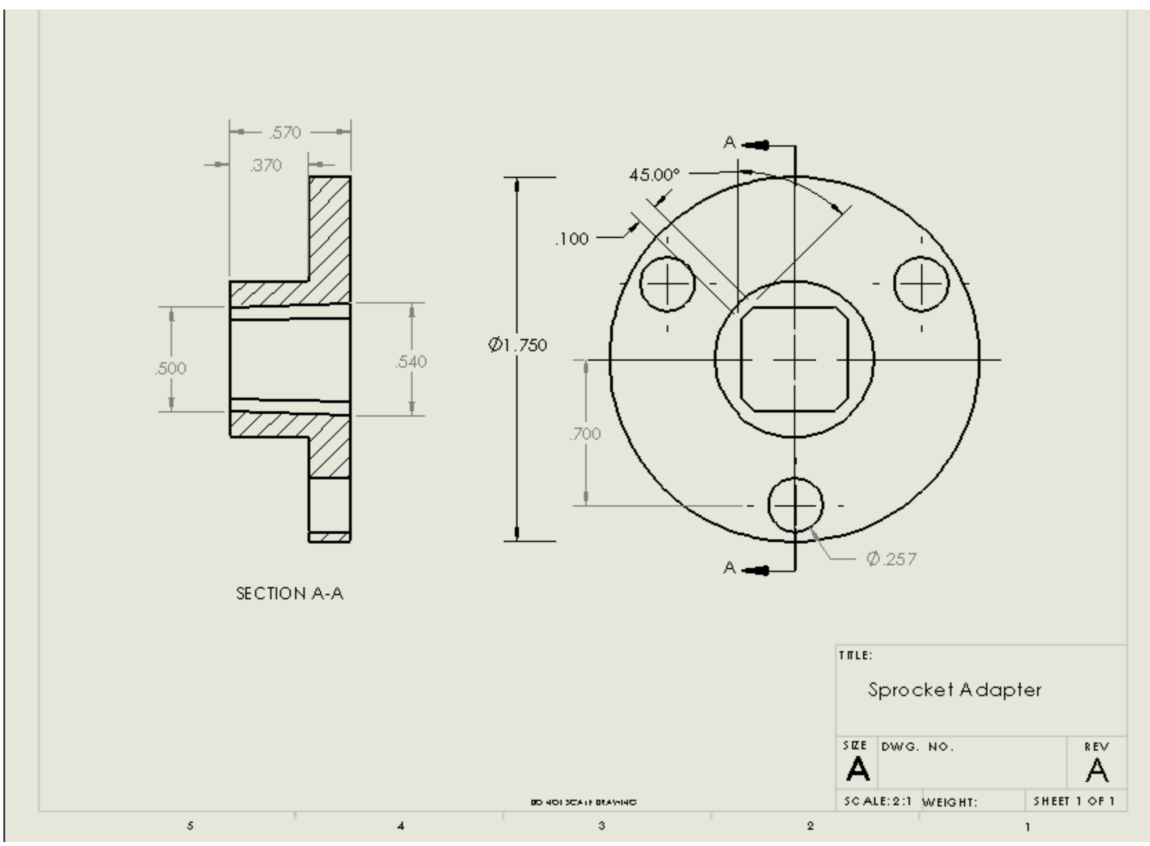

21.000
2.000
R9.500
1.000
19.000
18.500
No interface between cross members
No interface between cross members
Roll Protection System
SCALE 1:8
DIMENSIONS ARE IN INCHES


.570
.370
.500
.540
SECTION A-A
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SCALE: 2:1
WEIGHT:
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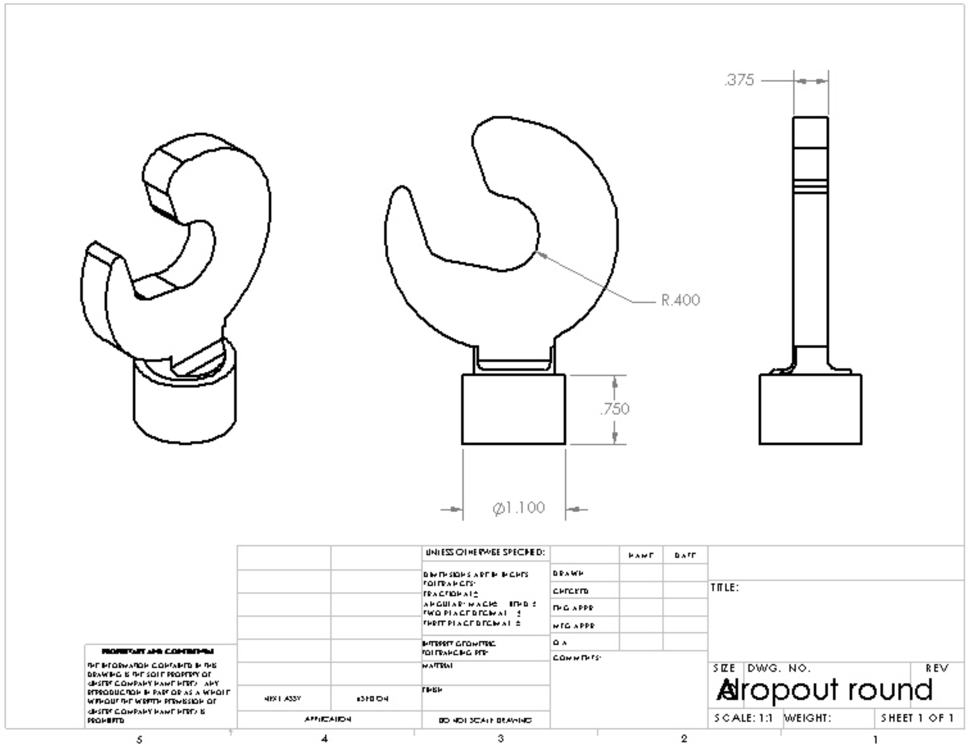

.375
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.750
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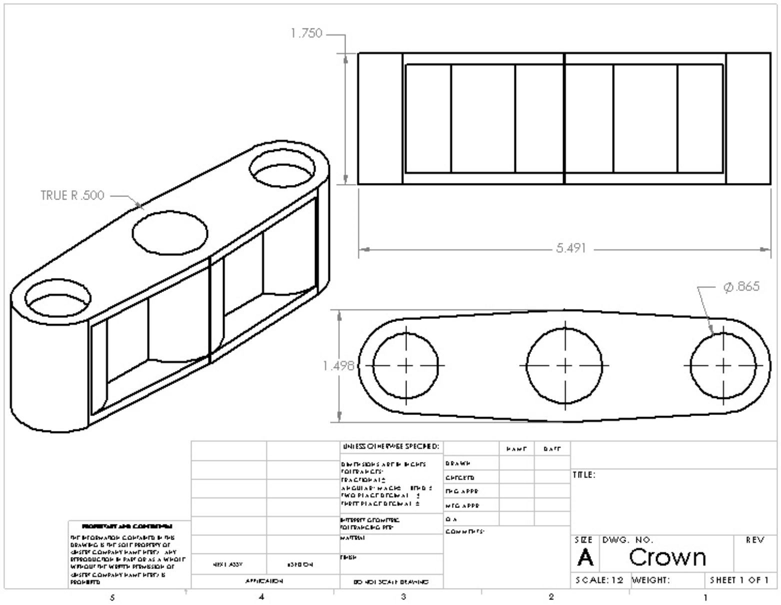
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1


1.750
TRUE R .500
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∅.865
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NEXT ASSY
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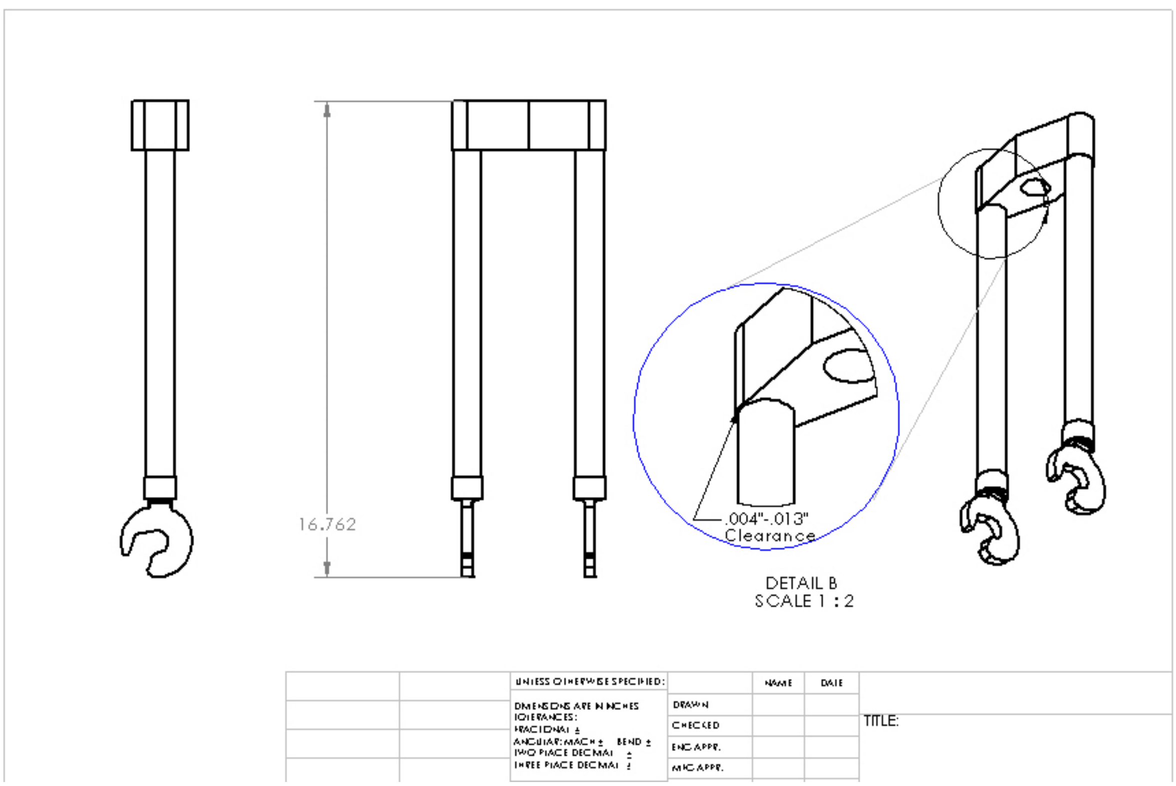
16.762
.004"-.013"
Clearance
DETAIL B
SCALE 1 : 2
UNLESS OTHERWISE SPECIFIED:
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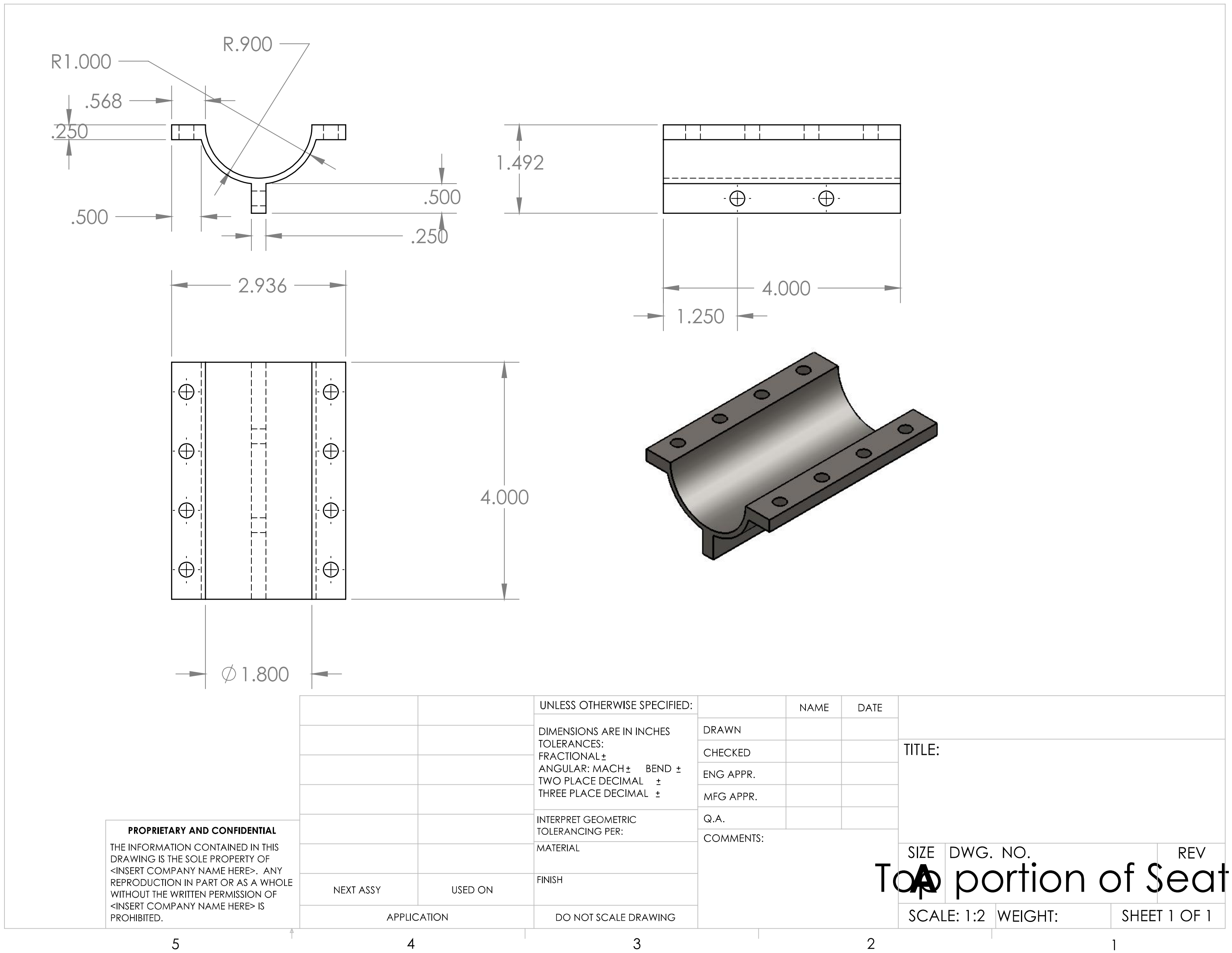
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Top portion of Seat
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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NEXT ASSY
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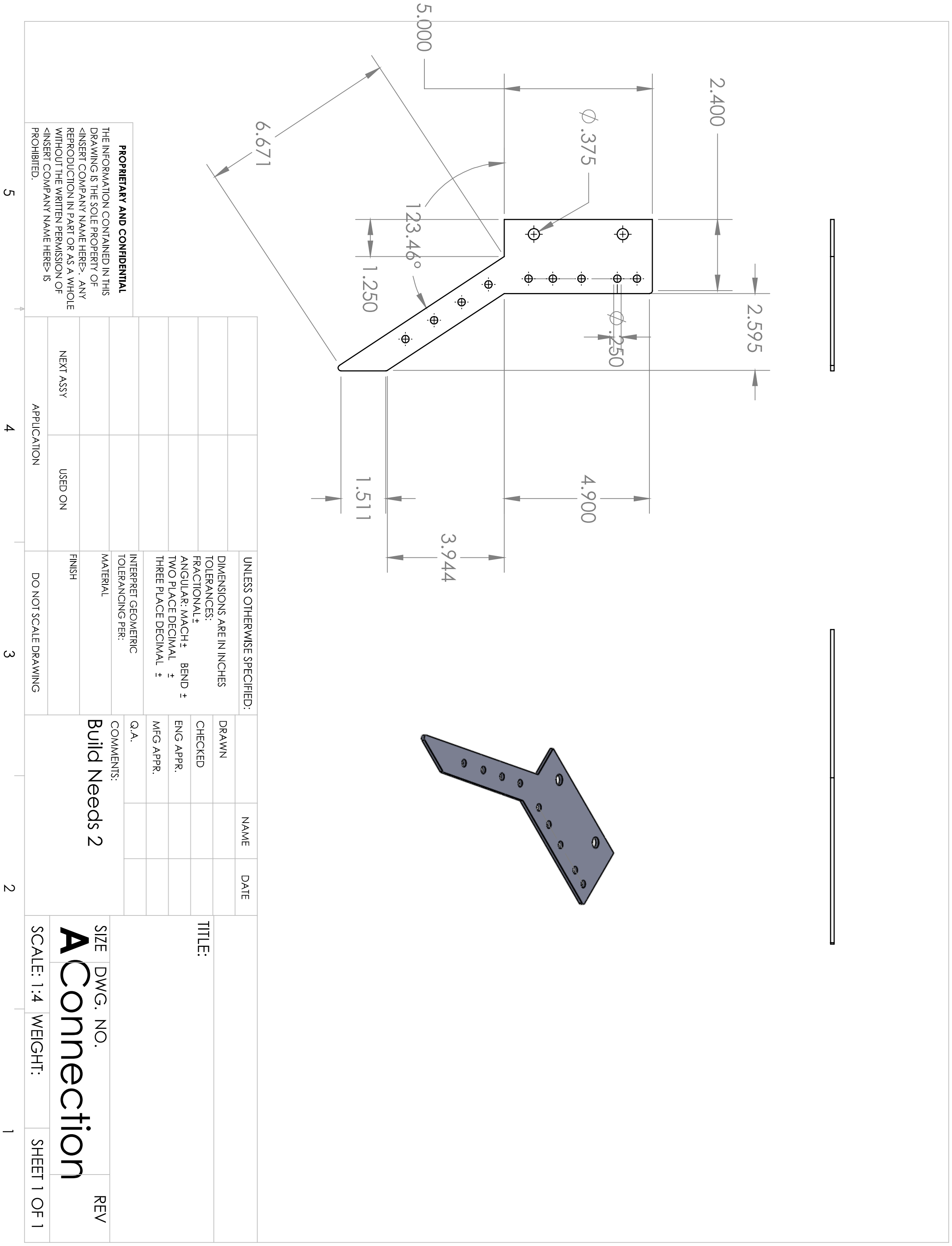
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PROPRIETARY AND CONFIDENTIAL
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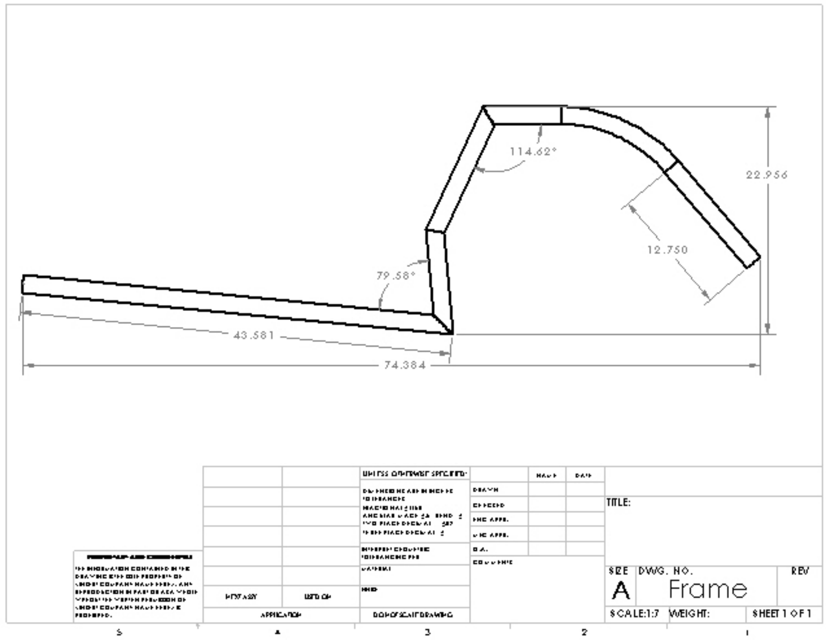
114.62°
22.956
12.750
79.58°
43.581
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