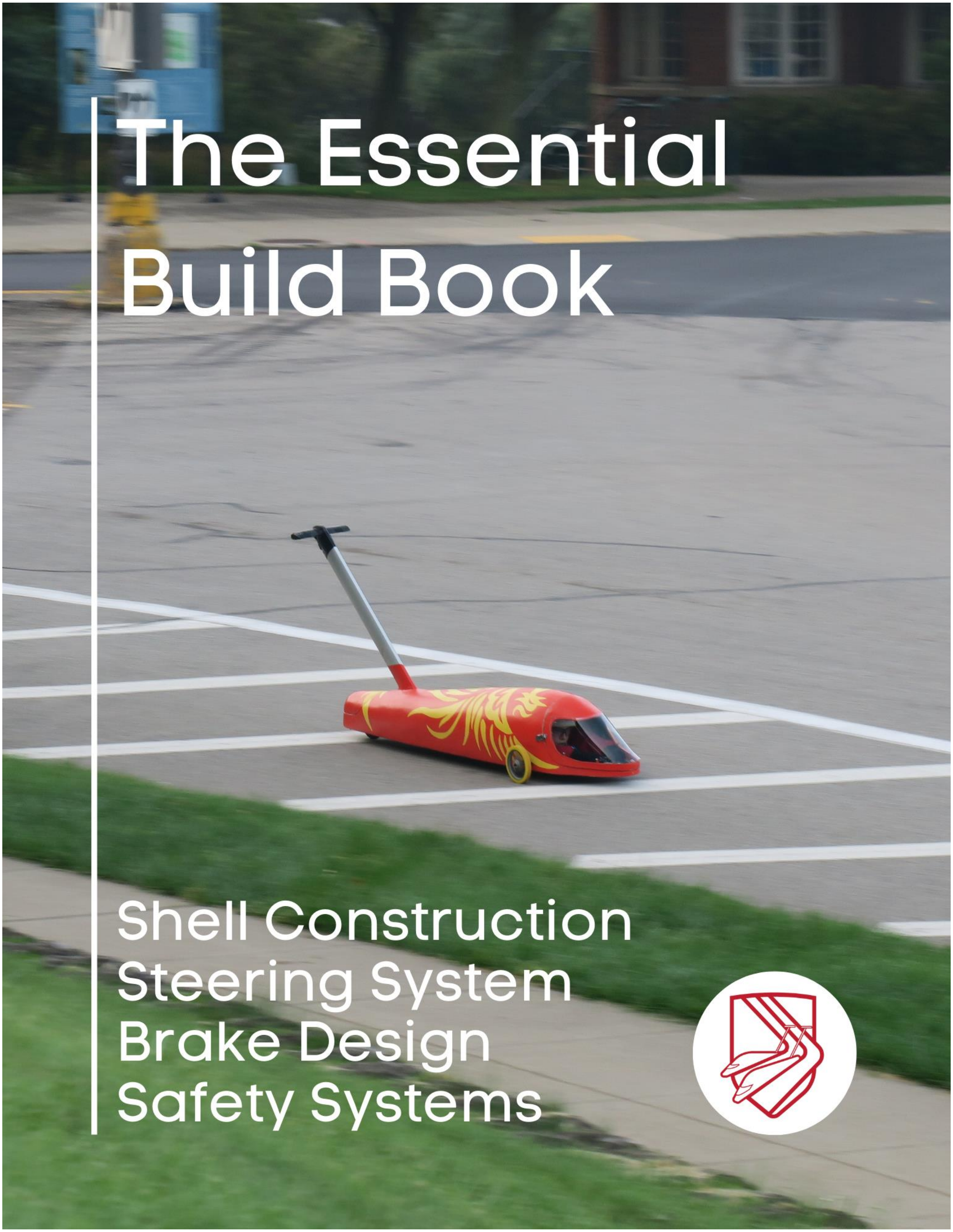
The Essential Build Book



Shell Construction
Steering System
Brake Design
Safety Systems

Buggy Build Book

A Guide to Building a Basic Buggy

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1 INTRODUCTION AND OBJECTIVES

Buggy, formally known as Sweepstakes, is traditionally a sport full of secrecy. This secrecy is particularly paramount when it comes to how teams design and build their vehicles. Each team has spent years or even decades perfecting designs and fine tuning their manufacturing processes. This institutional knowledge is fiercely protected, as teams loathe to give up any information that may give them even a microsecond of advantage. Unfortunately, this creates a high barrier of entry for new teams hoping to try their hand at the most unique sport at Carnegie Mellon University.

The purpose of this guide is to bridge that knowledge gap by walking new teams through the process of building a basic buggy. There are countless variables in the design and fabrication of a buggy, and the following instructions endeavor to present an introduction to principles and methods with a simplistic buggy design. Each section contains:

- A brief describing why design decisions were made
- A how to guide for completing that portion of the build
- A considerations blurb for alternative designs

The final product will be a buggy that is intended to be reliable, low maintenance and long lasting. As such, it will likely be heavier than the winning buggies. Rather than competing with the top teams, the aim is to produce a buggy that will last many years as a new team grows, while being fast enough to compete for a top 10 finishing position alongside a strong push team, solid prep, and a good set of wheels.

There are five goals for the buggy detailed in this guide:

- Easy to build
- Durable
- Low maintenance
- Easy to drive without spinning or crashing
- Relatively competitive

To achieve those goals, the buggy will be a reverse trike format (two wheels in front, one wheel in the back) with wagon steering and a carbon fiber with baseplate composite shell. This guide will explain unfamiliar terms or concepts and ensure new teams understand why this buggy design is effective.

Questions regarding content or the build process can be directed to Connor Hayes (cmhayesny@gmail.com), Diya Nuxoll (diyanuxoll@gmail.com), or the BAA (info@cmubuggy.org). Please send any errors found in this book or recommended improvements to Rachael Schmitt at schmitt.rachael@gmail.com. The BAA also offers a program that provides guidance and financial support to new teams.

Best of luck with your first buggy build!

2 DESIGNING THE SHELL

2.1 SHELL BRIEF

Skills: Basic knowledge of Solidworks and measuring techniques

Tools: Solidworks software, measuring equipment and paper

Materials: Broomstick handle or equivalent, long board that driver can lay on

Safety Tips: None

This section of the build guide covers a lot of material, as the shell is the most labor-intensive aspect of the overall build. It is important that the shell is designed around the drivers' dimensions, so they fit properly and the buggy will handle in a predictable manner through the turns. The mold design will be done in Solidworks, and this guide assumes a basic understanding of the program.

The first step in modeling the mold is to create a lofted 3D object of either the left or right side of the shell and mirror the object to create a symmetrical model. To make the loft, a "wire frame" model must be created for the middle of the shell. The wire frame will be used as the baseline for the loft function. Once this is completed, the process is repeated for the nose and the tail. This method will make it easier to use the loft function to create the mold design.

2.2 MEASURING THE DRIVER

Buggy shell designs typically start with measurements of a driver or drivers. Ensuring the buggy can fit not only your current drivers but a wide range of potential future drivers is key for a team's first buggy. Measurements should include all driving gear (helmet, mouth guard, athletic wear clothing). Use a flat board or table large enough for the driver to lay on, a round tube strong enough to hold ~100 lbs (mop/broom handle or cardboard shipping tubes work well) and a small tube that mimics a steering handle (Dry erase marker works well). The driver should lay down on their stomach on top of the board with their hands stretched out in front of them and head looking forward as if they are driving with the fake steering handle in their hands.

Once in this position, measure the distance from the steering handle in the driver's hands to a few critical points: the elbows, shoulders, crown of the head, hips, knees, heels and end of toes, as shown in Figure 1. Follow this by measuring the width of the driver at their hands, shoulders, hips, calves and feet while maintaining the driving position. Finally, record the height from the floor to the crown of the driver's head/helmet, hips/rump, calves, and heels.

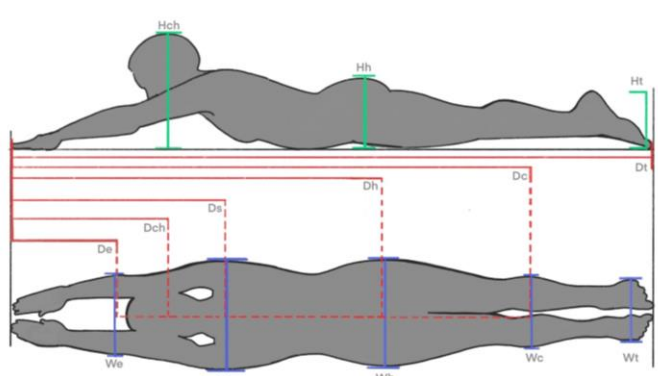


Figure 1 - Driver Measurement Guide (X Large)

A sample measurement guide is provided below, and a larger copy for usage can be found in Appendix A.

	Dist from Hands (in.)	Width (in.)	Height (in.)
Elbows	De	We	
Shoulders	Ds	Ws	
Crown of Head	Dch		Hch
Hips	Dh	Wh	Hh
Calves	Dc	Wc	
Toes	Dt	Wt	Ht
Center of Mass	CGh		

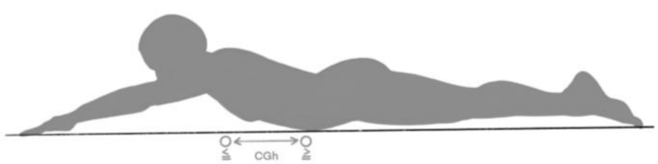


Figure 2 - Finding center of gravity

The final step is to remove the driver and place the board on top of the longer tube or broom handle, so the tube is perpendicular to the driver's body. Lay the driver back down in the middle of the board in driving position. Have one person stand by the driver's head and hold the front of the board, then roll the board forward and backwards until the board and driver are balanced on the tube. Measure the distance from the driver's hands to the center of the tube to capture where their center of gravity is located, as in Figure 2.

Place the measurements into an Excel table like the example below for easy reference during the next step. These measurements will be used throughout the instructions, and show the team the general driver shape to inform design decisions.

	Dist from Hands (in.)	Width (in.)	Height (in.)
Elbows	11.5	11.25	
Shoulders	20	13.5	
Crown of Head	17.5		13.5
Hips	43	13.5	8.25
Calves	62	10.75	
Toes	77.5	7.5	5
Center of Mass	36.25		

2.2.1 Alternate CG measurement - Scale Method:

Center of gravity (Cg) can also be measured using a board (like above), two scales (cheap bathroom scales are fine), and some simple force balancing (covered in most engineering intro courses). A thin bar/beam to rest between the board and scale to keep the weight centered is helpful, but not critical.

1. Place the scales with their centers spaced such that one would be underneath the driver's hands, and the other under the driver's toes.
2. Place the board evenly across the two scales
   a. If possible, lay a bar/beam across the center of each scale perpendicular to the length of the board. This will provide the most accurate measurement.
3. With the board in place, zero the scales (tare), OR record the baseline weight reading so they can be subtracted for your final calculations.
4. Carefully have the driver lay onto the board and check that her hands and toes are over the center of each scale. If not, repeat 1-4 until they are.
5. Record the weight readings with the driver on the board subtracting the respective baseline readings as needed.
   a. Adding the scale measurements together should be roughly equivalent to the driver's total weight
6. Since we are looking for the distance from the hands to the CG, in a static system (i.e. nothing moving) all forces AND torques are equal, so treating the hands as a pivot point, we know that:

   Weight of Driver * Length to CG = Weight at Toes * Length to Toes

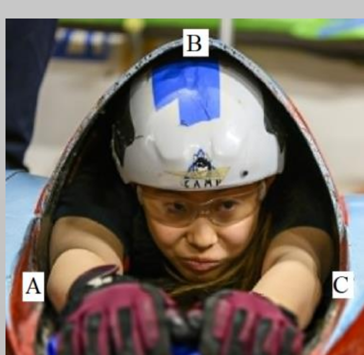
   $W_{driver} * Lcg = FToes * LToes$
7. Reorganizing that equation to solve for Lcg we get

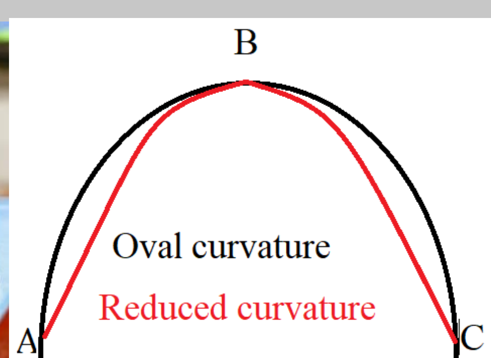
   Lcg = WToes * LToes / Wdriver
8. Typically, a person's CG is somewhere around their navel or just below their waist.

Advanced Design Tip: Cross Sectional Dimensions

To make the most aerodynamic and small shell designs, factor in the cross-sectional shape of the driver at the body points measured above (elbows, shoulders, hips, etc). A cross section in this case is the shape of the front fact of an object after it is sliced through at a certain point. After measuring the height and width of the driver, it's easiest to create an oval shape to connect the points, like the black line in the figure below. For an advanced design, the sides can be brought in closer to the red line, so the shape is tighter around the driver, like the shell in the picture shown.

Feel free to get creative with ways to measure this. One method is to use multiple rulers against the driver to record points along the red line. With these measurements you can graph the points to estimate the curvature of your driver. It is better to have a buggy that is a little bigger than the driver than smaller, so don't go overboard if using this method to shrink the surface area of the buggy.





2.3 Determine Wheelbase and Location of Driver

After driver measurements are recorded, the next step to designing a shell is determining the wheelbase and where the driver's center of mass is located along that wheelbase. The wheelbase of a buggy is the distance between the center of the front and rear axles. This distance is important in determining the handling characteristics of the buggy. A shorter wheelbase will make a buggy that will be easier to turn and scrub less speed in the chute, but at the expense of less stability while driving straight and during the bursts of energy from being pushed.

The next thing to consider is where the driver's center of gravity is located along the wheelbase. This will affect both how the buggy handles through the chute turn and the rolling resistance of the buggy (rolling friction on each wheel). As buggies have three wheels, the tradeoff for improving one of these characteristics is reducing the other.

For example, to minimize rolling resistance the weight distribution of the buggy with the driver would result in 1/3 of the total weight on each wheel. This results in 33.33% of the weight on the axle with one wheel, and 66.66% of the weight on the axle with two wheels. However, to maximize stability in the chute turn, the weight on each axle would be 50%. If the weight on the front axle is higher, during the chute turn the buggy will be more likely to understeer, and slide towards the outside hay bales. Accordingly, a buggy with more weight on the rear axle will tend to oversteer, or spin.

The following variable table and equations capture these tradeoffs to help determine where the driver should be located within the buggy. Figure 3 shows a visual representation of the equation and terms.

Equation 1: CGf = (Wr x WB)/W

This equation will find the distance the driver's center of gravity must be from the front axle to achieve the desired weight balance on each axle.

Equation 2: Dfaxl = CGf - CGh

This equation will reveal the distance the front axle will need to be from the driver's hands.

WB	Wheelbase
W	Total Weight being distributed (Driver Weight)
Wf	Weight on Front Axle
Wr	Weight on Rear Axle
CGf	Distance from Center of Gravity to Front Axle
CGh	Distance from Center of Gravity to Hands
Dfaxl	Distance from Steering Handle to Front Axle

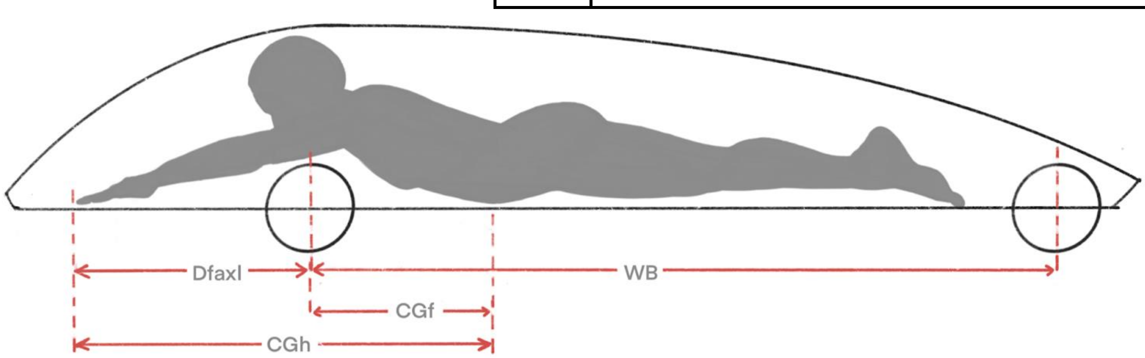


Figure 3 - Variable and equation diagram

Why this design was chosen: Wheelbase and wheel configuration

Because rolling resistance is so important to the top speed of a buggy, most teams strive for a weight balance that minimizes rolling resistance. That said, reverse trikes (two wheels in the front) designed to minimize rolling resistance will have more understeering characteristics in the chute where forward trikes (one wheel in the front) will have more oversteering characteristics. For a first build, it is recommended to build a reverse trike because it is easier for a driver to correct a slide than a spin. Therefore, the buggy laid out in this document will be a reverse trike.

For this guide the wheelbase will be 67". This relatively long wheelbase will lead to a buggy that is stable in a straight line and while pushing. Additionally, 39% of the weight will be on the rear wheel. This compromise weight balance has slightly worse rolling resistance but will lead to a more balanced buggy in the chute turn.

$$CGf = (Wr \times WB)/W$$

$$CGf = (39 \times 67)/100$$

$$CGf = 26.13$$

The driver's center of gravity needs to be 26.13 inches from the front axle to achieve a 39% balance.

Next calculate the distance the front axle will be from the drivers hands. To do this subtract the CGf from the measured distance from the driver's hands to the center of gravity. In this case:

$$Dfaxl = CGf - CGh$$

$$Dfaxl = 36.25 - 26.13$$

$$Dfaxl = 10.12$$

For ease of dimensioning, we rounded this result so the front axle will be 10" behind the drivers' hands

2.4 DETERMINE RIDE HEIGHT

The last important consideration with wheel location is the vertical location of the wheels, which is where the center of the wheels is located in relation to the baseplate plane. This height will be determined by the ride height the team decides for the buggy, which is a balancing act. A buggy should typically be as close to the ground as possible for handling to maximize stability in the turns, but if it is too low to the ground it will scrape, causing unstable handling and friction that will slow it down. To determine the vertical placement of the wheels within the shell:

1. Pick the desired ground clearance (rh)
2. Measure the radius of the wheels (rw)
3. Determine the thickness of the baseplate of your buggy.

Equations:

hW = rW - (Rh + bpt)
hW = 3.75 - (2.5 - .5)
hW = .75

hW	Height of Wheel Center above Baseplate
rW	Radius of Wheel
rh	Ride Height
bpt	Baseplate Thickness

This example uses a 2.5” ride height, a wheel radius of 3.75” and the baseplate of .5” thickness.

Advanced Design Tip: Ground Clearance

2.5” is a safe ground clearance. It is possible to go lower, but calculations are recommended before lowering this amount. A longer wheelbase will need more ground clearance as the belly gets lower to the ground cresting a hill. Different lines that the drivers take on the course will require higher or lower ground clearances as well. The amount of extra ground clearance the buggy has can be determined by attaching “skid plates” to the bottom of a buggy. Roll the buggy around the course, changing the thickness of the plates on each roll. The thickest plate that does not scrape is how much lower the ground clearance can be. Keep in mind, these shells are not perfectly rigid and can flex under more intense pushes, so it is a good practice to raise the ride height slightly from that lowest ground clearance to allow for unexpected or unforeseen road conditions.

2.5 Dimension-Specific Design Considerations

2.5.1 Crown of Head/Shoulders

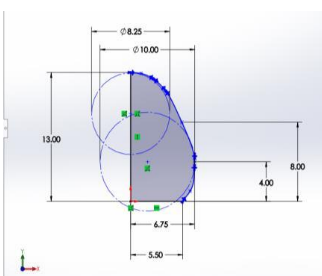


Figure 5 - Crown diagram

For the crown of the driver’s head and shoulders, ensure that there is a large enough radius to fit a helmet. A good estimate of the curvature of a Petzl climbing helmet is a circle with a radius of 4 inches. The curvature around the hip area should match the hatch cut for as long as possible to ensure a smooth shape. To further reduce cross sectional area, you may consider a slight concave shape along the side of this area. Apex, CIA and SDC buggies show this feature to varying extremes, as demonstrated below.

Hatch Cut

The hatch cut curve is where the driver will load into the buggy. It is important that the curvature here is both wide and tall enough for the driver's hips to fit in comfortably and that the crown is high enough for the driver to get their head into the buggy. The height does not need to be equal to the height at the crown of the shell, as the driver can load with their head lowered then raise it into driving position once inside the buggy. The minimum height of the entrance is 11.5". Ensure the curvature around the sides leaves enough room for the driver's hips. The curvature of the driver's hips or can be measured or estimated with a circle of radius 5.25 inches, and adjusted more finely with splines as discussed later.

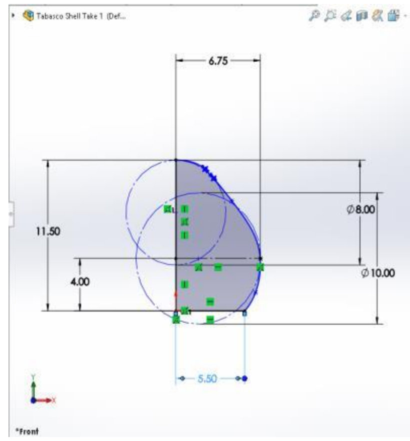


Figure 6 - Hatch cut

2.5.3 Calves

This cross section is not strictly necessary. If included, the purpose is to ensure the buggy doesn't taper too tightly in the back. Because the design presented here has the driver's feet on either side of the rear wheel, there is not an extreme enough taper to be concerned with this curve. In a buggy where the driver's feet are in front of the rear wheel, this curve should be included.

2.5.4 Toes

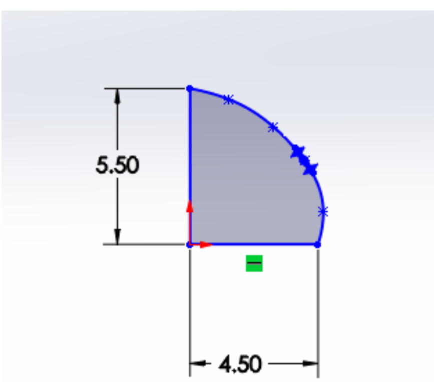


Figure 7 - Toes

For the cross section at the toes, there are two important considerations:

1. Ensure the driver has room to put their feet on either side of the rear wheel (reverse trikes only).

2. Ensure there is sufficient vertical clearance for the rear wheel so that it doesn't rub on the inside of the shell.

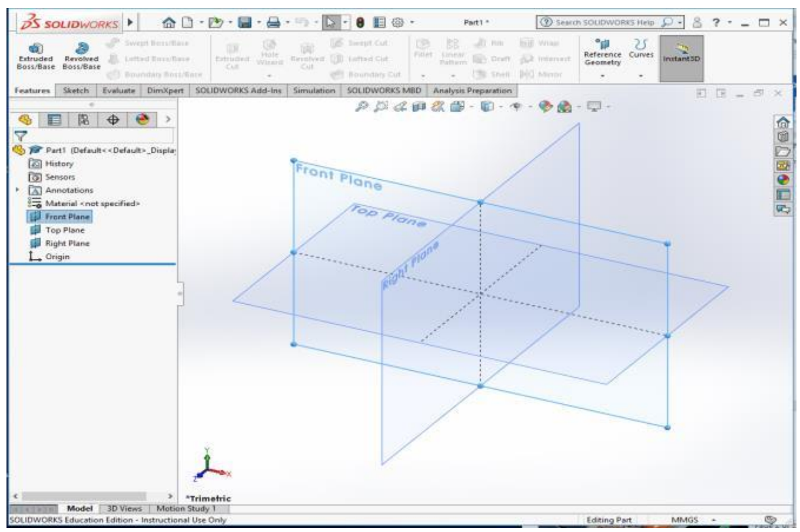
The first consideration will determine the width of this cross section. For the chosen design in these instructions, the driver will have their feet on either side of the rear wheel. Therefore, the width of the wheel, rear wheel mounts, and driver's feet must be summed to create a sufficiently wide tail. For the width of the rear wheels, it is important to know that most buggy wheels are based on the dimensions of Xootr scooter wheels. These wheels are either 1" wide (Zero Error wheels) or 1.25" (Xootr wheels) wide at the bearing seats (middle of the wheel hub). Therefore, in this design we added 1.25" in width to the driver(s) foot width measurement to account for the wheel. We also need to factor in the width of the rear wheel mounts, and add that width to the driver's foot measurement. While the team has likely not yet designed the rear wheel mounts, include an extra 1" on the foot cross section width at this time. This can be adjusted after designing the mounts if they end up being thinner than 1" in total width.

To ensure the height of this cross section is sufficient, consider the ride height chosen in "Determine the WheelBase and Location of Driver" and the thickness of the buggy's baseplate (this example uses .5", as explained in section 'Hardpoints and Baseplate'). Subtract the ride height and the thickness of the baseplate from the maximum wheel diameter this buggy might run (7.5", Zero Error Wheel diameter, as explained in section 'Wheels') to get the necessary height for this slice. Thus, this slice would have to be at least 4.5" tall to run Zero error wheels if the buggy has a 2.5" ride height and a .5" thick baseplate.

2.6 LAY OUT DRIVER DIMENSIONS AND WHEELBASE

For the purposes of this guide, Solidworks is the standard program to use for modeling. Open a new part file in Solidworks and set the front, top and right plane to visible by navigating to the features tab and right-clicking the plane. Click the hide/show symbol  to show the plane, so the screen looks like Figure 8. Once the default planes are visible, rename them to the following for ease of use:

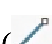
Figure 8 - Solidworks planes



Front Plane: Steering Handle
Top Plane: Baseplate
Right Plane: Centerline

To set the units to your preferred standard, click the gear symbol along the top toolbar, document properties tab, then units. This example uses IPS, or inch, pound, second.

Select "Sketch" in the upper left-hand corner and select the "Centerline" plane in the model view (it will highlight orange when you hover over it). The view will rotate to face the centerline plane--at this point, hide the steering handle and baseplate planes for convenience.

Within the sketch menu, select the line icon () to draw a horizontal line, representing the ground. Click once to begin drawing the line and define its start point, and click again to set the endpoint. Constrain the line as horizontal by setting the endpoint when you see the following yellow icon: . Once the line is created, click it again and select the "For construction" and

"Infinite length" options in the toolbar. This line is simply a visual aid and is not physically a part of the model.

Start another line at the red origin icon and create another horizontal line. Select "Smart Dimension" (Smart Dimension) and click the second line and define its horizontal length as the length of the driver from hands to toes (in this example, 77.5").

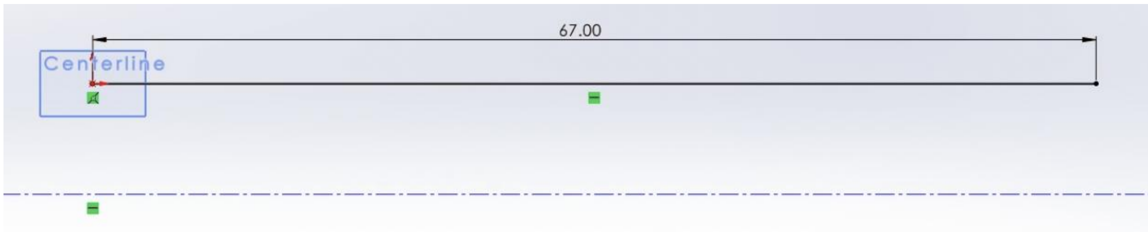


Figure 9 - Centerline

The ride height (the space below the buggy) was previously determined as 2.5" in this example. Smart dimension the vertical distance between the ground line and the centerline as 3" (the width of the baseplate plus the ride height).

Next, add the wheels into the 2D-sketch. Click "sketch" followed by the circle icon ( ), and then click anywhere above the driver line to sketch the center of the circle. Click again over the construction line representing ground (it will highlight orange and you will see the "tangent" icon:) to constrain the bottom of the wheel to the ground. Add another circle in a similar fashion further down along the centerline. Then, drop the circle tool, click one of the circles, and CTRL + click the other. Select "Equal" to constrain the two wheels as identical--defining the size of one will now also redefine the size of the other. In the circle options menu, select "For construction" as with the ground line and smart dimension the circle diameter to the wheel size (in this example, 7.5").

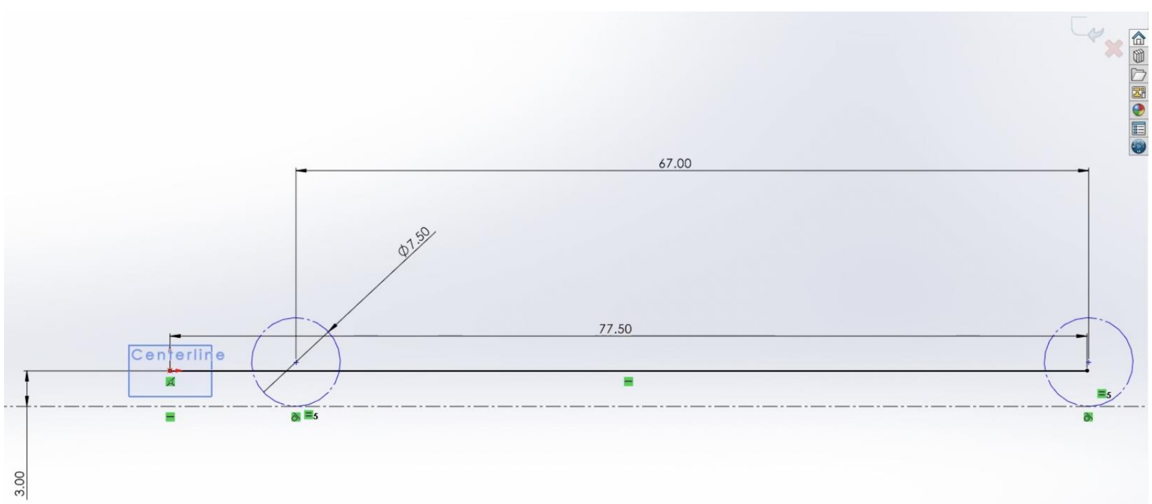


Figure 10 - Wheels added

Smart dimension the distance between the circles by selecting "Smart Dimension" and then clicking the midpoint of each of the two circles. Set the wheel distance equal to the wheelbase, in this case 67". The wheels are now constrained vertically and relative to each other, but not relative to the driver--smart dimension the horizontal distance between the front wheel and the driver's hands (i.e. the red origin point in the Centerline plane) to the desired value (in this case, 10.12"). At this point, every line in the sketch should be black (fully defined) rather than blue, indicating that all geometries have been assigned enough dimensions to be rigid. Hit "Esc" to exit the sketch.

2.7 SKETCH SHELL TOP PROFILE

Next, it's time to begin adding our driver's dimensions into the model. Begin a new sketch on the centerline plane and add a vertical line of any length to the leftmost point of the 77.5" driver line as shown below. This vertical line denotes the driver's hands and will be the reference for the rest of our measurement points. Also note the yellow vertical symbol (|) that appears when the sketch line is aligned vertically.

Figure 11 – Vertical line for hands

Using the driver measurements from the previous section, create vertical construction lines along the driver line at each of the corresponding distances from the hands. For example, the "elbow" line should be dimensioned 11.5" inches from the driver's hands as shown. Where a height value exists (i.e. for the crown of head, hips, and toes), also dimension the length of the line to the corresponding height value (ignore the width values for the time being). As you sketch each line, make sure the starting points are coincident with the driver line as indicated by the following icon: .

	Dist from Hands (in.)	Width (in.)	Height (in.)
Elbows	11.5	11.25	
Shoulders	20	13.5	
Crown of Head	17.5		13.5
Hips	43	13.5	8.25
Calves	62	10.75	
Toes	77.5	7.5	5

With some SolidWorks shell designs, the width of the hatch cut ends up thinner than the shoulders of the driver. When this happens, the driver may struggle to fit or need to load into the buggy sideways then roll into the driving position. To avoid this, move the shoulder plane 3 - 5 inches ahead of the elbows and rename it to Hatch Cut. Then, the elbows plane can be removed or ignored (although ensure that the driver will have enough arm space to rotate the steering handle). We highly recommend following this technique and as such, include it in the rest of this walkthrough.

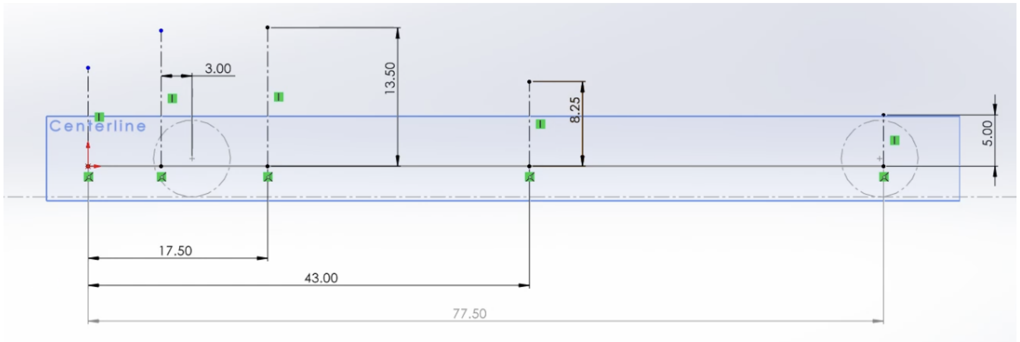


Figure 12 - Driver measurements added

2.7.1 LAYOUT NOSE OF SHELL

The main considerations of the nose of the buggy shape and dimensions are:

1. Long enough to include a crumple zone in case of a head-on crash (6” in this example).
2. Wide enough to allow the steering handle to turn without contacting the side of the shell.
3. Not too pointy or it will be difficult to construct and potentially illegal.

Additionally, design of the nose must include considerations for a windshield. Lexan can be difficult to form properly to compound curves, so careful attention must be paid to the shape of the nose profile to minimize complex shapes in this area. A general rule of thumb: if a piece of paper cannot be easily conformed to the intended curve, Lexan will be difficult to bend to that shape.

To add the nose to the 2D sketch, add a horizontal line the length of the crumple zone (6”) extending from either end of the driver line to the sketch. Then, add a centerpoint arc () to the end of the line whose radius (2” in this case) will define the sharpness of the nose. Also dimension the height of the nose curve above the baseplate, shown here as 1.5”. Next, add another centerpoint arc to the top end of the “crown of head” construction line, clicking first anywhere along the line, second at the top end of the line, and third at an arbitrary point to the left. These steps ensure that the arc will form a smooth curve to the highest point of the buggy.

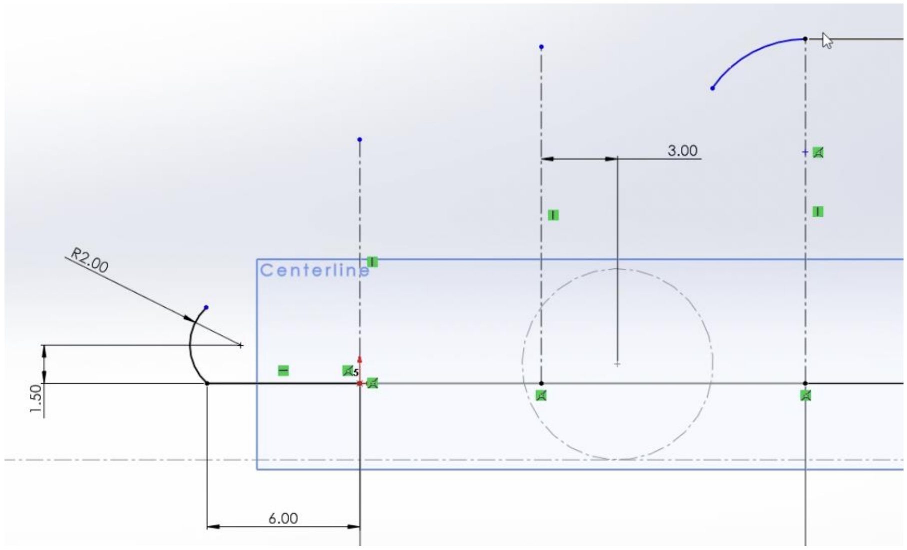


Figure 13 - Centerpoint arc

To connect the two arcs, use the line tool to draw a straight line between the open points of the two arcs, forming the windshield curve. Select each of the points where this new line meets the arcs and define them as tangent (Tangent) to create a smooth curve, found under "Add Relations" in the properties tab on the left of the screen.

The windshield curve, although affixed at either end, should still be highlighted blue and able to be manipulated. The front of the buggy needs to form a reasonable profile relative to the height and placement of the hatch cut. Depending on the desired shape of the front of the buggy, set a point on the windshield curve of the buggy and set it coincident to the top of the hatch cut construction line by selecting both features and adding a coincident relation (Coincident). At this point, the front of the 2D sketch should be fully dimensioned as shown.

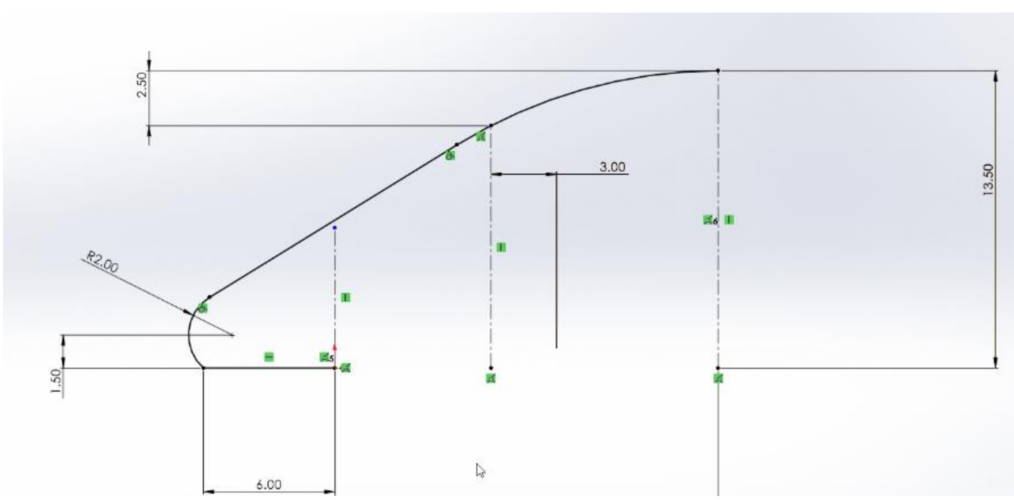


Figure 14 - Front of 2D sketch

2.7.2 LAYOUT TAIL OF SHELL

The considerations that come into play while designing the tail are almost entirely aerodynamic and construction based. This example follows the same 2D sketching process as the previous nose section. However, a 3D curve may be necessary depending on the desired shape and type of tail. The shape shown, for example, would be relatively difficult to construct using a wet layup method. Consider making a kammback or kamm-tail shape for this first build, and see https://en.wikipedia.org/wiki/Kammback for examples.

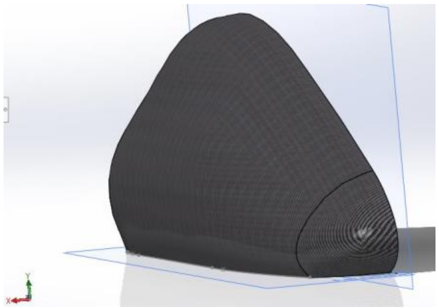


Figure 15 - Tail

In this example, begin by adding a centerline arc to the rightmost end of the driver line (this example again uses a 2" radius and a midpoint distance of 1.5" off of the baseplate). If the tail curve extends under the baseplate, select "Trim Entities" () and the default "Power Trim" tool () to remove the excess curve as shown below.

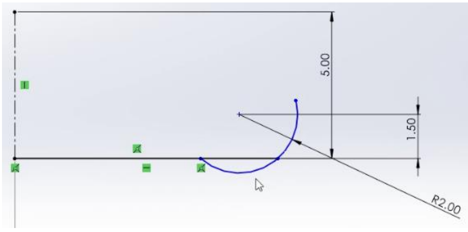


Figure 17 - Excess curve

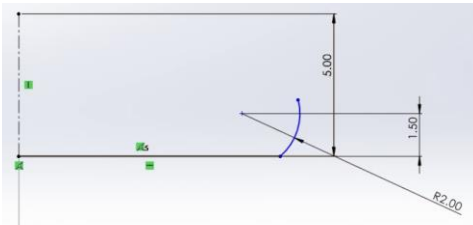


Figure 16 - Excess curve removed

The end of the tail arc needs to meet the top of the toes construction line, but the aesthetic details are largely up to team preference. In this case, the midpoint of the tail arc is set to be 8" from the driver's toes, and the remainder of the geometry can be defined in one of three different ways: Style Spline, Standard Spline, or Arcs and Curves. This book recommends the Style Spline.

Style Spline

The style spline is a variation of the standard spline tool that will limit the amount of adjustment needed after sketching the buggy spine.

Select the style spline tool () and sketch the spine by clicking first the crown of head construction line, second a point horizontally across from the top of the construction line such that the yellow tangent icon appears, and lastly the end of the tail arc. The generated spline is shown below as a solid blue curve, whereas the points clicked to generate the spline are shown as the dashed blue construction lines. Set the tail-end construction line tangent to the tail arc to ensure that the curve is smooth. Lastly, set the spine curve coincident to the toes construction line to fully define the sketch.

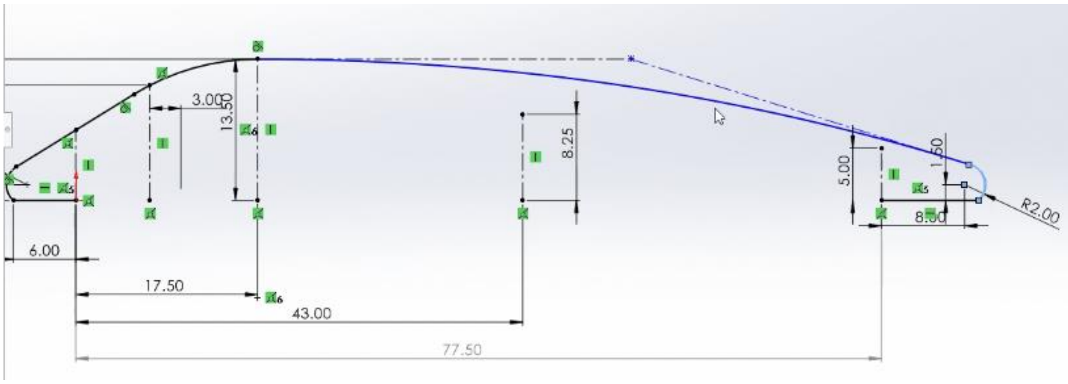


Figure 18 - Generated spline

Standard Spline

The buggy spine can be sketched using the spline tool ( ), or a highly customizable, non-circular variation of an arc.

To maximize the smoothness of the buggy's spine, aim to create as few control points as possible (i.e. points along the spline). Begin by creating a spline and selecting only the crown of head curve and the top of the tail as endpoints, which should look much like a straight line. Next, adjust the overall shape by setting the crown point and the spline to be tangent. The point between the tail and the spline can be set to either "tangent" or "equal curvature" depending on the desired aesthetics. If necessary, add additional control points or manipulate the geometry as necessary to create the desired profile.

Arcs and Curves

For a more straightforward alternative to splines, arcs and curves can also be used in conjunction with the coincident and tangent constraints to approximate a smooth curve from the crown of the driver's head to their toes. As long as the buggy reasonably accounts for the driver's measurements, the exact profile can be adjusted for any of ease of design, ease of construction, aesthetics, or aerodynamics.

Advanced Design Tip: Splines

To more closely examine the spline curvature (and as a more advanced method to adjust the shell shape), right-click the spline and select "curvature combs". This feature can be used to visualize the spine curve more effectively. The "Show Inflection Points" feature will highlight undesired curvatures within the spline that can then be removed. Lastly, selecting "Show Spline Handles" will allow for finer control over the curve shape if desired

Once the buggy spine has been drafted close out of the sketch. The 2D profile is complete, and should look like the figure below:

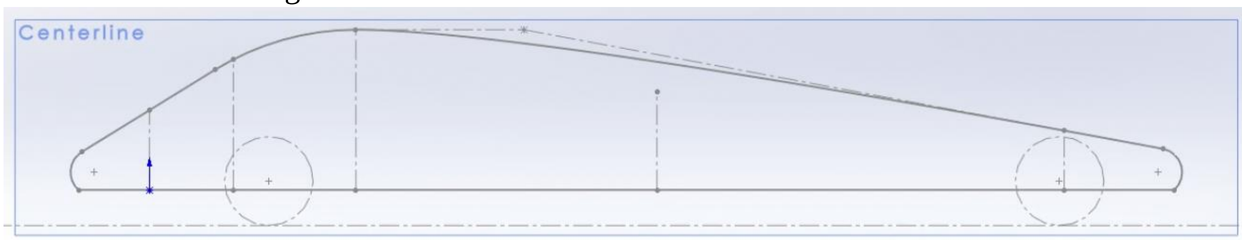


Figure 19 - Completed 2D profile

Rename "Sketch 1" to "Wheelbase" and "Sketch 2" to "Main Profile" in the Design Tree for future reference.

Now, adjust the view to be normal to the baseplate plane (i.e. the top-down view" of the buggy). Then, use the keyboard UP arrow to rotate the view by ten degrees. Tilting the view puts both existing sketches of the buggy in view such that the width lines of the buggy can be easily set coincident to the baseplate (*not* to the spline curve).

Sketch horizontal construction lines coincident to the baseplate for each of elbows, shoulders, hips, calves, and toes using the same process as the original buggy profile and the height measurements. Because the buggy geometry will ultimately be mirrored from the left to the right (or vice versa), these construction lines only need to be drawn on one side of the profile. As a result, the length of the construction line at each measurement point should be also dimensioned to half of the width recorded from the driver's measurements.

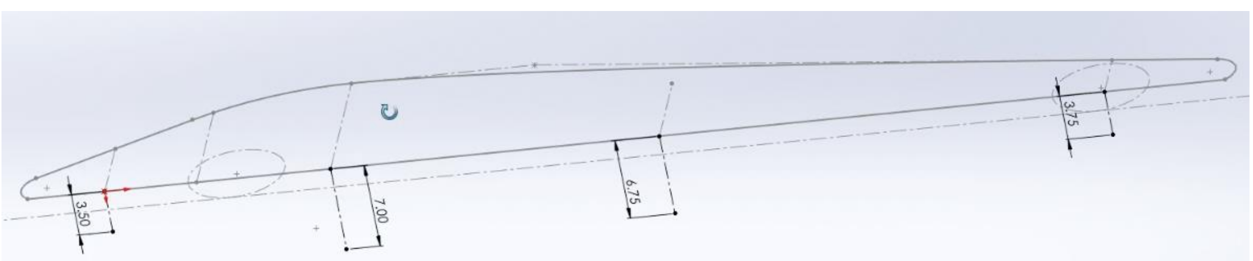
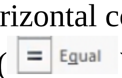


Figure 20 - Tilted view

Because the widest point of the average driver is at their hips, the width of the buggy at the hips and hatch cut should be roughly equally wide to accommodate for driver loading. Add an additional horizontal construction line at the position of the hatch cut, and constrain it to be of equal length (

) to that of the hips.

To sketch the profile of the width of the buggy, first draw a spline from the buggy nose to an arbitrary point along the hatch cut construction line (i.e. not at either end). Then, draw an additional horizontal construction line from the nose to the opposite side of the sketch as the spline, and set this line tangent to the spline as shown in figure 20.

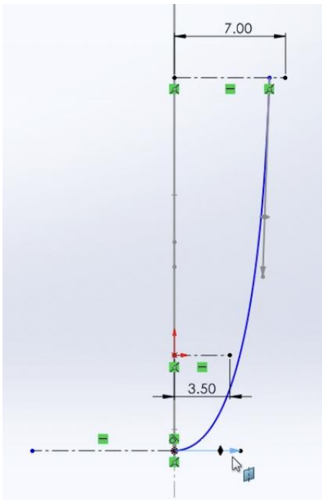


Figure 21 - Horizontal construction line

Once the first spline from nose to elbows has been drafted, sketch a straight, vertically constrained line from the hatch cut to the hips construction line. Then, create an additional spline with control points along (i.e. not at the ends of) each of the remaining horizontal construction lines and finally, the tail point. Set the hatch-to-hips line tangent to the most recent spline at the point where they meet and constrain the spline at the buggy tail to be horizontal.

The widest point of the driver will not be at the baseplate, meaning the buggy should ideally taper in towards the bottom. Generic values for the severity of the taper are provided below as an alternative to the instructions in 'Advanced Design Tips: Cross Sectional Measurements' at the end of 'Measuring the Driver'. These values are indicators of how much thinner the baseplate can be than the measured width values at each of the key locations. Account for these values by dimensioning the width spline to be half of the inset thinner than the measured widest point.

	Width Inset (in.)	Height of Widest Point (in.)
Hands	0 – .5"	2"
Hatch Cut	1.25"	4"
Shoulders	1.25"	4"
Hips	1.5"	4"
Toes	.5"	2.5"

Using the construction lines as a guide, adjust the splines to eliminate inflection points and as necessary to fit the driver's measurements while limiting excess space until a desired profile is obtained. Then, exit the sketch and rename "Sketch 3" to "Top Profile."

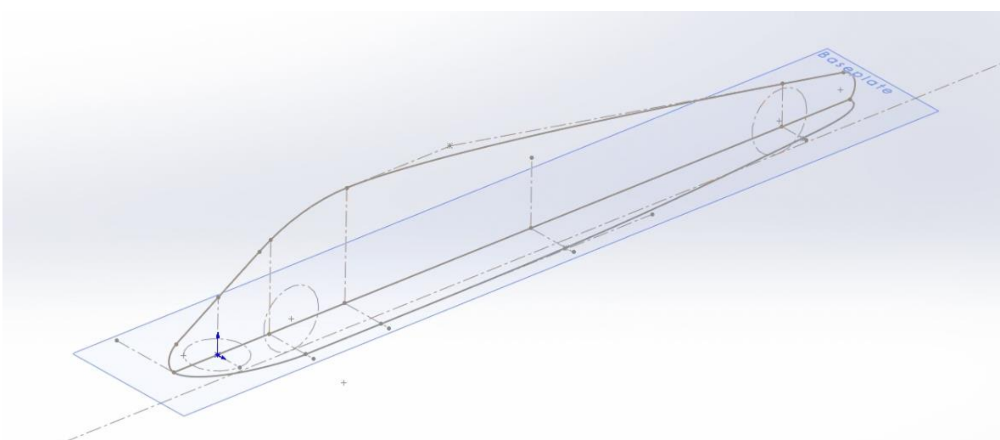
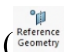
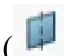


Figure 22 - Top Profile

2.8 Creating Cross Sections

Before the 3D shell is generated, we need to add cross sections for each of the key points we've already outlined. Every cross section will be parallel and measured relative to the Steering Handle plane, which should be made visible. Hide the remaining planes as well as the "Top Profile" at this point.

Select the Steering Handle plane and navigate to the Features tab, then to "Reference Geometry" (

), and finally to the plane icon (). The figure below shows the necessary settings to create the hatch cut cross section off of the steering handle plane:

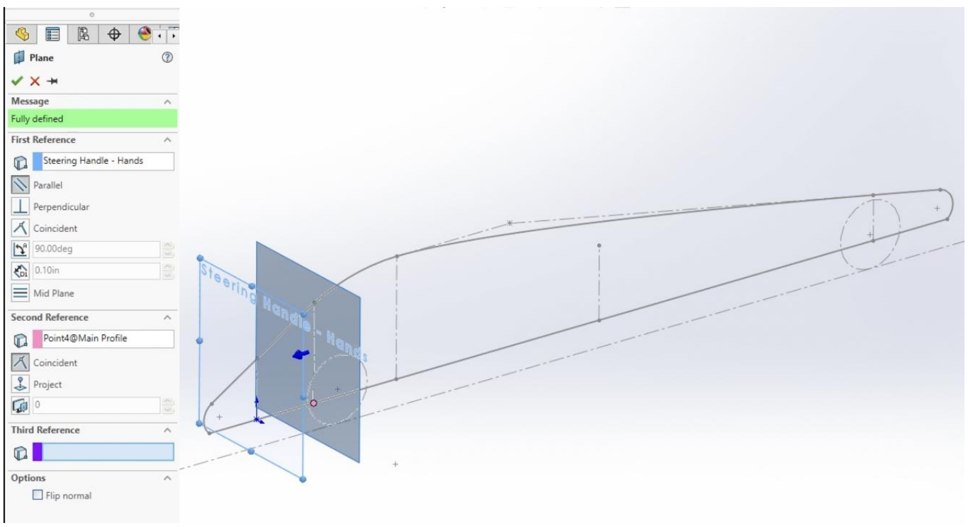


Figure 23 - Settings bar

When the plane feature is selected, the first reference should automatically populate to "Steering Handle – Hands." Highlight the "Second Reference" field and select within the model the point joining the hatch cut construction lines to the baseplates. Rename the newly created plane to "Hatch Cut."

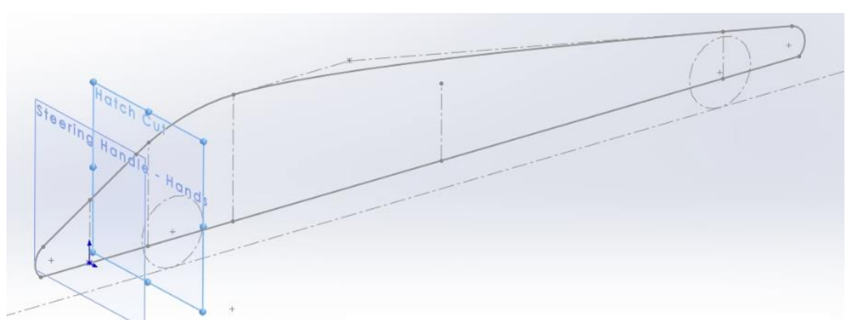


Figure 24 - Steering and hatch cut plane

Repeat this process for each of the remaining planes (at least crown of head, hips, and toes). Once complete, the model should look like the following:

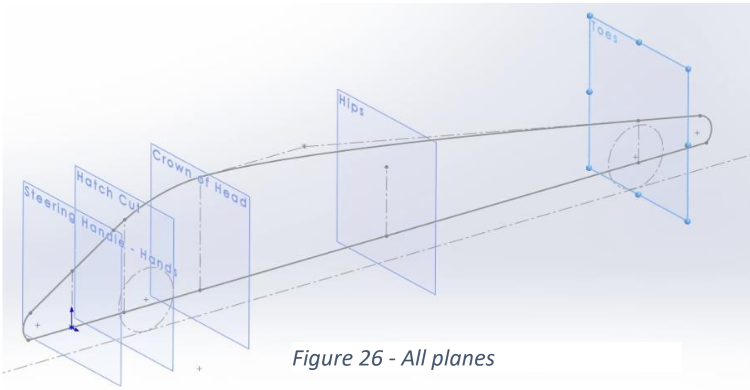
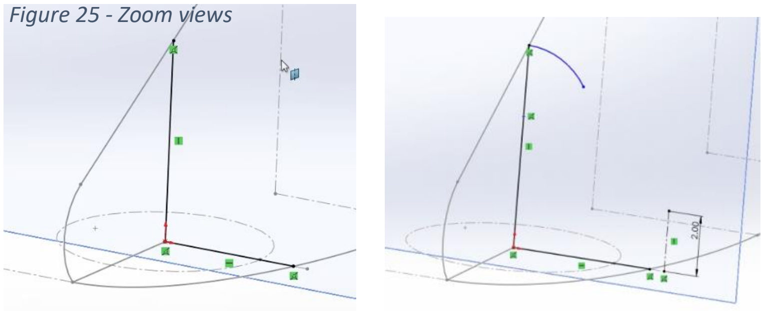


Figure 26 - All planes

Now, show the top profile, hide the just-created planes, and begin a new sketch on the steering handle plane. Begin by sketching solid lines over the existing construction lines that define the height and width of the shell at the steering handle. Then, draw a centerpoint arc starting from the top of the vertical line to ensure a simple curve that will allow for windshield manufacturing. Sketch a vertical construction line starting from the steering handle width construction line (*not* the width profile itself) and dimension it to the height of the widest point from either driver measurements or the suggested values tabulated above (it is dimensioned here to 2”). A zoomed-in view of these features is shown below:

Figure 25 - Zoom views



To close the cross section, add a tangent line to the end of the top arc. Then, add a spline with control points at the steering handle width profile location and at the end of the just-created tangent line. Finally, set the spline coincident to the top point of the new 2” construction line and set all of the points between each feature to be tangent.

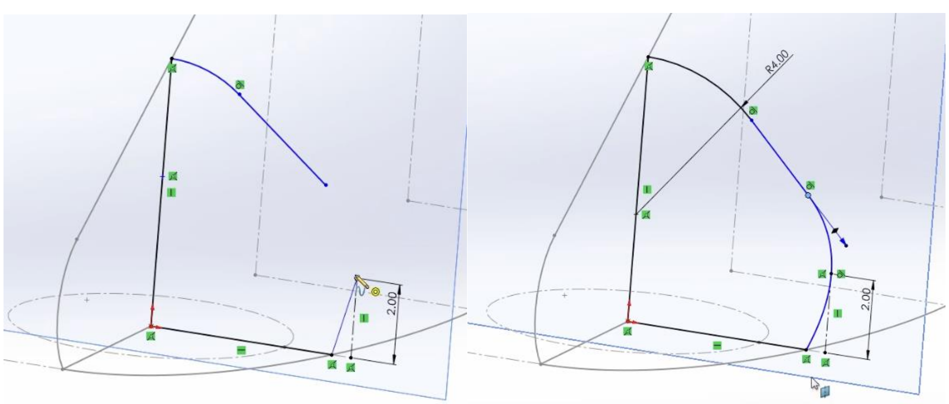


Figure 27 - Points set to be tangent

As with previous uses of the spline tool, the shape can be adjusted and manipulated to meet geometric and aesthetic constraints. Once the desired profile is achieved and constrained, rename the sketch to “Steering Handle Cross Section.” Then, repeat the process for each of the remaining planes.

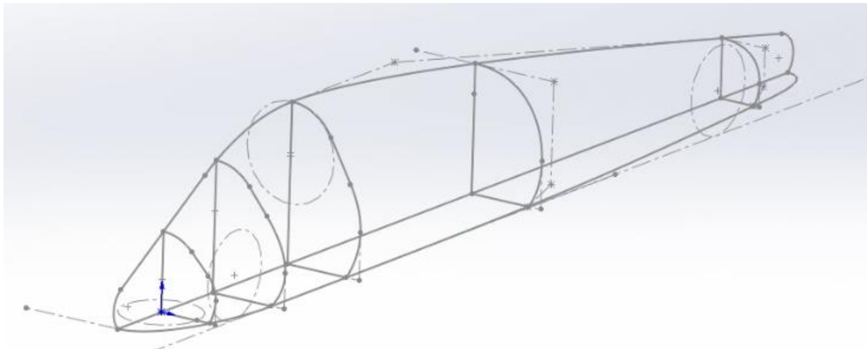
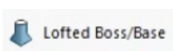


Figure 28 - Completed profile

2.9 Creating Lofts

To create the 3D shell, navigate to the “Features” tab and select the “Lofted Boss/Base” tool (

). Within the Loft menu, select the crown of head, hips, and toes cross sections as profiles. If the yellow loft preview does not show the desired contour, drag the green points to adjust the desired geometry. Then, select the wheelbase, main profile, and top profile as guide curves. Lastly, select “Normal To Profile” under “Start constraint” to ensure that the body of the buggy connects properly to the nose loft in the next step.

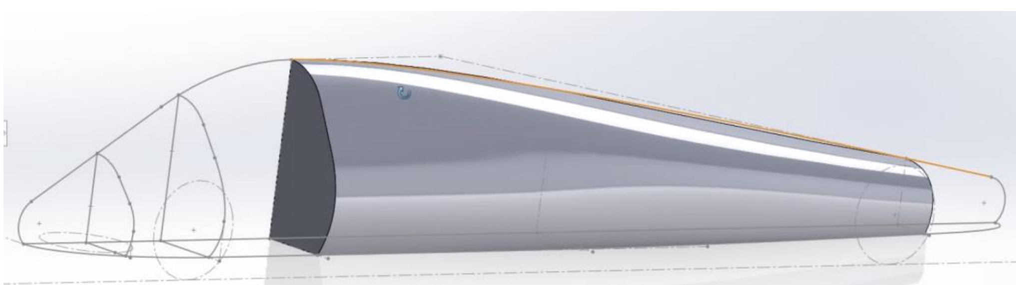


Figure 29 - Loft

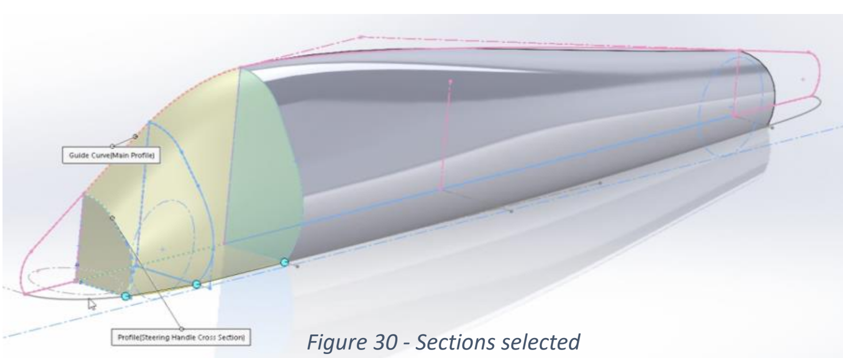


Figure 30 - Sections selected

Select the loft tool again and use the front face of the loft we just created, the hatch cut cross section, and the steering handle cross sections as profiles. Select the wheelbase, main profile, and top profile as guide curves, and select “Tangency to face” as the start constraint.

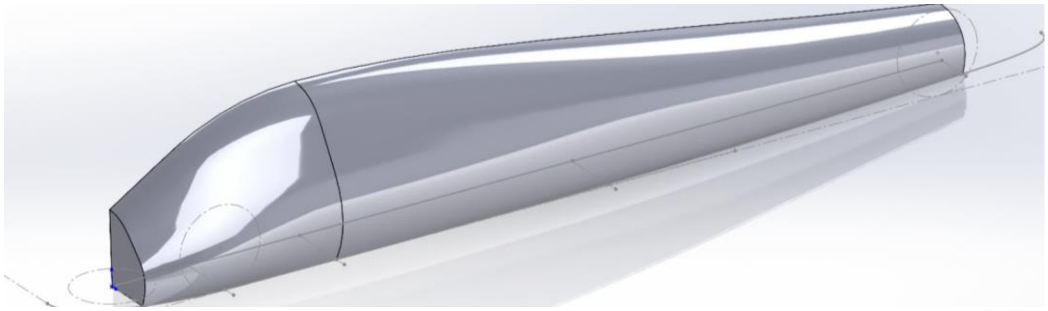


Figure 31 - Tangency to face

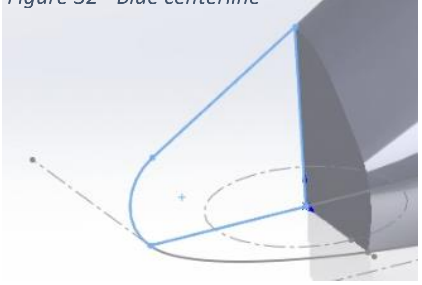


Figure 32 - Blue centerline

To create the nose, show the main profile in the Design Tree. Select the windshield curve of the main profile, nose arc of the main profile, and the centerline up to the existing loft (shown in blue in figure 32), and then select “Convert Entities” under the “Sketch” tab.

(

)

Trim any entities outside of the closed profile if necessary and name the generated sketch “Nose Cross Section” as in figure 33. Repeat the same process for the shown profile of the tail.

For the nose and tail, use the existing loft face and the new cross section sketch as profiles and the top profile as the guide curve. Set the start constraint as “Tangent to face” and the end constraint as “Normal to Profile” in both cases.

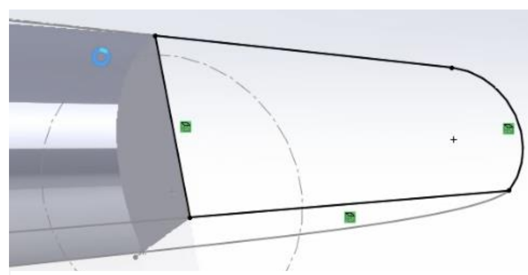


Figure 33 - Nose cross section

Once the lofts are confirmed, the left half of the buggy should be fully complete:

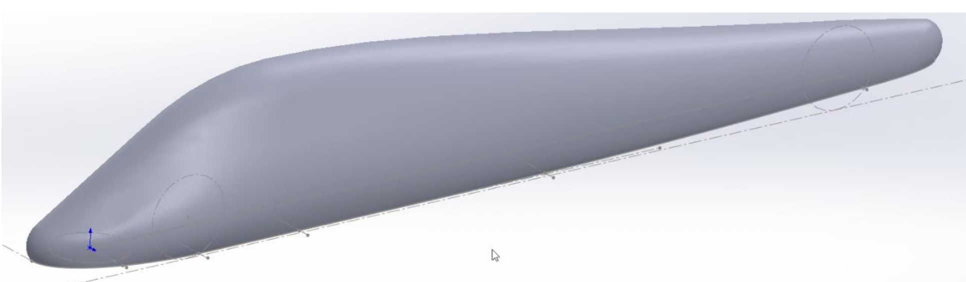
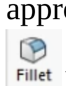


Figure 34 - Left half

Under the “Features” tab, navigate to “Linear Pattern” (

) and select the shell half as “Bodies to Mirror.” Ensure “Merge solids” is checked and select the Centerline plane as the Mirror Face/Plane. Confirm the loft and the buggy shell will populate as a solid.

Figure 36 - Full shell

The easiest way to smoothen the bottom edge of the buggy is to create a fillet along the edge around the baseplate. (Note that it can also be added in-process to each of the cross section geometries, which is a more advanced approach). To add this feature, select the "Fillet" icon (

) from the "Features" tab and select the bottom edge of the baseplate. This example uses a symmetric fillet radius of 1.5", although the size of the fillet is largely up to preference. The preview and final filleted shell are shown below:

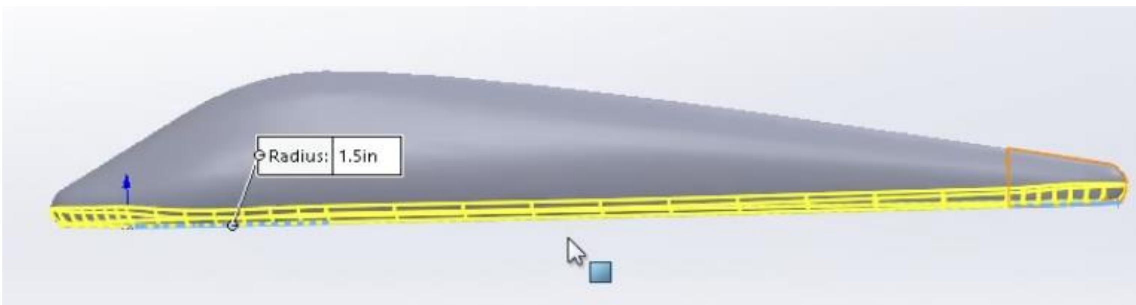


Figure 35 - Preview

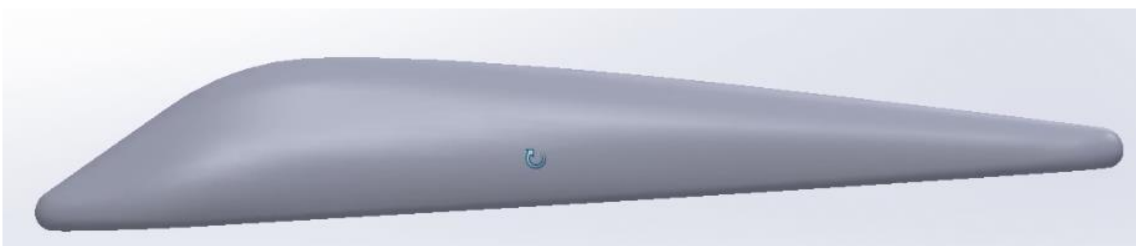


Figure 37 - Final filleted shell

2.10 Create Groove for Guide Bar (Optional)

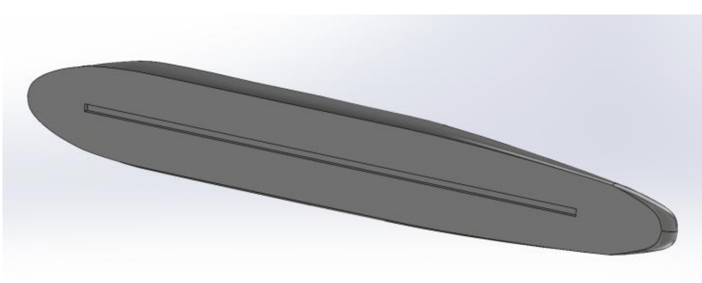
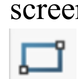
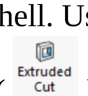


Figure 38 - Bottom view with groove

Flip the mold until the bottom is on the screen. Sketch a 1" x 72" rectangle () onto the baseplate and center it on the shell. Using the extruded cut feature (

), cut the rectangle 1" deep into the solid shape. This step will assist with mold construction, as covered in later sections.

2.11 Preparation and Print of Slices

Due to SolidWorks feature changes, the shell file may need to be converted to an STL file. Try the steps below, but if they do not work save a copy of the file in an STL format and retry.

Click Insert then go down and select ‘slicing’. This triggers a side bar that asks for the number of slicing planes and the offset to each plane. Set the number of planes to the length of the buggy in inches divided by the thickness of the foam the team is using for the mold (If using 1” thick foam, and the buggy is 98” long, set the number of planes to 98 inches). Set the offset to the thickness of the foam. Measure the foam directly to determine its thickness; do not rely on the manufacturer’s numbers. When in doubt, err on the side of the buggy being a little longer than designed rather than too short.

Next, number each slice from the front of the buggy to the back. This can be done in Solidworks or by exporting the slices to a program like Adobe Indesign or Adobe Illustrator.

> **If using Illustrator**: Select the slices in Solidworks and go to file -> save as -> and save as an .ai file type. Open this file in illustrator, then click file -> document setup -> edit artboards. Set the width of the art board to the width of the plotter (36” or 48” are typical widths) and the length of the artboard to 96” to start. The artboard may need to be made longer at some point to fit all of the slices. Drag and place the slices within the artboard, numbering each slide from front to back. Use the text or text box tool to add the numbers.
>
> **If using Solidworks**: start a new Solidworks Drawing. Remove the sheet layout -- in the Solidworks task pane, click the drop down for the sheet (titled “Sheet 1” as a default). Right click “sheet format” and delete. This will give a clean sheet to insert the slice cross sections. Use the “section view” tool and insert a section view from each plane on the drawing, **making sure the scale is 1:1**, and that the sections don’t overlap. Next, resize your drawing page to the width of the plotter, and extend the drawing in length to fit all of the section views on one sheet. Finally, export the drawing to a PDF.

The easiest way to print the slices is on a plotter. Architecture, art and design students typically have access to plotters or they can be printed at Tartan Ink – email them and ask for a quote and the width of their plotters. The slices can also be printed on 11 x 17 or 8.5 x 11 sheets of paper, and larger slices will need to be tapped together. It is doable, but less reliable/convenient.

Advanced Design Tip: Shell Aerodynamics

In buggy there are 3 forces that will slow the buggy down on the free roll: rolling resistance/friction, energy loss in the steering, and aerodynamic drag. While aerodynamic drag has the smallest effect of the 3 forces, it is something that should be considered. Solidworks has a suite of aerodynamic testing simulations and there are other, more advanced programs that CMU students have access to as well. If someone on the team knows how to use these features or have a mentor/professor willing to help, aerodynamic simulations can be run after mirroring lofts to mockup the finished mold design. The team can then iterate on the shape to minimize the coefficient of drag of the buggy.

3 BUILDING THE MOLD

3.1 MOLD BRIEF

Skills: Experience with a bandsaw and jigsaw and knowledge of the applicable safety equipment

Tools: Band saw, jigsaw, hot wire foam cutter, caulking gun, plotter or printer

Materials: ½" insulation foam, adhesive, and a 1"x1"x96" rectangular aluminum tube

Safety Tips: Debris and vapors from cut foam can pose an inhalation hazard. Try to find a well-ventilated area if using a hot wire foam cutter and wear a dust mask to prevent dust inhalation when cutting with bandsaws or jigsaws. Dust protection should also be worn during sanding. Know the hazards associated with the adhesive you select and mitigate appropriately. Utilize all relevant protective equipment when working with power tools.

The mold of a buggy shell serves to bring the Solidworks file to life, creating a true-sized, solid model of the buggy shape. This is later used during layups to create the hollow buggy. As is the case for all aspects of a buggy, there are many ways to create a proficient mold. The techniques chosen for this build guide are relatively simple, straightforward, and inexpensive.

Why this design was chosen: Male mold

This buggy is intended to be designed and built with a male mold created by hand. A male mold requires the least steps and raw materials to build of any mold building method.

This specific method is a proven process used for decades in buggy. It utilizes the cheapest materials and has no outside/external labor cost. It is time consuming but requires few special tools and anyone can complete it with enough time and patience.

3.2 BUILD INSTRUCTIONS

The first step in creating a tangible mold is to print out the slices that were created in the final step of designing the mold. This is ideally done on a large printer, like a plotter as discussed in section 2.11, but can also be pieced together from standard sheets of paper. Next, cut the paper slices out and use a glue stick or spray adhesive to glue them to insulation foam purchased from any hardware/home improvement store (See Figure 39).

Figure 39– Slices glued to foam

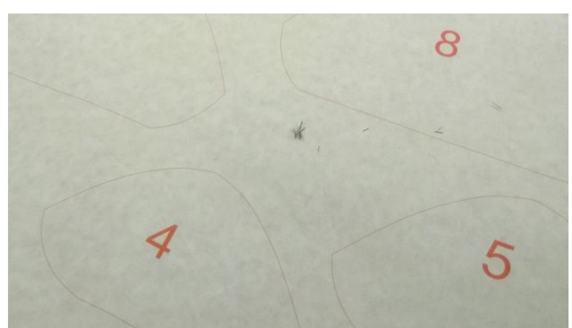


Figure 40– Slices on plotter paper

Figure 41– Cutting with bandsaw

Use the bandsaw, jigsaw or hot wire foam cutter to trim the foam boards to the shape of the paper slices. For the slices with the square notch in the bottom, cut the notches out with a box cutter.

Once all the slices are cut, label the number of each slice along the edge. Remove the paper slices from the foam slices. Grab the caulking gun, foam board adhesive and rectangular tube. Liberally apply the adhesive to groups of 10-15 slices, align them on the metal tube, and press them together until the adhesive dries. Once all the slices are connected in groups, adhere the groups together to complete the mold.

After the adhesive dries, sand the curved top of the slices using electric palm sanders and 100 grit sandpaper until the shape of the mold approaches the desired shape of the buggy.

Figure 42 - Sanding mold

Figure 43- Assembling mold on rod

Fill any remaining lumps and imperfections in the areas where more material needs to be built up with bondo and spackle. Then sand the mold smooth. Continue this process until all but the flat bottom of the mold is smooth.

Figure 44 - Sanded mold

To achieve a smooth bottom, rather than sanding (which is time intensive) a different process can be used. A "pan" made of ½" insulation foam will be added to the bottom of the mold. Then the edges should be sanded to match the curvature of the upper portion of the mold.

To do this, lay the mold on top of a remaining ½” slice of foam and trace the shape of the bottom of the mold onto the foam. Cut this shape out and glue it to the bottom of the mold. Do not remove the metal bar, this helps keep the mold in one piece. Once attached, sand the edges and bondo/spackle the join line.

The final mold should take a few weeks to complete. It will be destroyed in the process of building the buggy so do not get too attached!

Alternative Design Option: Mold

Male molds have a few downsides:

1) One time use: They take a lot of time to make but cannot be reused in future years.

2) Poor Finish Quality: Male molds lead to wrinkly surface quality, requiring time consuming and heavy body work to get a smooth surface finish on the buggy.

A female mold would resolve these issues. If the team chooses to build a female mold, consider designing a multi-piece mold with “leaves” to allow for larger or smaller buggies from the same mold.

If the team has access to a CNC or enough funding to pay for the mold to be outsourced, this will save significant time and will lead to a smoother shape and finish on the buggy.

Other mold foams that are denser would be better for the mold building process. However, they are more expensive and more difficult to remove from inside the buggy but won’t bend or get damaged as easily as the insulation foam.

4 HARDPOINTS AND BASEPLATE

4.1 HARDPOINTS AND BASEPLATE BRIEF

Skills: Experience with a bandsaw and drill press

Tools: Clamps, a bandsaw, drill press, file, #7 drill bit, W drill bit, and ¼-20 tap

Materials: Balsa wood (2 or more 2' x 4' sheets, depending on length of the buggy), wood glue, Nylon (4" x 24" x 0.5"), and 5-minute cure epoxy

Safety Tips: When using a bandsaw, keep hands clear of the saw even when trying to make very precise cuts. A "push stick" may be helpful. When using epoxy, wear gloves to prevent epoxy from contacting skin and consider wearing an apron or shop shirt. Exposure to epoxy can cause skin reactions and epoxy can easily ruin clothing.

This guide details the 'pan and shell' method of buggy fabrication. A pan and shell construction consists of a carbon fiber monocoque with 2 different kinds of core material. A thinner, more pliable core is used for the curved upper portion of the buggy shell while a thicker, stiffer core is used for the bottom. This minimizes weight, increases strength along the bottom and thus buggy durability, and is easier to build than using 1 core over the whole buggy. There are hardpoints embedded in various places in the shell, which serve as fasteners for mechanical systems, or attachment points for safety systems.

Why this design was chosen: Pan and shell

A "pan and shell" construction minimizes weight, increases strength along the bottom, and is easier to build than using one core over the whole buggy.

End-grain balsa wood was chosen as the base plate core material because it is low cost compared to other lightweight and rigid core materials such as Rohacell. It is also incredibly stiff in sandwich structures and has great shear strength, ideal for a durable build.

Hard points made from plastic or metal replace relatively small areas of the core materials and are necessary anywhere you plan to bolt through the composite structure of the buggy. Composite structures are strong, but they wear easily and can fracture under heavy loads.

In this design, there are two major types of hard points: those that support the **steering**, and those that support the **driver safety points.**

For the steering hardpoints: the core materials are generally not strong enough to support the interface between the baseplate and the steering. High impacts (from potholes, etc) will ream out bolt holes, creating dangerous slop in the steering. Bolting down on cored composite structures will crush the core, potentially causing delamination issues.

For the driver safety points: these hard points improve the fracture resistance of the structure. This is crucial in case of a crash; the safety hard points in the baseplate keeps harness mounts from easily ripping out in an impact.

Having small hard points wrapped into the baseplate provides a stiff, high-strength interface for the buggy's steering and driver safety points, while still allowing the team to use a relatively lightweight material for the rest of the baseplate.

4.2 PREPARATION

4.2.1 Prepare the Balsa

Take the roll of end grain Balsa and lay it flat on a table. Place the mold on top of the balsa and trace the bottom of mold ½" thicker than the bottom of the mold. Cut the shape out with a box cutter or a band saw. If the material cannot be purchased in a length long enough for the entire baseplate, gluing 2 pieces together is adequate and is covered further in Section 4, 'Hardpoints and Baseplate'.

4.2.2 Cut Nylon Hardpoints

Use the bandsaw to cut the nylon into the following seven blocks.

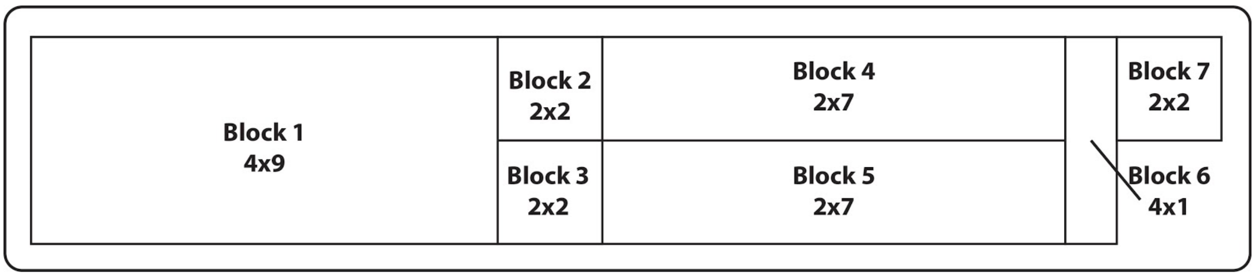


Figure 45 – Nylon blocks diagram

These blocks will be used as follows:

- Block 1 -- rear wheel mount and rear harness mount point
- Block 2 -- left harness mount point
- Block 3 -- right harness mount point
- Block 4 -- left steering mount
- Block 5 -- right steering mount
- Block 6 -- steering handle mount
- Block 7 -- center steering mount

4.2.3 Cut the Wheel Slot

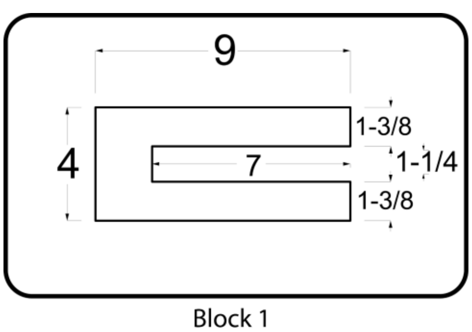


Figure 46 - Block 1 diagram

Measure and mark a slot on Block 1 as depicted in Figure 38. Cutting this slot with a bandsaw requires creative work. Make cuts along the long edges of the slot, then cut an x going to the back. There will be a point jutting out in the middle of the slot. Make a series of diagonal cuts across this triangular obtrusion to slowly flatten it down (shown by the numbered grey lines). To finish flattening the back edge of the slot, use a file, or a dremel with a grinding bit.

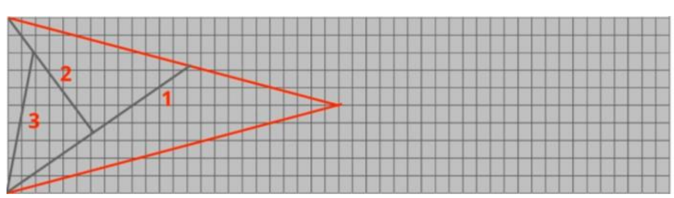


Figure 47 - Diagonal cut technique

4.3 Drilling and Tapping

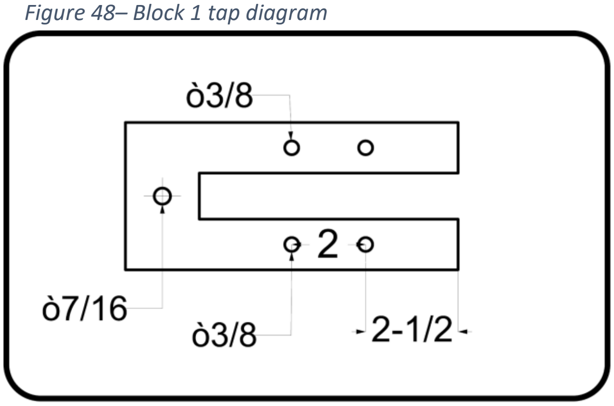
Holes need to be drilled in the hardpoints to allow for hardware and mount points to be attached to the buggy. It is important to get the holes in the proper locations when manufacturing the hardpoints as the internal hardware (internals) are built to fit into the hardpoints as designed with minimal tolerance.

To ensure the holes end up in the proper location, measure and mark the location of the holes to be drilled. Use the diagrams in each block subsection below to know where to locate these holes. Once marked, grab a punch, place the pointy end in the center of the hole, and tap with a hammer until a small dent is left in the nylon. This will prevent the drill bit from "dancing" when you drill the holes.

The actual drilling of the holes should be done on a mill with a drill press chuck as multiple holes need to be drilled parallel to each other. This is easier to accomplish on a mill than on a drill press. A drill press will work if necessary but be extra careful marking the locations of the holes. For all blocks, it is important to use a one of these machines to ensure the holes are vertical.

Block 1

Figure 48– Block 1 tap diagram

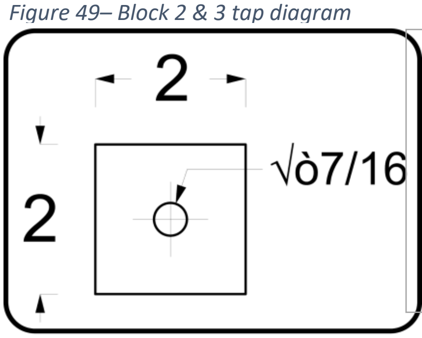


Block 1

Put a 7/16" drill bit into the drill press and create the hole furthest to the left in figure 40. This hole will be used for the rear harness mount. Then, switch the drill bit for a ⅜" bit and drill the 4 other holes. Make sure the holes are perfectly parallel to the edges of the arms on the block. These holes will be used for the rear wheel mounts, and those mounts must be parallel to fit a wheel.

Blocks 2 and 3

Figure 49– Block 2 & 3 tap diagram

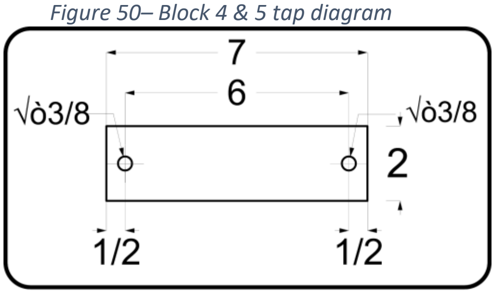


Block 2 & 3

Insert a 7/16" drill bit into the press and drill a hole in the center of block 2 and block 3. These holes will be used to mount the front harness points.

Blocks 4 and 5

Figure 50– Block 4 & 5 tap diagram

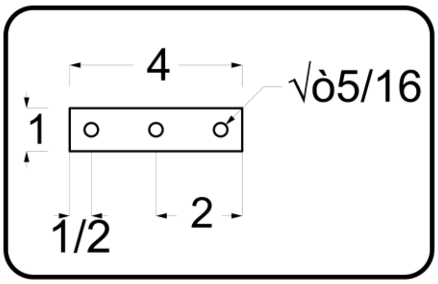


Block 4 & 5

Insert a ⅜" drill bit into the press. Drill the two holes pictured in figure 42 into **block 4** and **block 5**. Once again, ensure these holes are parallel to each other

Block 6

Figure 51 - Block 6 tap diagram

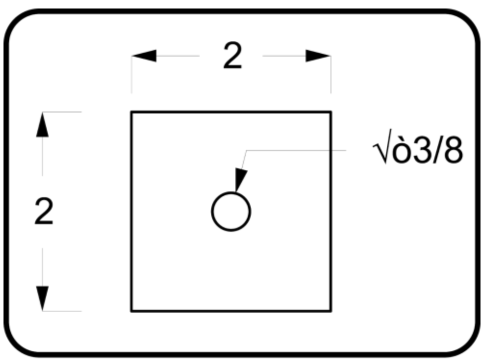


Block 6

Insert a 5/16" drill bit into the mill and drill the 3 holes shown in figure 43.

Block 7

Figure 52 - Block 7 tap diagram



Block 7

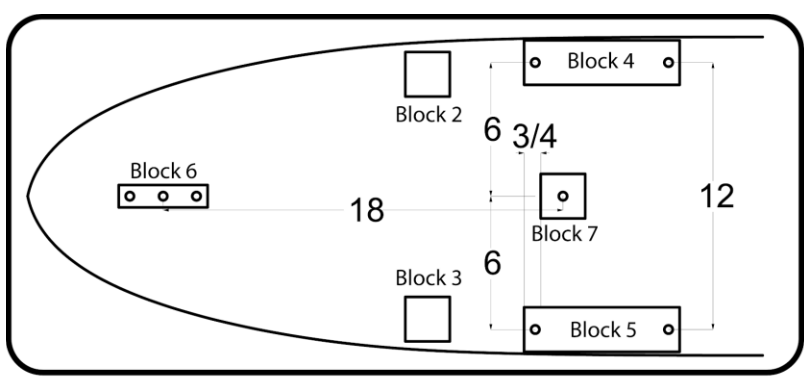
Switch the drill bit to a 3/8" bit and drill a hole in the center of **block 7,** as in figure 44.

4.4 Baseplate Hardpoints

4.4.1 Hardpoint Placement

Correct placement of the hardpoint blocks from the previous step into the baseplate is described below and referenced in the diagram to the right.

Figure 53 - Hardpoints



Front Hardpoint Diagram

Block 1: This should be centered in the buggy and placed with the slot opening facing towards the back of the buggy. Refer to the CAD file created in "Designing Your Shell" to determine the placement of this hard point.

Blocks 2 and 3: Placement of the front safety points varies from team to team and buggy to buggy. For a buggy with wagon steering, it is least obtrusive to place your safety points as close to the left and right edges of the baseplate as possible. Blocks 2 and 3 should be 5-6 inches in front of the front axle, or 2-3 inches in front of blocks 4 and 5. The location of the axle will be dictated by the CAD design.

Blocks 4 and 5: These blocks should inset only .5" - 1" from the edge of the baseplate. The middle of these blocks should line up with the centerline of the axle. In other terms, there should be 3" of the hardpoint in front and behind the centerline of the axle.

Block 6**:** This should be along the centerline of the buggy and placed about 6 inches back from the nose--depending on the dimension you used for the nose loft in your shell. If you aren't sure, check the distance between your "steering handle" plane and the tip of the nose in the CAD file.

Block 7: This block will be placed along the centerline of the buggy. The hole in the center needs to be placed 1 ⅞" of an inch in front of the centerline of the axle or the front edge ¾" behind the front edge of Block 4 and 5.

4.4.2 Hardpoint Alignment

Before performing layups, the hardpoints need to be inserted into the balsa wood core in the positions described above. With most steering designs, the alignment of block 1 is one of the most crucial in determining the speed of the buggy. With this guide's wagon steering this is less important, but still good practice. Block 1 (the c-shaped block, containing a slot for the wheel and the rear safety point) needs to be centered, and pointing towards the nose of the buggy. If this block is angled by even a fraction of a degree, the rear wheel will be angled as well. This could lead to misalignment from the front wheels which would slow down the buggy.

This alignment is often done by using a physical jig or laser alignment device. However, as the alignment affects the speed rather than the safety or overall functionality of the buggy, the particulars of aligning this block can be used an exercise for your team.

4.4.3 Hardpoint Insertion

Before installation of the hard points, it is crucial to sand the nylon. The purpose is to "scuff it up" to provide a rougher surface to bond with the epoxy. After, wipe it down with acetone. Once it is wiped down be sure to only handle the nylon with gloves to avoid getting any oils on it. A rough and oil-free surface helps bond the carbon fiber, which will limit the chance of any delamination issues down the road. (Delamination is explained in depth in section 5, "Layups")

Holes for the hard points can be cut with a box-cutter knife. However, make sure the knife is sharpened, as cutting balsa with a dull blade will cause the wood to splinter. Alternatively, Rabbit laser cutters in TechSpark can be used to get a more precise location on the hard points.

Once the holes are cut, use a 5-minute cure epoxy to glue the hard point in their respective holes. Press the baseplate and hard point against a flat surface (a table) to make sure the hard points sit flush with the balsa wood. If the baseplate is being made from 2 or more rolls of balsa, glue the two pieces together first with 5 minute cure epoxy. Lay them on a flat surface, spread the epoxy along the two edges to be joined, press them together and clamp firmly in place until the epoxy cures.

4.5 Baseplate Template

Once the baseplate is assembled with hardpoints, use a large sheet of paper to trace out the shape of the bottom of the baseplate. Mark the location of the hardpoints as well as the holes drilled in the hardpoints. This will be key to finishing the buggy so make sure this information is saved.

Alternative Design Option: Core

Many buggies on the course use Rohacell for the core material of their baseplate. If you have more money to spend, feel free to upgrade to a lighter weight material--it will not substantially alter the build process.

Some buggies on the course may not have hard points for their driver safety points. However, in our opinion that is profoundly unsafe.

Hard points will also vary based on your steering configuration. The hard points in this design were placed as necessitated by this guide’s steering design. For more information on this, see “Why this design was chosen” in the steering section.

Hardpoint material can be plastic, metal or carbon fiber. Each has their pros and cons, so do research about each material before deciding to change to a different type of plastic or different material.

5 LAYUPS

5.1 LAYUPS BRIEF

Skills: Patience, planning, and problem solving

Tools: Vacuum Pump, Epoxy Squeegees, Trauma Shears/Rolling Cutter, Masking Tape, Small Scale, Measuring/Mixing Cups (not Solo Cups), Popsicle Sticks, Stop Watch, gloves

Materials: 3k 3x3 5.9oz Twill Carbon Fiber, Uni-directional Carbon Fiber, Kevlar, Nidacore, Balsa Pan (pre-prepped), Epoxy, Vacuum Bag, Peel Ply, Breather, plastic sheeting,

Safety Tips: Acetone is a harmful solvent. Contact and fume inhalation should be mitigated. Dissolved organics such as foams or glove material can also contain carcinogenic substances and should not be handled directly. Many gloves are susceptible to degradation by acetone; latex or other acetone resistant material is preferred. Consider using extra plastic sheeting on the floors and getting aprons or extra shirts for “wet hands” to make cleanup easier and reduce epoxy exposure. Long sleeves are useful for reaching under parts of the shell. Dry carbon fiber can also become embedded in and irritate skin, so wear gloves while handling dry carbon fiber.

Layups is a technique for composite structures; the process by which a carbon fiber monocoque is created. Materials are layered onto the mold in stages, gradually building the structure from the inside out. Carbon fiber, kevlar or other composite fabrics must be soaked with epoxy (a process called “wetting out”) before being layered onto the structure. Once a layer is added to the mold, it is put into a large plastic bag, sealed on all edges, and a vacuum pump is used to extract all air from the bag. This process, vacuum bagging, is important for 3 reasons.

1) It ensures the materials stay in place while the epoxy is curing
2) It maximizes strength by eliminating air pockets/voids and
3) It minimizes the chance of delamination, when composite layers peel apart from each other.

Delamination is the main problem that retires buggies. The structural integrity of a buggy relies on sandwich theory. When the skins in a composite structure (layers of composite fabric) separate from the core material, the strength and stiffness of the entire structure is compromised, requiring the buggy to need extensive repairs or be retired.

Why this design was chosen: Composites

The composite material makeup and build process of this buggy design was chosen because it was used successfully on Apex’s buggy Phoenix, which as of this writing has been rolling for 9 years without any structural issues. The layup process uses a male mold, where layers of carbon and core material are laid over the top of a foam plug. This is the least time consuming way of building a mold.

Twill weave carbon fiber is easy to use, comparatively cheap and relatively flexible around the complex curvature seen in buggy shell shapes. Each layer of carbon is added and vacuum bagged separately for time concerns and to pull as much excess epoxy out of the matrix as possible.

5.2 PREPARATION

5.2.1 Planning

The layup process, also known as wraps, can be a fun bonding activity for a team but is also one of the more stressful aspects to a build. Epoxy has a "work time" before it begins to harden, so it is important to work quickly for the best results. Each layer of carbon must be wet out, layered onto the mold, wrinkles flattened, covered in peel ply and breather and sealed in the vacuum bag before the work time expires. Depending on the epoxy used, work time is typically 30 mins to 1 hour. When juggling so many tasks the minutes go by fast, so having a lot of manpower and a solid plan for this process will vastly benefit the team.

5.2.2 Shop

To prepare the shop or garage space for wraps, vacuum and mop the location to eliminate as much dust as possible. Dust in the air will attach to the epoxy/carbon matrix and weaken the bond. For a work surface, acquire two tables as close to 3'x9' as possible and place them together to make a 6' x 9' working area. Cover both tables with thick plastic sheeting to prevent epoxy from building up on the surface. Use a 3rd table for storing the carbon fiber and bagging materials for each wrap, and cover this in plastic as well. If space and supplies allow, set up a 4th table covered in plastic as an epoxy mixing station. On this table place the epoxy, epoxy squeegees, popsicle sticks, mixing cups and scale. If a 4th table isn't possible, make space on the materials table while spacing wet epoxy apart from the composite materials.

5.2.3 Materials

For each wrap session (each layer of material added to the buggy) the materials required are the composite material being added (either carbon, kevlar or core material), peel-ply, and bleeder/breather cloth. It is important that these materials are prepared, cut to size and organized ahead of time.

To confirm all the materials are the correct shape and size, create a trace/stencil. Measure out an 8' by 5' rectangle of some cheap pliable material (such as breather fabric, peel ply or paper in a pinch). Place the mold on top of the material and pull it around the buggy, cutting it to shape. Make any relief cuts needed to remove pleats/ wrinkles. The material should overlap itself by at least 2 inches since the outer layers will need to be larger than the inner layers. Use this trace to cut all 4 layers of carbon fiber, 4 sheets of peel ply and 6 sheets of breather cloth. Cut one more sheet of peel ply by making a trace 3-4" wider than the bottom of the mold. Cut 2 pieces of unidirectional carbon fiber in the same size as the top and bottom face of the baseplate. Cut a hole in the unidirectional carbon that aligns with the rear wheel hole. Carefully fold the materials, label them, and stack them on the materials table. This creates 6 stacks for:

Wrap 1	Wrap 2	Wrap 3	Wrap 4	Wrap 5	Wrap 6
- 3x3 Twill Carbon Fiber - Breather - Peel Ply	- 3x3 Twill Carbon Fiber - Breather - Peel Ply	-Unidirectional Carbon - Breather	-Unidirectional Carbon - Breather - Peel Ply (baseplate only)	- 3x3 Twill Carbon Fiber - Breather - Peel Ply	- 3x3 Twill Carbon Fiber - Breather - Peel Ply

The final step for materials prep is to create a vacuum bag. There are two main types of bagging materials; the process for each is described below.

Vacuum bagging tube film (or tube bag)

> Gather the vacuum bagging film and cut a 12’ length. Take the vacuum bagging seal tape (or tack tape) and remove the protective paper from one side. Press this side down along one open end of the tube, ensuring there are no wrinkles in the bag. Any wrinkles along the tape will allow air to seep out, reducing the effectiveness of the bag and potentially leading to structural deficiencies in the shell. Once the tape is pressed down and all wrinkles are removed, remove the protective paper from the other side and complete the seal on one end of the tube.

Flat sheet bagging film

> Cut a 12’ length of the material. Measure out 2 pieces of vacuum bagging seal tape, one 12’ long and one half the length of the short side of the bag. Take the 12’ piece of tape and remove the protective film from one side. Press this side down along the long end of the film, ensuring there are no wrinkles in the bag. Any wrinkles along the tape will allow air to seep out, reducing the effectiveness of the bag and potentially leading to structural deficiencies in the shell. Repeat this with the smaller piece along the short end, overlapping the tape at the corner. Fold the film over, and seal it to create a shape like a plastic sleeping bag.

The vacuum bag should be reusable for the entire process, but a prepared backup is recommended in case the bag is torn during the process. Tube bags will leak significantly less air due to the long end not being sealed by tack tape.

5.2.4 Nomex

To prep the Nomex, lay the core for the upper shell over the mold and trim it to size. Make relief cuts to allow the material to lay flat on the mold. Near the hatch cut, make two transverse cuts, then another up the nose. In the rear, make one cut up the middle along the long axis. Sew the “forked pieces” together through the open cells to keep the material together for easier handling during wraps.

5.2.5 Baseplate

Preparation for the baseplate primarily consists of confirming that it is completely assembled and ready to be installed. Additionally, cut a piece of foam or wood that fits flush into the rear wheel hole in the baseplate, which will be used during the 3rd wraps session.

5.2.6 Mold

An hour before the first wraps session, wrap the mold in packing tape strips laid along the short axis of the buggy. Next, wax the entire mold with 2 - 3 layers of mold release wax to prevent the mold from sticking to the inside of the shell. Tape the bottom first, then tape of the top of the buggy with separate strips. The tape and wax will prevent spackle and bondo from getting stuck to the inside of the buggy and will make it easier to remove the mold after layups are complete.

5.3 LAYUPS

5.3.1 Schedule

Six separate layups/wraps sessions are used to build the shell. They should be spaced out by 6-8 hours at minimum depending the cure time of the epoxy. An example schedule of wraps is below.

6 Rounds of Wraps:

1) Inner Layer of Carbon 1 - Friday Night at 7pm
2) Inner Layer of Carbon 2 - Saturday at 8am
3) Pan - Saturday at 3pm
4) Nomex - Saturday at 10pm
5) Outer Carbon Layer 1 - Sunday at 8am
6) Outer Carbon Layer 2 - Sunday at 3pm

This tight turnaround causes all layers to bond together before the epoxy "flashes" which makes bonding layers to other layers tougher. It is also okay to do steps 1-4 in one weekend and come back the next weekend to do the final 2 layers.

The overall process of wraps is to wrap 2 layers of carbon fiber on the inside and outside of the core material with an extra layer of unidirectional carbon fiber along the top and bottom edge of the baseplate. A team should prepare to use between 7-10 people during the wraps process with the following jobs:

Leader - watches the time to ensure buggy is in the bag within epoxy work time

Epoxy Mixer - responsible for mixing proper amounts of epoxy & carbon

Dry Hands - Person to hand out tools, materials etc (can be same person as epoxy mixer)

Wet Hands (5-7 people, wearing gloves) - Responsible for wetting out carbon, adding materials to mold

5.3.2 First Wrap

The first wraps will cover the mold with the inner layer of carbon. Lay down a sheet of plastic on the table and tape it down. Weigh the sheet of carbon for this wrap and record the weight for the following step. Lay the carbon fiber out on the table and gently push out any wrinkles, ensuring you don't pull the fiber strands apart. The Wet Hands crew should don gloves and the Dry Hands person can pass each one a squeegee.

When everything is ready, the Epoxy Mixer should mix an amount of epoxy and hardener equivalent to 70% of the weight of the carbon sheet. Mix the epoxy and hardener for a few minutes to ensure they're fully mixed. Start a stopwatch to track the remaining work time of the epoxy. The Epoxy Mixer should drizzle the epoxy over the carbon as evenly as possible, retaining 15-20% of the epoxy for dry spots or patches. The Wet Hands crew can spread the epoxy across the entire sheet with the squeegees, being careful to not pull the carbon fibers apart. Drizzle a little more epoxy on dry spots and squeegee it into the fibers.

Once the carbon is wet out everywhere, use the squeegees to pull any excess epoxy out of the carbon. This is achieved by pressing down and dragging the epoxy off to the sides with the squeegee. After removing the excess, place the mold on the carbon and wrap the carbon over the mold. Push out all wrinkles and look for any places where there are holes in the carbon. If there are any large holes, cut a patch of carbon, wet it out with the excess epoxy, and cover the hole. Now that the carbon is in place, have 2 people hold up the buggy and remove the layer of plastic on the table saturated with epoxy.

The Dry Hands person can lay the peel ply down on the table and place the mold on top of the peel ply. Have 2 people keep on their gloves and convert everyone else to dry hands. Pull the peel ply up over the carbon and tape it in place with masking tape. Remove all of the wrinkles, cutting relief cuts where needed. Once peel ply is smooth and taped in place, have the people with gloved hands lift the mold again, lay down the breather cloth and repeat the process.

Once the breather and peel ply are applied and all wrinkles are removed, bring the vacuum bag over to the main table and place the buggy inside. Place the retaining ring for the vacuum hose inside of the bag on the top of the buggy. Have somebody hold the ring in place while others with dry hands seal the bag shut. Seal the bag with vacuum bag sealant tape, following the same instructions from "Carbon/Bagging Material Prep". Using a utility knife, cut a small hole in the bag right in the center of the retaining ring. Insert the connecting ring on the end of the vacuum hose through this hole and into the retaining ring, then twist the connecting ring until it locks into place. Turn on the vacuum pump and push out any wrinkles in the bag as the air is sucked out. After a few minutes, turn off the vacuum pump and listen for any leaks. Seal the leaks by pushing out wrinkles in the bag or adding more tape. Turn the pump back on until air is sucked out of the bag. Repeat this 2-3 times to ensure the bag is sealed, then let the pump run until the next layups.

The mold may begin to bend like a "banana" shape under vacuum pressure. If this happens, place weights on the buggy to keep it flat. Bags of salt or sand work well and can be found in the basement ramp of east campus garage. The buggy must be flat along the bottom to aid in construction and ensure ground clearance when rolling.

5.3.3 Second Wrap

The second wraps will cover the first layer of carbon with another layer of carbon. This procedure begins by turning off the vacuum pump and gently removing the shell from the bag. To remove the shell, cut open the bag as close to one of the short-sealed ends as possible. The bag is used for each wrap and will lose a little length each time, so cutting it close will help the shell to fit for the last wrap. Pull the mold out of the bag and carefully fold and place the bag on the materials table. Cut, pull and remove the breather cloth and peel ply, throwing it all away. At this stage, the mold is covered in the first layer of carbon fiber. Congratulations!

For the rest of the second wrap process, lay down a new sheet of plastic over the table and repeat the process from the first wrap with the next layer of carbon fiber.

5.3.4 Third Wrap

At this point, one side of the overall carbon fiber sandwich is complete. The purpose of the third wrap is to attach the baseplate, or pan, to the bottom of the buggy. First, remove the mold from the vacuum bag again. Next, wet out the two layers of unidirectional carbon. Set the pieces on the top and bottom of the baseplate and place the buggy on top of the baseplate. Grab the piece of foam or wood and place it in the rear wheel hole. Screw this into the mold to ensure the baseplate does not shift out of alignment during layups. Place the peel ply on the buggy, wrap it in breather and put it into the vacuum bag. Be mindful to have a ½" overlap in the baseplate around the entire buggy. The Nidacore will butt up against this "shelf" during the next step.

5.3.5 Fourth Wrap

This wrap will add nomex to the surface of the shell, everywhere except the flat bottom. Again, remove the buggy from the bag. Mix Epoxy and add the thickening agent. Use paint brushes or squeezees to liberally apply to the shell in a 1/16" to ⅛" thick layer. Fit the Nidacore over the shell and tie it into place with twine to keep it stable during vacuum bagging. Cover in breather and vacuum bag.

A good bond between the core material and carbon fiber is vital to building a strong buggy. Thus, epoxy can be applied more liberally at this step. Extra weight in epoxy for this wrap is acceptable as it benefits the buggy's strength and durability.

5.3.6 Fifth Wrap

The fifth wrap will add a layer of carbon fiber around the entire buggy, closing in the nomex and the baseplate. Remove the buggy from the vacuum bag. Prior to adding the layer of carbon, about an hour's worth of final work is needed for the nomex layer. Inspect the nomex for any places where it did not bond well to the carbon. Mix and place epoxy in those places. If there are any gaps in the nomex or joint between the nomex and baseplate, they must be filled before adding the outer layers of carbon. This is accomplished by attaching pieces of rohacell, nomex, or balsa with fast curing, 5 minute epoxy. Smaller gaps can be filled with 5 minute epoxy mixed with the thickening agent. Sand or trim any areas where the baseplate sticks out beyond the nomex until it is flush. If there are a lot of places where the nomex needs to be filled in or adjusted, this prep would could also function as a separate session.

After the prep is completed, mix up 20% more epoxy than in prior steps. Paint the nomex with the extra epoxy then proceed with the carbon fiber stage as in the first and second wraps.

5.3.7 Sixth Wrap

The purpose of the sixth wrap is to add an additional layer of carbon fiber, so that each side of the nomex/core has two layers. Repeat the process from 2nd wraps. This will be the outer layer of the buggy so remove as many wrinkles as possible. Keep the buggy in the vacuum bag for two days before removing it for the next steps.

5.3.8 Hatch Cuts

When the layers of the shell are completed, the next action is to cut the hatches out. Draw the left side of the hatches and create a trace to transpose the shape to the right side. Use a black cut off wheel and a dremel to cut the hatches out, wearing protective equipment to guard against the carbon fiber dust. Gently pull the hatches off the mold. If they get stuck, don't pry at the shell as this could crush the core material. Instead, pour acetone down into the cracks with epoxy syringes to melt the mold foam, and use a hand saw or a broken band saw blade to weaken the mold enough to remove the hatches.

The major considerations for the front hatch cut are its ability to fit the driver, and safety. The design of the shell is important for meeting these criteria. The front hatch should be drawn and cut so that the cut is in front of the steering and the drivers head cannot be seen from the side with the hatch removed (see 'a' in Figure 46). It must also have enough height for the driver to load into the buggy. Cutting the hatch at the widest point in the buggy will allow it to fit the driver. Make sure there is a gradual taper from the vertical to horizontal cut for strength. The bottom part of the hatch should be ~ 2" above the bottom of the baseplate. Lower will compromise the strength of the baseplate and higher will make it difficult for the driver to see the road. Cut the rear hatch as small as possible with enough room to install the rear wheel mounts and clip the driver into the rear harness mount (see 'b' in Figure 46).

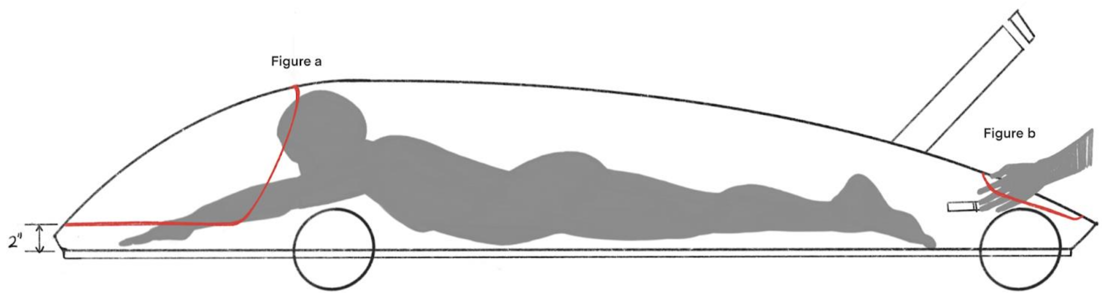


Figure 54 - Hatch cut diagram

5.3.9 Sealing the Hatch Cut Edges

To ensure delamination does not occur at the edges where the hatches are cut, the edge of the shell and the hatch need to be sealed. There are two options to accomplish this.

> 5 Minute Epoxy: This is the stronger but messier method. Mix up 5 minute epoxy and add a bit of the thixotropic silica. Using a knife, epoxy squeegee or epoxy syringe, place the epoxy into the edges, wiping up anything that drips onto the outer or inner edges of the shell.
>
> Epoxy Putty: Mix the 2 parts of the epoxy putty together with your hands until you have a ball that is all one color. Then roll the putty into thin "snakes" or tubes, as wide as the edge of the shell. Squish the putty tubes into the edge until it is flush. Remove extra with a fine edge tool. Wear gloves and take care to avoid carbon fiber splinters.

Alternative Design Option: Layups

Wet layups as described in this guide are the easiest way to build a buggy but result in the weakest and heaviest monocoques. Using prepreg carbon fiber or VARTM layup methods will create a better shell overall. The drawback to these methods is that they require special tools, female molds and lots of practice.

Different types of carbon fiber can be used and additional or less carbon can be used in specific areas for the express purpose of adding strength or saving weight. Kevlar can be included in any places that might take an impact. Carbon shatters whereas kevlar is more resistant to fracturing in impacts. It is heavier and less stiff overall and shouldn't be used for the entire shell, but makes sense around hatch cuts, the pushbar and the nose of the buggy.

Additionally, there are different types of carbon fiber that can be considered. Plain weave carbon stays together really well when wetting out but is stiff and hard to form curves. Conversely, satin weave carbon is more flexible around curves and stronger but falls apart easier during wet layups. Satin is best used in pre-preg or VARTM.

Bi-axial and unidirectional fibers are nonwoven fabrics and are the strongest carbon sheets. They are best used as the main strength and structure layers. They should be covered with a woven layer like twill, plain or satin to better hold the fibers of the non-woven fabrics together. Patches of unidirectional fibers around hardpoints, hatch cuts, and the pushbar are commonly added for additional strength and stiffness.

6 STEERING

6.1 STEERING BRIEF

Skills: Lathing, Welding, Drilling

Tools: Lathe, Welder (or outsource to welding shop), Drill Press/Mill

Materials: ⅝" Steel Tube, Steel L Stock, Aluminum Plate, Aluminum U channel, Steel Plate

Safety Tips: Proper knowledge of power tools and safety gear. It is recommended to read additional guides for tapping if the operator is unfamiliar with it as poor tapping technique can lead to shattered tools or parts.

The steering component to a buggy is the means by which the driver controls the front wheel or wheels. This guide details a reverse trike, so the driver will move a handle to shift an axle that extends outside the buggy and holds the two front wheels, as depicted in Figure 47. This style of steering is called wagon steering.

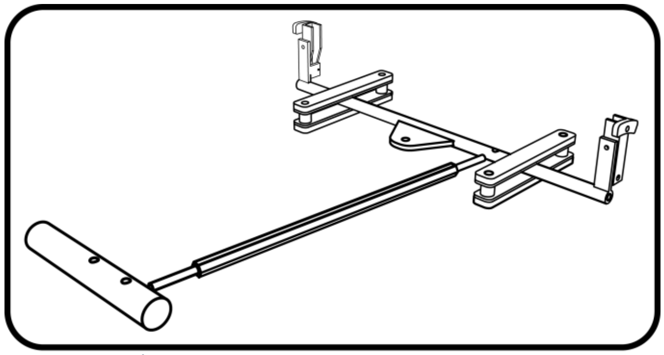


Figure 55
Steering Assembly Overview

Why this design was chosen: Steering

Wagon Steering is a simple way of building steering for a reverse trike. It consists of an axle that pivots around a central point with wheels attached to the end of the axle. The axle is connected to a steering handle by a tie rod. This tie rod should be adjustable to allow for alignment.

For this version of wagon steering, the axle is supported on each end by 2 "support brackets". They aren't required, but they help disperse the load, prevent the buggy from leaning in the turns and allow for a thinner axle. If the support blocks are not included, the pivot point and axle will need to be reinforced considerably to handle the added load.

Additionally, the pivot point is not drilled directly through the axle. It is drilled through a trailing arm, welded to the front of the axle. This trailing arm creates "trail" when the buggy is rolling downhill, which leads to more dynamic stability and an easier buggy to drive.

The last quirk to this design is that the brakes are attached to the front axle. Many reverse trike wagon steering buggies have brakes on the rear axle. They are highly unstable and make it more difficult to pass both capes and drops testing. The brakes are mounted vertically which is worse for aerodynamics, but necessary for clearance. Due to the trailing arm, as the steering turns the axle "pulls inside" the shell slightly, reducing the distance between the shell and the brakes. By mounting the brakes vertically this issue is avoided. Mounting them towards the ground is better from a center of gravity standpoint but exposes the brakes to contact with the ground and road debris.

6.2 DRILLING/TAPPING PARTS

This section describes the process of preparing the materials for internal mechanics of the buggy. This requires both drilling and tapping. If drilling or tapping is new to the people building the buggy, see the below for instructions.

Tapping: To properly tap, start by greasing the hole with tapping or cutting fluid. Then insert a taper bit tap and rotate clockwise (or counter clockwise for LH threads) until you feel resistance from the threads cutting into the material. From there, for every full rotation in the cutting direction, make a half rotation in the opposite direction. This will prevent the threads from getting deformed by chips or build up in the tap. If there is excessive tension at any time, back the tap out, clean the hole, re-grease the hole and retry.

Drilling: To properly drill holes in metal, use the mark, center punch, drill then reem method. Start by marking the center of the hole with a sharpie. Then place the pointed edge of a center punch on this mark and hit it with a hammer to indent the material. This prevents the drill bit from wandering while drilling

6.2.1 Axle

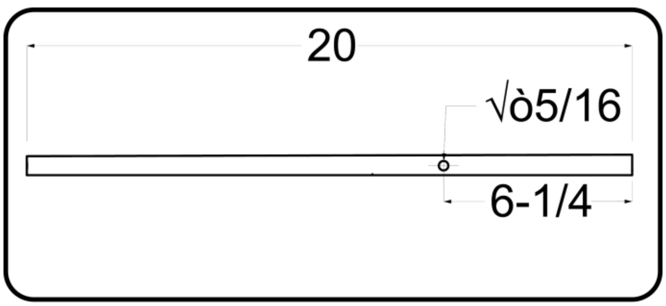


Figure 56 Axle

1. Take the ⅝" diameter steel tube and cut it to 20 inches with a bandsaw, hack saw or angle grinder. If the mold is wider than 14", add length to the axle that coincides with the added width. For example, if the mold is 16", add 2 inches to the length of the axle (1 to either side).

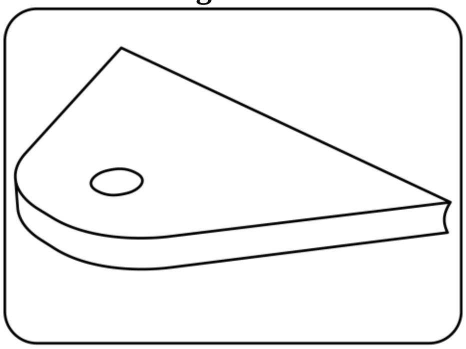
2. Place the axle in a lathe and insert a 5/16" drill bit to the drill chuck opposite the rotating chuck on the lathe. Drill a 5/16" hole about 2" deep into the axle. Let the axle cool off or wear heat resistant gloves, then flip the axle and drill the same size hole on the other side.

3. Grab a left hand and right hand ⅜" - 16 tap. Tap the holes that were just drilled, one left handed and one right handed.

4. Using a Sharpie, label the left hand threaded side. This must be the left hand side of the axle when installed into the buggy. As the buggy rolls down the course the rotation of the wheels will loosen the axles if they are not left hand threaded on the left and right hand threaded on the right.

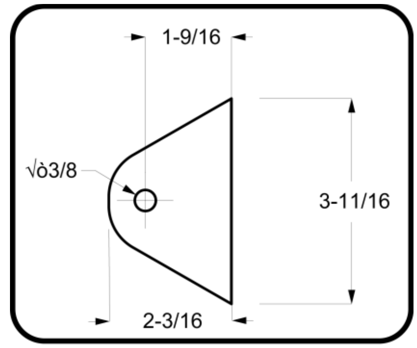
5. Using a sharpie, make a mark 6 ¼' in from the left hand side of the axle. Mark this point with a center punch. Place the axle in a drill press/mill and drill a 5/16" hole on this mark.

6.2.2 Trailing Arm



Trailing Arm

Figure 57 - Trailing arm



Trailing Arm

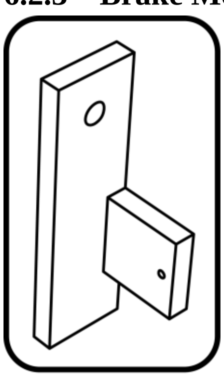
1) Using a cutting wheel or band saw, cut the plate to roughly the shape of the diagram above.

2) Drill a ⅜" hole along the centerline of the now trimmed steel plate, 1 - 9/16" away from the long flat end of the plate.

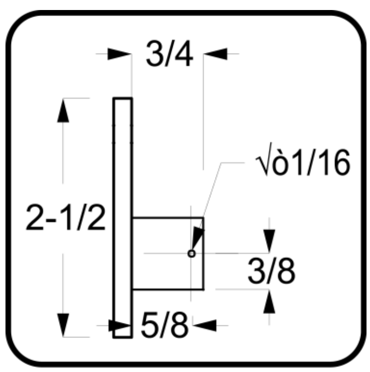
Drill the first hole into this indent using a small drill bit such as 1/16". Replace this bit with a slightly larger size and drill a hole, continuing this process until you reach the proper size for the hole. Use smaller step ups in size with hard materials like steel.

6.2.3 Brake Mounts

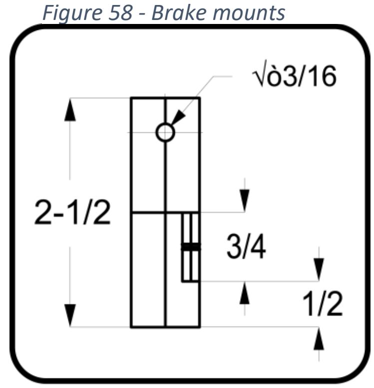
Figure 58 - Brake mounts



Brake Mount



Brake Mount Side



Brake Mount Top

1. Measure two 2 - ½’”” lengths of steel L stock.

2. Using a bandsaw or angle grinder cut out the two lengths.

3. With a sharpie marker, mark the shape and location of the spring retainer (the square piece with a tiny hole drilled in it). Use the dimensions in the Brake Mount Side diagram. Mark one identical to the diagram and one mirrored.

4. Using a bandsaw or cutting wheel, carefully cut out the shape of the brake mounts.

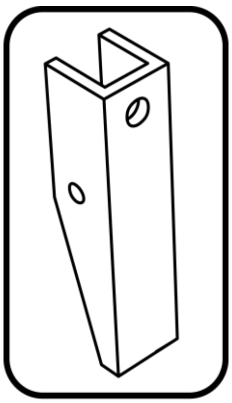
5. Sand and debur the edges with a file, sandpaper or belt sander.

6. Drill a 3/16" hole in the long flat of both mounts. Make these holes ⅜" from the ends that don't have the spring retainer.

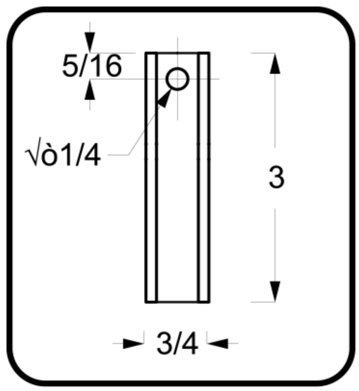
7. Drill a 1/16" hole in the spring retainers, ⅜" from the side and ⅛" from the top. At this point there should be two arms that are mirror images of each other.

6.2.4 Brake Arms

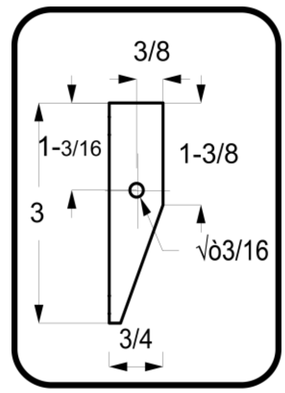
Figure 59 - Brake arms



Brake Arm



Brake Arm Front



Brake Arm Top

1) Cut two 3" long lengths of Aluminum.

2) Rotate the aluminum so the open end of the U is facing to the side. Make the angled cut in the aluminum, visible in the Brake Arm Top diagram above. This cut is to ensure the brake arm has enough travel to stop the wheels. It may need to be altered depending on build tolerances.

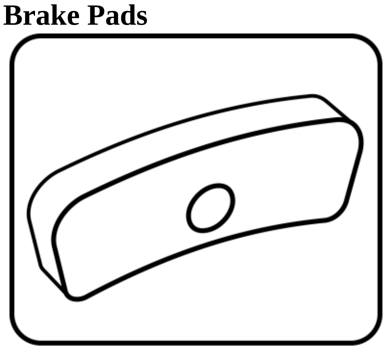
3) Sand and debur the cut edges.

4) On the top of each brake arm, drill a 3/16" hole along the center of the arm, 1 - 3/16" away from the non-angled end. Make sure the speed of the drill press is set properly for aluminum which is a much softer metal than steel.

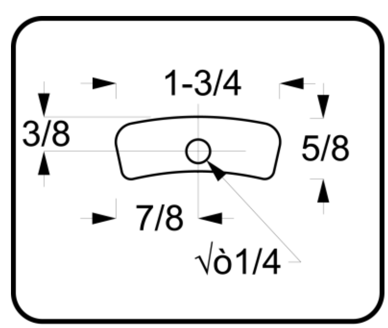
5) On the front of brake arms, drill a ¼" hole 5/16" from the non-angled end. Then drill a 1/16" inch hole, 11/16" from the angled end of the arm.

6.2.5 Brake Pads

Figure 60 - Brake pads



Brake Pad



Brake Pad

1) Draw two 1 - ¾” x ⅝” rectangles on the ¼” aluminum plate.

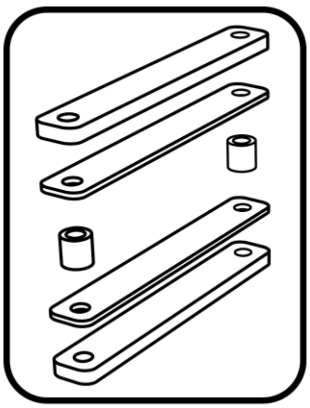
2) Cut the aluminum with a band saw or cutting wheel.

3) Drill a ¼” hole in the middle of the rectangles. Swap the drill bit for an 82 degree countersink bit with a body width of at least 9/16” and countersink the hole.

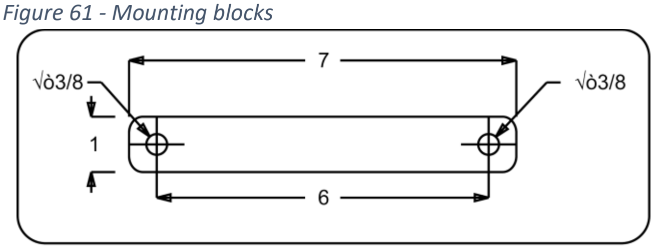
4) Using a belt sander, band saw or angle grinder and cut a 6” diameter curve out of the top and bottom of the brake pad. The curve is important to maximize contact patch between the wheel and the pad while preventing the pad from rubbing on the rim. If the pad is rubbing or the contact patch is too small, the buggy will not brake effectively.

6.2.6 Mounting Blocks

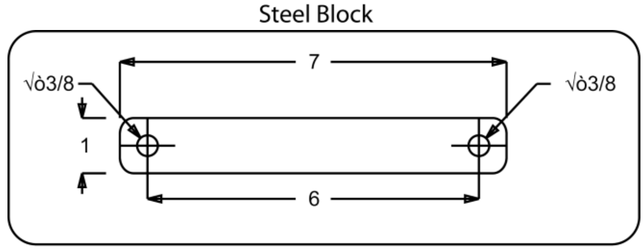
Figure 61 - Mounting blocks



Support Bracket (Exploded)



Steel Block



Teflon Block

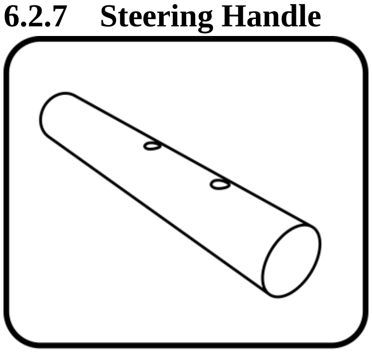
1) Cut four 7” lengths of each steel and teflon with either a band saw, cutting wheel or hacksaw.

2) Drill two ⅜” holes in each piece, exactly ½” from the long and short edges.

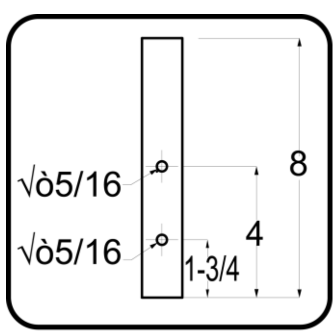
3) Filet the corners of the material and sand/debur the cut edges.

6.2.7 Steering Handle

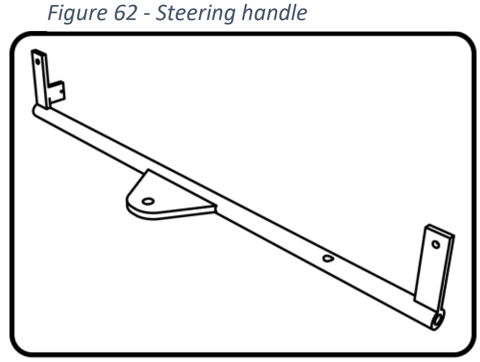
Figure 62 - Steering handle



Steering Handle



Steering Handle



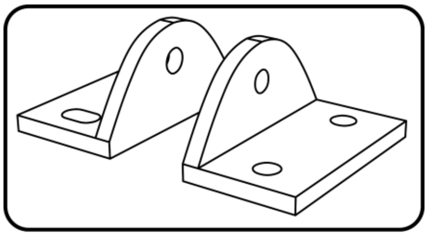
Front Axle

1) Cut the aluminum tube to the longest length that will fit within the nose of the buggy.

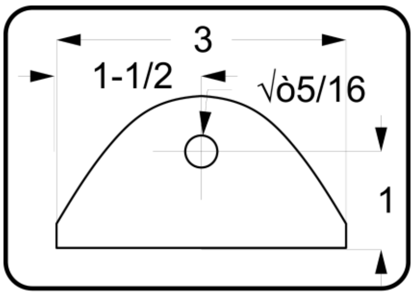
2) Drill two 5/16” holes, one directly in the middle and one 2 - 1/4” to the left of the center hole.

6.2.8 Rear Wheel Mounts

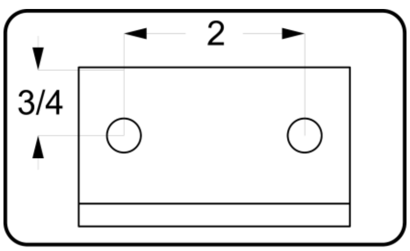
Figure 63 - Rear wheel mounts



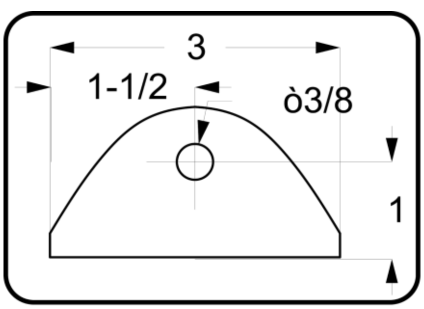
Rear Wheel Mounts



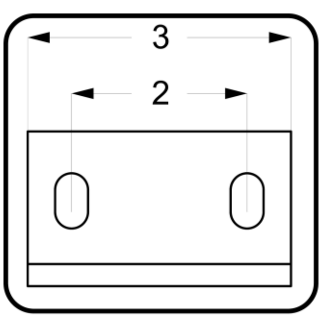
Left Rear Wheel Mount (Front)



Left Rear Wheel Mount (Top)



Rear Wheel Mount Right Front



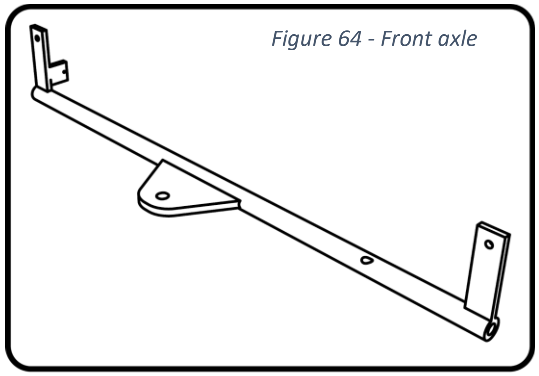
Right Wheel Mount Top

1. Grab the ¼” thick, 1.25” arm length L-stock.
2. Cut off two, 3 inch long pieces of the stock.
3. Insert a ⅜” drill bit into a drill press. On each piece of stock drill 2 holes on one of the arms. These holes should be located 2” apart, along the centerline of the arm.
4. Insert a ⅜” mill bit into a mill. Take one of the L stock pieces and mill the drill holes into ½” long slots.
5. On the other arm of the L stock, drill a ⅜” hole into one and a 5/16” hole into the other piece of L stock. **In this example, these holes are 1” from the bottom of the face. If you plan to make the ride height of you buggy lower, you may need to purchase L stock with longer arms and move the holes higher on the face**
6. Take the ⅜” - 16 tap, and thread the 5/16” hole, using the method described in Preparing Rar Materials - Axle.
7. (Optional) Using a bandsaw, trim excess material on the arm with the single hole. Then sand corners smooth with a file or belt sander.
8. Get washers with a ⅜” inner diameter and a ⅞” or less outer diameter and JB weld or 5 min epoxy. Glue the washers to the L pieces, concentric to the single hole, on the side facing away from the other arm of the L. (These washers will ensure there is no rubbing between the wheel hub and the rear wheel mounts. Washers could be added to the axle when installing the wheel, but it is better to have the washers integrated to the mounts for faster wheel install on raceday.)

6.3 WELDING FRONT AXLE

Most students do not have welding expertise or access to welding equipment. That is okay. In the past teams have had help from FSAE, a maker shop, or have sent their pieces to a welding or machine shop to have this work done. There are many such shops in Pittsburgh. For example, Atomatic is a well-known shop 30 minutes outside of Pittsburgh that has made buggy parts for teams in the past. Figure 56 shows an overview of the front axle, and the steps below describe the individual parts.

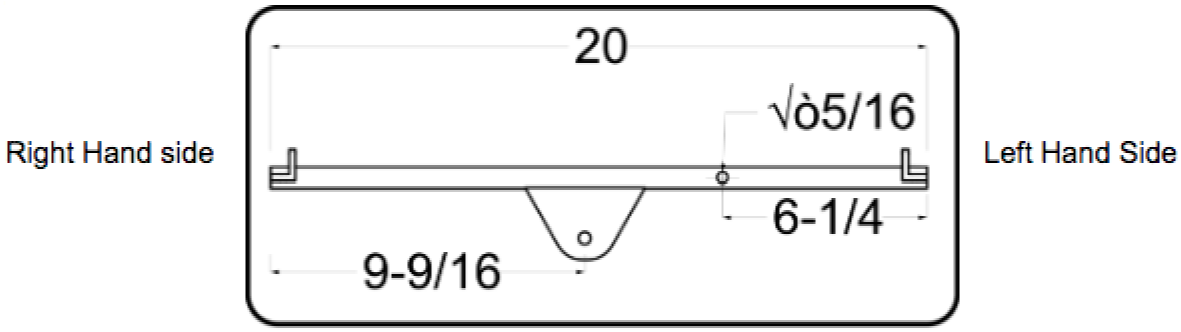
Figure 64 - Front axle



Front Axle

6.3.1 Trailing Arm

Figure 48 – Trailing arm



Axle Weld Diagram

Weld the center of the trailing arm, one inch towards the right hand side of the axle.

Having the trailing arm off center to the right allows the axle to stick out more on the left hand side, known as an offset or outrigged axle. This gives more grip in the chute turn, without significantly affecting downhill pace or handling on other portions of the course. The offset can be 2” if desired as well, just ensure there is an extra inch on the axle if this method is chosen.

6.3.2 Brake Mounts

The brake mounts need to be welded at the farthest ends of the axle, along the centerline and parallel to its length. The mount should be 90 degrees around the circumference from the trailing arm welding in the previous step. Thus when the trailing arm is parallel to the ground, the brake mounts are pointed vertically. The small “upright” section should be inboard from the end of the axle, rather than inline with the outer edges.

Alternative Design Option: Steering

There are nearly endless ways to design a buggy steering. Below are the main types of steering with a brief description.

Reverse Trike Options

Wagon Steering: Design in this example. Simple and robust, but a bit heavy and takes up a decent amount of space inside of the buggy. Requires a slightly taller shell which is bad for aerodynamics. Fairly difficult to build a slow wagon buggy, just ensure the axle is strong enough that it won't bend and that the tie rod to steering handle connection doesn’t have a lot of slop.

Ackerman Steering: Similar to that found on a car. Each wheel is on its own spindle which pivots around a kingpin. Look to Go-Karts or wagons with Ackerman steering for inspiration. It is important to consider caster, camber and ackerman angles with this design. The most important factor in making a faster ackerman buggy is ensuring it stays in alignment. Tolerances and flex must be as small as possible.

Forward Trike Options

Fork: Similar to what is found on a bicycle or motorcycle. Consider rake angle, trail and wheel flop. Can make ingress and egress difficult for the driver, so it may need to be easily removable/installable.

Plate/Track: Effectively the wheel sits in the middle of a lazy susan supported on the edges either by a track or a bunch of bearings. It can also be set up with a pivot arm in front of the wheel and a track behind the wheel to support the load.

Spend time to build a steering design in Solidworks and run load simulations both vertically and horizontally on the steering to ensure it will hold up to the forces of the road. Once the design is complete, merge it with the mold file to ensure that it fits within the shell and the driver can fit with the added materials from the steering. Iterate and analyze multiple steering systems before choosing a final design.

7 HATCHES AND ATTACHMENT

7.1 HATCHES AND ATTACHMENT BRIEF

Skills: Lots of patience, knowledge of power tools

Tools: dremel, black cutoff dremel disk, vice, bandsaw, drill / drill press, file, #7 drill bit (0.2010in), F drill bit (0.2570in), 1/4-20 tap

Materials: 5-minute cure epoxy, 6"x 6"x ⅛" aluminum plate, delrin scraps

Safety Tips: In addition to tips previously discussed, be mindful of heat buildup while using handheld cutting tools. Wear eye protection as cutoff disks are prone to shattering. It is recommended to read additional guides for tapping if the operator is unfamiliar with it as poor tapping technique can lead to shattered tools or parts.

For this section, it is important to note that most of the information is approximate, considering the exact placement of your hatch tabs will vary based on the shell and hatch cut, so alter accordingly. This method of hatch attachment, while simple and cheap, is very craftsmanship based. As such, testing the hatch attachment is crucial. Jostle the hatch and check if it is rattling--or even fully detaching. Adjust hatch tab placement, number, and/or length to resolve the issue. Do **not** put the buggy on the course until it is clear that the hatch tabs are sufficient.

Why this design was chosen: Hatches

This hatch attachment design was chosen largely because of its affordability; this procedure can be followed using almost entirely tools and scrap produced from previous steps of the build.

The front hatch attachment mechanism chosen is simple, and very secure. Use of a 1/4-20 screw in place of a latch reduces the likelihood of the hatch detaching in an impact with a pothole, although it does slow down extraction time.

On the flipside, for the rear hatch the chosen design has a less secure attachment mechanism, since loss of the rear hatch is not as big of a safety concern. The rear hatch attachment was designed for quick extraction.

7.2 FRONT HATCH

7.2.1 Nose Tabs

Prepare 1-2 nose tabs. For each nose tab, cut a rectangle of aluminum that is approximately 1"x 2.5". Once the nose tabs are cut, determine where they will be placed on the hatch. If the design uses only one nose tab, it will go at the tip of the buggy. If the design uses two tabs, they should be symmetrical around the nose, and not more than 6 inches (along the length of the buggy) back from the nose. The nose tabs will be shaped like a hook, and hook into the shell.

To prepare the slots for the nose tabs, put the hatch on the buggy and mark on the lip of the buggy (not the hatch) where the tabs will slot in. Use a dremel with the black cutoff disc to cut 1in wide slots in the shell of the buggy, along the baseplate. These slots should only go about halfway through the shell; proceed carefully.

Once the slots are cut, mark where the windshield tabs will be bent so that they tuck against the inside of the hatch of the buggy. The windshield should not yet be on, so team members can reach through the windshield hole of the buggy to achieve this while the hatch is in place. Slot your tabs into the slots that were just cut, then use a sharpie to mark where they stick out. Use a vise to make a bend along this line.

Next, glue the nose clip(s) in place. Put the hatch on the buggy and fit the nose clips into the slots that were cut in the body of the buggy. Use chalk to mark where they line up with the hatch, then use a fast-cure epoxy to glue them in place. Before proceeding, hold the top of the hatch in place and jostle the bottom. If the nose clips come unhooked, the hooks may not be slotting deep enough in the shell. Remake the hooks and/or cut the slots deeper to resolve this issue.

Finally, wrap them into place with twill or kevlar. As this is a mini-layup, there is no need to vacuum bag--just use electrical or duct tape to hold the epoxy-saturated carbon fiber against the hatch.

7.2.2 Main Tab

Prepare one hatch tab, approximately 1” x 3” in size. Drill the hole pictured below with a #7 (0.2010in) drill bit. Then, tap this hole with a 1/4-20 tap.

Figure 50 – Main hatch tabs

To place this tab, drill a hole with a F (0.2570in) drill bit through the hatch of the buggy, centered at the top of the hatch. It should be about 0.75” away from the back edge of the hatch.

The following step needs to be completed with the hatch tab screwed in and the hatch in place, to make sure that the hatch tab is located correctly. Screw a 1/4-20 thumb screw through this hole and into the tapped hatch tab, then place the hatch on the buggy with the nose clips slotted in. Position the hatch tab such that it is pointing backwards, towards the tail of the buggy, then use fast-cure (5 minute) epoxy to secure it in place. After the tab is in place unscrew the thumb screw, remove the hatch, and wrap over the tab with twill and/or kevlar. Use electrical or duct tape to hold the carbon securely against the shell of the buggy.

7.2.3 Supplementary Tabs

Prepare 2-4 supplementary tabs, depending on the shape of the hatch cut. Experimenting will help determine how many are necessary. These tabs should be approximately 1” x 2” rectangles.

The location of the supplementary tabs is very dependent on the shape of the hatch cut. Thus, trial and error is common practice for supplementary tabs. Tack the hatch tabs in place with a small amount of fast-cure epoxy, then pull on and jostle the hatch to make sure that it's secure. If it isn't, remove the hatch tabs and try them in a different location. Once a location works, secure them in place with fast-cure epoxy, and wrap them into the hatch with twill and/or kevlar. As with the other hatch tab "layups", use electrical or duct tape to hold the epoxy-saturated carbon fiber against the hatch.

7.3 Rear Hatch

The rear hatch requires one or two tabs, which can be centered around either the front or back of the hatch. The shape of this tab will depend on the shape of the rear hatch. These tabs will likely need to be smaller than the ones used on the front hatch, and can be 3D-printed, or made out of aluminum or delrin. Glue these tabs in place with a fast-cure epoxy. The addition of neodymium magnets may be necessary to hold the other side of the rear hatch in place.

Note that this design favors quick extraction over a secure rear hatch, so the team will also need to tape down the rear hatch when rolling to avoid loss of mass.

Alternative Design Option: Hatch

For the front hatch, many teams use off-the-shelf latches to secure their hatches to their buggies. While this allows for a quicker extraction, it increases the risk that the latches will pop open and the hatch will come off under relatively routine impacts, such as those from potholes on the course.

If desired, a threaded hatch tab and a screw can be used to secure the rear hatch, as is done with the front hatch. While this will practically eliminate the need to tape down the rear hatch, this will further lengthen the extraction time

8 WINDSHIELD

8.1 WINDSHIELD BRIEF

Skills: Ability to use a heat gun and bandsaw

Tools: Bandsaw, heat gun, allen keys and wrenches

Materials: 1/16" polycarbonate sheet (at least the size of your windshield cutout), small screws & lock nuts (size is not important), a large sheet of paper (wrapping paper, etc. works fine)

Safety tips: Heat guns can cause burns or start fires, use common sense

The windshield protects the driver from road debris. It is made from polycarbonate and needs to be molded/bent to fit the curvature of the hatch. The cut of the hatch for the windshield will vary amongst teams, but the windshield and attachment methods are fairly uniform across the course, as it is primarily a safety addition.

Why this design was chosen: Windshield

This is a simple way to make a windshield and adheres to all safety regulations. Polycarbonate is required.

8.2 INSTRUCTIONS

8.2.1 Cut the Polycarbonate

To cut the polycarbonate to size, use the carbon section from the windshield that was cut out while digging out the foam core. Drape a large sheet of paper over it and trace its shape. Then draw a second outline about ¼" larger than the windshield cutout. This will ensure that the windshield overlaps with the hatch, and there are no gaps in the windshield. Trace this larger outline onto the polycarbonate sheet and cut the polycarbonate out with a bandsaw. In a pinch, a hack saw works—but is more challenging due to the tight curves.

8.2.2 Shape the Windshield

Determine where the windshield needs to bend to fit on the buggy--if the design team successfully made the windshield cut to avoid a 3D curve, this should be primarily a single line down the front. If the windshield shape ended up more complex (likely if you have a tall windshield), the team can still follow the same shaping procedure--with a couple more bends and be extra careful with the polycarbonate.

Remove the protective film from the polycarbonate. Heat along the area that needs to be curved with the heat gun, until it can bend around the carbon windshield cutout. Work slowly, keeping the heat gun moving and a safe distance away to ensure you do not melt the plastic or introduce bubbles. Use medical gloves while handling the hot windshield to prevent fingerprints from baking into the plastic. It will take a few rounds of heating the polycarbonate and bending it into shape to get the windshield to conform to the shape of the hatch. This can be frustrating, but it'll get there. If the team doesn't have access to a heat gun, other heating methods like an oven can be used. To utilize an oven, use something oven safe – like a piece of wood with some slits in it – to hold the polycarbonate bent in approximately the desired curvature. Experiment with temperature and bake time to heat form the material.

8.2.3 Attach the Windshield

It is important that the curve on the windshield is as similar to the hatch as possible before proceeding. If the windshield isn't molded well to the shape of the hatch, attaching it may warp the hatch over time.

The simplest way to attach the windshield is by bolting it directly into the carbon. The windshield can be attached to either the inside or outside of the hatch. For a smoother look, put the prettier one on the outside. If there is a clean cut around the windshield but the hatch cutout is rough, place the windshield on the outside to hide the rough cut. Otherwise, put the windshield on the inside. Determine where the windshield needs to be secured to the hatch, which will vary based on the windshield shape. Mark these locations with Sharpie, then drill clearance holes through the windshield and hatch and secure them together with screws.

Alternative Design Option: Windshield

The other commonly used technique for securing the windshield to avoid screwing directly through carbon, uses windshield tabs. These are like hatch tabs--on one end, they are wrapped onto the hatch, and on the other they are screwed into the windshield.

Teams also have the option of tinted or mirrored windshields. These are not recommended for new teams as they may make it harder for the driver to see--particularly when buggies are out in the dark, during drops and midnight rolls. The mirrored/tinted windshield can be achieved either by buying specialty polycarbonate or a film to stick to the windshield.

9 PUSHBAR

9.1 PUSHBAR BRIEF

Skills: Knowledge of power tools

Tools: Band saw, cut-off wheel or hacksaw

Materials: Aluminum airspace grade airfoil, ~1” aluminum tube

Safety tips: Use caution and gloves when handling carbon fiber

The dimensions for the pushbar in this guide are not fully prescribed, because the shell shape will play into the final dimensions and is unique to each build. The handle of the push bar should be about one foot or more behind the back of the buggy and 44-48 inches above the ground. The location of the bar attachment to the baseplate is also important. It must not be too far forward to impede the driver from sliding back into driving position, but far enough forward so that it does not interfere with the rear wheel.

Why this design was chosen: Pushbar

This is an easiest and cheap way method of building a pushbar. All parts can be bought off the shelf and a finished pushbar can be installed in the buggy in an hour. An aluminum airfoil was chosen as the pushbar due to its combination of relative lightweight, affordability and low cost.

9.2 INSTRUCTIONS

Create a diagram to determine the angle of the bar and how far in front of the rear wheel the bar should be mounted to the floor. Mark the angle on the bottom of the aluminum airfoil and cut the bar with a band saw, cut-off wheel or hacksaw. Trim the top of the bar and mark where the push handle will go. Grab a 1” hole saw bit (or a bit the same size as the push handle if the handle size is different than described in this guide) and drill a hole through the aluminum bar with a drill press.

Place the bar next to the buggy in the proper position. Mark on the top of the buggy where the bar will pass through the top of the shell, which will be behind where the bar is going to attach to the baseplate. Trace the bottom of pushbar on the top of the buggy and use a dremel and black cutoff wheel to cut the pass through hole in to top of the shell. Once the hole is cut out, vacuum out all the dust and clean the area where the bar will be mounted with a small amount of acetone. Clean the bottom of the bar with acetone as well to remove any oil from hands.

Mix a batch of 5 minute epoxy and smear it on the bottom of the push bar. Slide it through the hole and have 2 people hold it in place until the epoxy cures. Have somebody stand in front of the buggy to ensure the bar is not leaning to the left or right. Once this sets (about 20 Minutes) add more epoxy around the edge of the joint between the baseplate and the bar. Then fill in the gap between the pass through hole and the bar with 5 minute epoxy. If it is too runny, add a thickening agent like kevlar pulp or microspheres. After 24 hours, the bar will be fully set in place. The pushbar handle can then be installed and glued into place.

Alternative Design Option: Pushbar

Carbon Fiber Airfoils are available for purchase and can be used in place of the aluminum airfoil. These are much more expensive than aluminum but stiffer and lighter. If the team can afford it, this should be your material of choice.

Pushbars can be made out of carbon fiber as well, but it will take time to develop a process that produces a high quality part. It is cheaper to build a carbon bar over buying one, but most attempts are heavier, wrinkly and less stiff than their purchased counterparts.

Pushbars can be made to be removable with a bolt in mount attached to the baseplate. This mount can be glued to the floor or bolted in. If this design is chosen, make sure to add another hardpoint for this mount. Removable bars are convenient for storage and allow different height bars for men’s and women’s races. However, it will be flimsier and might make it harder to push the buggy if there is slop in the joint, so this guide does not recommend this method.

10 SAFETY EQUIPMENT

10.1 SAFETY BRIEF AND INFORMATION

Skills: Research and common sense

Tools: None

Materials: Store bought harness and equipment, climbing rope, webbing

Safety tips: No build necessary

Harnesses can be purchased off the shelf, provided that they comply with the rules listed below:

- The straps from which a safety harness is constructed must be at least 1.75 inches wide.
- The lower portion of a safety harness may consist of straps less than 1.75 inches wide, with prior approval from the safety chair.

Off the shelf options that meet the requirements are:

- Fall Arrest Harness
- Childrens Climbing Harness
- Full Body Climbing Harness

Auxiliary loops of webbing may need to be added to the front of the shoulder straps to attach the harness to the buggy. If the purchased harness purchase doesn't have these loops, they must be attached with box stitching, by professional stitchers, performed on a heavy-duty industrial sewing machine, and deemed adequate by the Safety Chairman.

To attach the harness to the buggy, use heavy duty climbing rope or webbing, looped through a metal adjustment piece such as a slide, tibloc or strap adjuster. There must be a carabiner on either end of the rope or webbing to clip the rope to the harness and buggy. All harness clips must be d-ring carabiners and certified by the UIAA (International Mountaineering and Climbing Federation). Additionally, all components to the safety system must be rated for a load of 1,000 pounds, although the higher rated, the better.

Helmets can change the amount of headroom for a driver significantly. One driver may fit easily with one helmet, but not with another. Women's climbing helmets, both plastic and foam, tend to have the shortest profile.

Other required equipment for drivers are: leather gloves, a fitted mouthguard, and safety goggles. A chinpad is useful to absorb the bumps of the road and rest the driver's neck muscles.

11 WHEELS

11.1 WHEELS BRIEF

Skills: Lathe skills

Tools: Lathe, vice/bearing press

Materials: ¾" steel rod, 5/8" steel tube

Safety tips: Lathe safety is outside the scope of this guide but must be followed. Spend considerable time seeking training, guidance, and oversight when using a lathe. Never machine alone.

This guide recommends purchasing 5-6 Xootr wheels. Extra wheels are necessary because during Capes, there is a chance the wheels will develop flat spot from braking. Buggies should not be rolled on flat spotted wheels as it makes it less comfortable for the driver and slows the buggy down. It is good practice to have a specific set of wheels for capes, as the driver will be braking on them a lot, and they will develop flat spots relatively quickly. As the team grows, research and experimentation can be invested into wheel tech.

Why this design was chosen: Wheels

Since 2000, most wheels found on the buggy course have been based on the basic dimensions of a wheel from a Xootr scooter. These wheels are cheap ($25 a wheel), readily available, and initially were very fast when heated and chemically treated. As these wheels waned in quality, teams began sending Xootr hubs to polyurethane manufacturers to get custom wheels made.

Today, this wheel size has maintained popularity even with teams building custom hubs and rims. Competitive wheels in this size are readily available from a local machine shop called Zero Error. There is a lot of knowledge and infrastructure built around these wheels (bearing spacers, axle sizes on buggies, etc.) so it is easy to find wheels and bearings in this size range.

11.2 INSTRUCTIONS

Xootr wheels use a standard R8 bearing (Dimensions: 1.25" Outer Diameter (OD), .5" Bore/Inner Diameter (ID) and .3125" Width). Purchase sealed bearings to use for practice. For raceday, unsealed bearings should be used as they have less friction. Clean these with acetone and lubricate them with a small amount of bearing oil (such as Speed Cream). Make sure to keep any dirt or debris from getting inside the bearings. Do not buy full ceramic bearings, as they are known to break in the chute. Hybrid ceramic bearings are acceptable.

If the team has the budget ($600 plus tax) for 3 Zero Error wheels, these can be bought to increase speed on Truck Weekend and raceday. These wheels are slightly thinner than Xootrs and use a different sized bearing (R8 "thin": All dimensions the same except width which is .25" on these bearings).

Figure 65 - Bearing spacer or 'hop'

To prevent the bearings from being side loaded, which causes friction, place a spacer between the bearings when the wheels are bolted down. A commonly used spacer in buggy is a small piece of steel referred to as a “hop”. The beauty of these spacers is that they stay in line with the bearing and don't “float” inside the wheel, making it easier to install wheels. A hop has an inner diameter of ⅜”, an outer diameter on the steps of .5” (equal to the Bore/ID of the bearing) and an outer diameter in the middle larger than .5”. The width of the steps will be equivalent to the thickness of the bearings (.3125 for Xootrs and .25 for ZE’s) and the width of the center must be equal to the “step” in the middle of the wheels. These hops can be made out of steel tube on a lathe or at a machine shop for better precision.

After wheels and Hops are made or acquired, assemble the wheel. First, install one bearing (a bearing press may be needed to get the bearing into the wheel). Then insert a hop into the first bearing and install the bearing on the other side, sandwiching the hop into the middle of the wheel. Now it is ready to be installed onto the buggy.

Figure 66 - Bearing removal tool

To remove hops and bearings from the wheels, a bearing removal tool is incredibly useful. To build one, use a solid tube of steel or aluminum about 5” - 6” in length. Lathe 2 steps into one end of the tube, with the first step slightly smaller than ⅜” in diameter and the second step slightly smaller than .5” in diameter. This tool, portrayed in Figure X, can be placed into the wheel where the axle would normally go, and tapped with a hammer to knock the hop and first bearing out. Flip it over and do the same to the other bearing to remove that one.

Alternative Design Option: Wheels

In the past, teams used 10” diameter pneumatic wheelchair racing wheels called panaracers. They were very light and competitive, but fragile. They no longer exist, but there is likely a replacement product that could be viable.

Smaller custom wheels have also been used with varying success rates. Inline speed skating wheels are an option. They’re slightly more competitive than Xootr wheels but require smaller spindles, different sized bearings and spacers, and modified steering to ensure proper ground clearance.

Different types of spacers can be used in order to fit a thicker axle for the buggy. ⅜” has proven durable enough with the right metals to not require a thicker axle.

Custom wheels can be made as well but expect the cost of hubs and wheels to run nearly $400 a wheel. The team will need custom wheels or a wheel provider with fast wheels to compete at the top of the field. It is best to determine wheel performance with a simple wheel testing rig.

12 FINAL ASSEMBLY AND TESTING

12.1 BRIEF

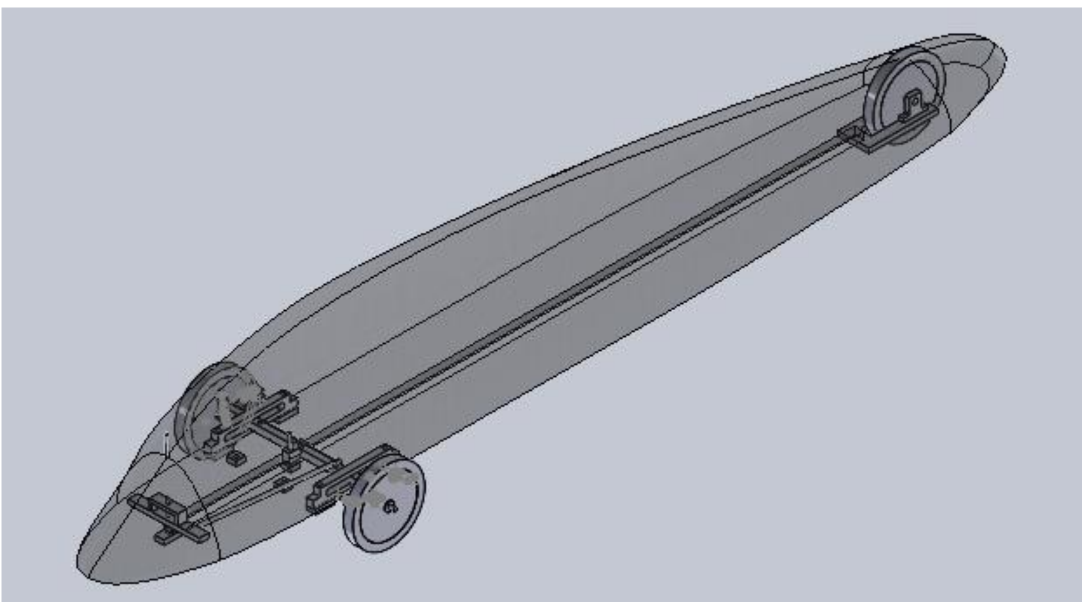
Skills: Lathe skills

Tools: Lathe, vice/bearing press

Materials: ¾" steel rod, 5/8 steel tube

Safety tips: Lathe safety is outside the scope of this document, but must be followed. Spend considerable time seeking training, guidance, and oversight when using a lathe. Never machine alone.

After all the parts are made, this section outlines how to assemble them into the shell to create a fully functioning buggy.



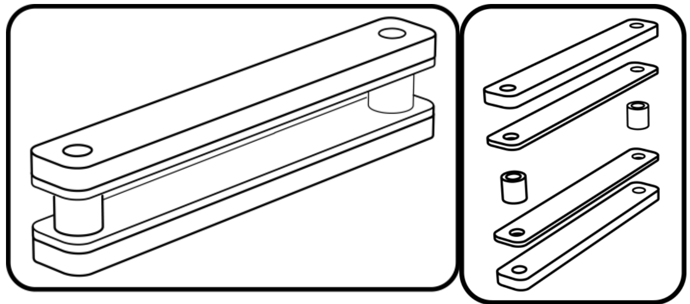
12.2 FINAL ASSEMBLY

12.2.1 Shell Preparation for Installation

Locate the holes in the hardpoints along the baseplate of the buggy and mark them with a sharpie or paint pen.. There should be visible indents in the baseplate where the holes are but if not, get the template made after completing the baseplate, and use that to mark the holes. Grab a corded or cordless hand drill and drill bits slightly smaller than the holes in the hardpoints. Drill through the carbon fiber to reveal the mount point holes, then ream the carbon out to their full size either with bigger drill bits or a dremel and sanding bit.

12.2.2 Steering Assembly

Figure 67 - Brackets



Materials: spacers, mounting block pieces (teflon and steel), axle, ⅜" inner diameter mounted bearing, ⅜ -16 2.5" long bolts and ⅜ -16 lock nuts, and thrust bearing.

The finals steps for the steering include installing mounting blocks and axle.

Before installing the steering, two slots must be cut into the side of the buggy shell that will allow the axle to pass through for install and turn while being driven. Mark a square, ¾" tall by 6" long on each side of the shell, 1/2" above the baseplate of the buggy. Align the ends of the squares with the location of the mounting block hardpoint holes in the bottom of the buggy. Grab a drill and a ¾" drill bit. Drill two holes in the side of the shell, aligned with the ends of squares that were just marked. Then use a dremel cut off wheel to cut along the lines and finish cutting the holes in the side of the buggy. Pass the axle through the hole, rotating it as needed to fit through the holes. Then build the mounting blocks around the axle, steel, teflon, spacers, teflon, steel, as shown in Figure 59.

Pass a ⅜" bolt through each mounting block and place a nut on each bolt. Tighten these down with wrenches until the nuts are snug, but not so snug that the axle cannot turn. If these cannot be tightened enough to remove play/movement in the mounting block without causing too much friction on the axle, feel free to sand the axle down slightly or add washers to the spacers.

Once the axle can move relatively freely, albeit with some friction and limited slop/movement, place the mounted bearing over the hole in hardpoint #6. Place the hole in the trailing arm of the axle over the mounted bearing and install any washers needed to have the axle laying flush. Place the thrust bearing on top of the trailing arm, centered over the hole. Pass a ⅜" bolt through this hole and tighten it in place with a nut and washer on the bottom of the buggy.

12.2.3 Steering Handle

Materials: Aluminum steering handle, 5/16" mounted bearing, 5/16" nuts, 5/16" x 3" long bolts.

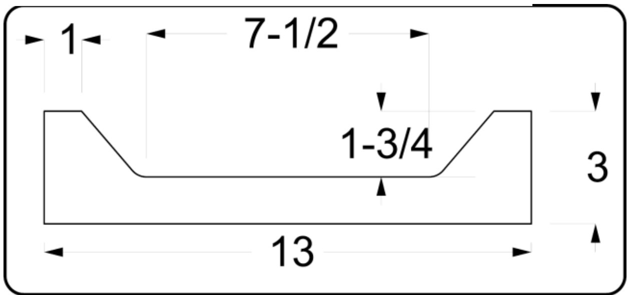
Place the mounted bearing over the hole in the hardpoint for the steering handle. Place the steering handle on top of the bearing and lock it in place with a nut and bolt. Turn the handle so the exposed 5/16" hole is on the left hand side of the buggy. Slide the brake handle onto the handle, left hand side for right handed drivers and vice versa.

12.2.4 Steering Cover

In a wagon steering buggy, the steering is inside the buggy and directly under where the driver will be laying. To prevent the driver from being uncomfortable and more importantly prevent the steering from getting stuck in the drivers clothing, a steering cover must be built. This method of building the steering cover will introduce the team to female mold construction and layups.

Making the Mold

Figure 68 - Steering cover mold trace



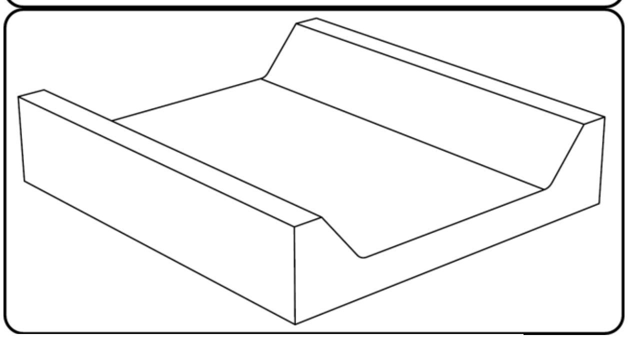


Figure 69 - Steering cover mold

This mold will use a similar method to build this mold as the mold for the shell. Create a trace based on the design in Figure 60. Make it wider or thinner depending on how wide the shell is. Use the trace to cut slices and cut enough slices that, when glued together, form a mold the same width as the inside of the buggy. Glue the slices together, spackle/bondo and sand until smooth. The final product should look like Figure 61.

Carbon Fiber Layups

Prepare the materials prior to the layup. Gather 2 sheets of the twill weave carbon and 5-6 layers of unidirectional carbon sheets big enough to fill the inside and flanges of the mold. It is optional to vacuum bag this part but is recommended. If you chose to vacuum bag, cut peal ply, breather cloth and construct a vacuum bag before moving to the epoxy impregnation stage. The bag should be just slightly larger than the mold, so if the team used tube bag for the wraps it can be cut into a flat sheet, trimmed to size and built with the flat sheet method described in Layups: Material Prep.

Once the materials are prepared, set up a table with plastic covering and prepare for a wet layup. Prepare the mold as for the shell, wrapping in packaging tape and covering in wax. This only needs to be done in the “valley” of the mold.

For the layups, wet out all of the layers of carbon fiber and place them into the mold in one layup session, rather than splitting it into multiple sessions like the shell. Layer the carbon fiber in this pattern, twill weave, 5-6 layers of unidirectional (ideally alternating the direction of the fibers with each layer), twill weave. If vacuum bagging, set up the bag as done previously. Let sit in the bag for 24 hours then remove.

Trimming and Finishing

Once the part is removed from the mold, place it into the buggy and try to lay it flat. The tie rod and potentially the harness mount points will likely be in the way. Mark what needs to be trimmed for the cover to fit using a paint pen. Trim the carbon with a dremel or bandsaw so the cover will fit flat on the baseplate without interfering with the steering. Install the cover and turn the steering to make sure it doesn't interfere at any point in the full range of motion in the steering.

12.2.5 Tie Rod

Materials: 5/16" x 1.5" bolts, 5/16" lock nuts, Hexagonal turnbuckle, LH and RH thread rod ends.

Place 2 nuts and the rod ends onto each end of the turnbuckle, leaving the nuts and rod ends loose from each other. Bolt the rod end into place first on the axle. Ideally the tie rod would attach to the bottom of the axle, but if there is not enough room, attach it to the top of the axle. Then bolt it into place on the steering handle.

12.2.6 Brakes

Materials: Springs, brake cable, brake cable housing, knarps, brake cable crimp caps or soldering gun, brake arms, brake pads, brake handle, shoulder bolts, #8-32 lock nuts, 3/16" washers, countersunk screws, ¼"-20 lock nuts.

Attach the brake pads along the flat side of the brake arms with the countersunk screws. Leave them slightly loose so they can be rotated. The final position will be set, and the screws tightened, during final testing and tweaking. Attach the brake arms to the mounts on the axle with a shoulder bolt and lock nut, placing a washer between the mount and brake arm. Leave the nut loose enough that the arms can turn freely.

Grab the brake cable and cable housing. Measure out a length that will pass through the brake arms, run along the axle and reach the brake handle, allowing for 5 or more inches of extra slack in the housing and 9 or more in the cable.

Cut each brake cable, keeping the cylindrical bulbed ends on and cutting the smaller round ends off. This step is ideally completed with a bike brake cable cutter. If the team does not have one, tightly tape around the cutting section and use sharp wire cutters to trim. The tape prevents the cable from fraying, which could render the brakes useless and require replacement of the brake cable. If the team has access to a soldering gun, gently remove the tape and put a tiny amount of solder on the end to keep from fraying. If not, add a crimp cap to the end once everything is assembled.

For the cable housing, mark the length and use a dremel or bandsaw to cut. Do not use wire cutters or other forms of crimp cutters as they can crush the end of the housing, preventing the cable from passing through freely and rendering your brakes useless.

Pass one cable through the housing until the large cylindrical end is against the cable housing. Slide the cable through the small hole in the metal "upright" on the left side of the axle, then slip a spring over the cable. Feed the cable through the small hole in the aluminum brake arm. Slip a knarp onto the end and tighten loosely with about 3-4 inches of space between the knarp and the brake arm.

Repeat this process for the left hand side. Then, take the brake handle and insert the cylindrical ends into the locking mechanism of the handle. Lock them in place and set the handle down inside the buggy.

12.2.7 Steering and Brake Adjustment

Alignment: Rotate the tie rod turnbuckle until the axle and steering handle are parallel when the axle is pointed straight ahead, then tighten down the two bolts to lock the rod ends in place.

Brakes: Loosen the knarp on the left hand side. Slide it until it is snug against the brake arm. Tighten the set screw down to lock the knarp into place. Cut off the excess cable, using the same process as before, leaving about an inch of excess cable past the knarp. Solder the end of the cable or place a crimp cap on it to prevent fraying. Repeat with the other side.

Install a wheel on each side. Rotate the brake pads until they do not contact the rim then tighten to lock in place. The wheel may need to come off to tighten the pads down. Reinstall the wheels if they were taken off.

Spin the wheels and pull the brake handle to see if they stop the wheels. Use the adjusters on the brake handle if extra tension is needed to stop the wheels. If the brake pads are rubbing, try loosening the tensioners on the brake handles. If loosening the brake tensioners does not stop the rubbing, remove the wheels, sand the brake pads down and try again. If loosening the tensioners works, but the wheels no longer stop, there is not enough travel in the brake arms. Remove the arms and trim or sand the angled cut further to allow for more travel.

12.2.8 Rear Wheel Mounts

Materials: Bolt

Insert a wheel between the two rear wheel mounts and tighten into place with a bolt. Place this assembly into the back of the buggy and bolt it into place. To easily install and remove the rear wheel with the mounts installed, you may need to drill a hole in the side of the buggy. This can be seen on the tail of Apex and Fringe Buggies, like Phoenix in Figure 60.

Figure 70 - Hole for rear wheel access

12.2.9 Harness Mounts

Materials: D Rings, ⅜" bolts, ⅜" lock nuts, washers

Place the harness mount points over their respective holes and lock them in place with bolts and nuts, placing washers on the bottom of the buggy.

12.3 TESTING

Once the buggy is complete, areas to test are: loading and unloading drivers, driver vision, and steering and brakes.

First, check over all of the hardware for burrs, or sharp points, and file those down as needed. Check the inside of the buggy for any bits of carbon that could give the driver splinters, and sand those down as well. After the interior is checked for safety, load driver(s) in the shop to receive comfort and ergonomic feedback and to adjust the harness straps.

To load the driver, place the buggy on milk crates or similar objects and practice loading a driver and installing all hatches. Ask the driver if anything inside the buggy is uncomfortable and note them. Install the hatch and have the driver steer the buggy, making sure they have full range of motion in the steering without hitting the hatch. If not, note what changes can be made to resolve this. Check that they have full vision to 45 degrees both left and right. If not, note this and plan to enlarge the windshield. Check if the driver's feet are close to touching the back wheel. If so, build or 3d print a wheel cover to prevent the driver getting their toes caught in the wheel. Before unloading the driver, adjust the harness straps and perform a pull test to see if they move more than an inch forward. Once all the ergonomic issues are noted, create plans to resolve them.

Once the buggy is comfortable and the driver can sufficiently see, run a practice capabilities (capes) test to check the brakes and steering. Find a flat open area that has smooth pavement and is free of cars. A closed parking lot or an empty parking lot is used by many teams on campus. Sidewalks on campus during the evenings or weekends are usually free of traffic as well. Start slow pushing the driver around and having them steer to ensure the buggy can turn reliably. Then test the brakes, gradually building up to a full speed run. The final run should simulate a capes test, measuring the distance it takes to stop and ensuring it is within the regulations. If the buggy passes all these tests, you are ready to schedule capes with the safety chair!

13 FINISHING

13.1 BRIEF

Skills: Patience, art skills

Tools: sandpaper, stirring sticks, paint gun, file

Materials: bondo, 5-minute cure epoxy, microbeads, primer, paint, clear coat, denatured alcohol (for cleaning)

Safety tips: Wear a dust mask for sanding and when using microbeads to avoid inhalation. Wear a respirator for painting. Denatured alcohol is a strong organic solvent and should be handled accordingly; reduce exposure to skin and lungs where possible and dispose of it mindfully.

This is the time to make the buggy look sleek and give it a personality. You'll notice the buggies on the course have a wide variety of paint jobs. This is your team's turn to decide how you want the final buggy to look!

Why this design was chosen: Finishing

This method is used by most teams on the course and serves to smooth out any wrinkles or inconsistencies in the shell without compromising the structure of the carbon fiber.

A few options of paint jobs are laid out so the team can choose what best fits with the available resources.

13.2 INSTRUCTIONS

13.2.1 Bodywork

Bodywork is the first step in the finishing process. Begin by lightly sanding down the body of the buggy with a medium to high grit sandpaper—be very cautious not to over-sand. Once this is done, inspect the buggy for any major imperfections. Use bondo (a two-part auto body filler) for any large lumps or dents, as it is easy to spread and easy to sand. Fill in dents or smooth over lumps until the shape of the buggy is satisfactory.

Next, use epoxy mixed with microbeads to get a smooth surface for painting. While bondo works well for large imperfections in the shell, epoxy with microbeads will result in a smooth finish. Mix a fast curing (~5 minute) epoxy with glass microspheres; use approximately 1 part microbeads to 3 parts epoxy. Spread a thin layer of this mixture over the entire body of the buggy, then *wait for it to cure*. Do *not* start sanding until this layer is fully cured, or the sanding will heat up and soften the epoxy. Then, sand down this layer to the desired smoothness. If problem areas are identified on the shell, go back over these with smaller batches of epoxy and microspheres. Ultimately, the extent of bodywork is entirely up to the team—but keep in mind, paint often amplifies flaws in your shell, rather than masking them.

13.2.2 Painting

Once the bodywork is complete, paint can be applied. There are two options for this: high quality and low quality.

The simplest method of painting a buggy is to buy spray cans of primer, paint, and vinyl painters tape. Start by removing or taping off (covering the piece with tape or tape and paper to prevent it getting covered in paint) the windshield and steering parts that you do not want painted. Spray on a few layers of primer following the instructions on the can that say how long to wait before adding another layer. Sand it smooth with 1000 grit or higher sandpaper. Next, begin spraying on the color. Start with the lightest color in your design, spray on a few layers following the can instructions and let it dry for a few hours. Then lay tape in the shape you want that color in the design. Continue this gradually adding the darker colors. This process will likely require a full day to complete or it can be spread across a few days. Keep this in mind when painting before raceday/design comp.

The highest quality paint job uses automotive grade paint and a pneumatic spray gun. This will require access to a compressed air tank (as of Spring 2020 there was one in the East Campus Garage Ramp) and a gravity fed pneumatic spray gun (can be purchased from Harbor Freight cheaply). Purchase automotive paint from the Sherwin Williams automotive paint store in East Liberty (they know about buggy and are helpful when it comes to buying paints). The best way to learn how to paint with this setup is watching car painting tutorials on YouTube or the equivalent video share website. Make sure to clean the gun thoroughly after each coat of paint is added. Do this by filling the paint canister with acetone and spraying through the nozzle. Then clean the exterior of the gun with acetone as well

14 Appendix A: Measurement Worksheet

	Dist from Hands (in.)	Width (in.)	Height (in.)
Elbows	De	We	
Shoulders	Ds	Ws	
Crown of Head	Dch		Hch
Hips	Dh	Wh	Hh
Calves	Dc	Wc	
Toes	Dt	Wt	Ht
Center of Mass	CGh		

15 Appendix B: Budget Example

Budget & Links to Purchase Tools

Item	Used for	Source	Link	Quantity	Cost per Unit	Total Cost	Required	Notes
Socket Wrench Set	Maintenance	Harbor Freight	https://www.harborfreight.com/sae-metric-socket-set-51-pc-63013.html	1	14.99	14.99	Yes	1 Required, should buy 2
Utility Knife	Maintenance	Harbor Freight	https://www.harborfreight.com/utility-knife-3359.html?_br_psugg_q=utility+knife	1	1.99	1.99	Yes	
Saw Set	Maintenance	Harbor Freight	https://www.harborfreight.com/18-piece-professional-saw-set-90446.html?_br_psugg_q=hacksaw	1	14.99	14.99	No	
Dremel Set	Maintenance	Harbor Freight	https://www.harborfreight.com/rotary-tool-kit-80-pc-63235.html?_br_psugg_q=dremel	1	9.99	9.99	Yes	
Drill Press	Maintenance	Harbor Freight	https://www.harborfreight.com/8-in-5-speed-bench-drill-press-60238.html?_br_psugg_q=drill+press	1	69.99	69.99	No	Can Use Campus Shops
Drill	Maintenance	Harbor Freight	https://www.harborfreight.com/38-in-variable-speed-reversible-drill-60614.html	1	17.99	17.99	Yes	
Palm Sander	Maintenance	Harbor Freight	https://www.harborfreight.com/14-sheet-orbital-palm-sander-61311.html	2	13.99	27.98	Yes	
Ruler	Maintenance	Harbor Freight	https://www.harborfreight.com/48-in-aluminum-ruler-69365.html?_br_psugg_q=ruler	1	4.99	4.99	Yes	
Tape Measure	Maintenance	Harbor Freight	https://www.harborfreight.com/25-ft-x-1-in-quikfind-tape-measure-with-abs-casing-69030.html	1	2.19	2.19	Yes	
Calipers	Maintenance	Harbor Freight	https://www.harborfreight.com/6-in-digital-caliper-with-sae-and-metric-fractional-readings-63731.html?_br_psugg_q=caliper	1	19.95	19.95	No	

Drill Bits	Maintenance	Harbor Freight	https://www.harborfreight.com/impact-rated-hex-shank-titanium-drill-bit-set-15-piece-64897.html?_br_psugg_q=drill+bits+for+metal	1	19.99	19.99	Yes	
Cut Off Wheel	Maintenance	Harbor Freight	https://www.harborfreight.com/corded-4-12-in-5-amp-angle-grinder-60372.html?_br_psugg_q=angle+grinder	1	19.99	19.99	No	
Sharpie	Maintenance	Amazon	https://www.amazon.com/Sharpie-Super-Permanent-Markers-Point/dp/B002764UJW/ref=sr_1_6?dchild=1&keywords=sharpies&qid=1601344473&sr=8-6	1	9.62	9.62	Yes	
Screw Driver Set	Maintenance	Harbor Freight	https://www.harborfreight.com/screwdriver-set-6-pc-62570.html	1	2.99	2.99	Yes	
Clamps	Maintenance	Harbor Freight	https://www.harborfreight.com/6-inch-bar-clamp-96210.html	4	2.99	11.96	Yes	
Jig Saw	Maintenance	Harbor Freight	https://www.harborfreight.com/5-amp-heavy-duty-tool-free-variable-speed-orbital-jig-saw-69582.html?_br_psugg_q=jig+saw	1	29.95	29.95	No	
Tap & Die Set	Maintenance	Harbor Freight	https://www.harborfreight.com/carbon-steel-sae-tap-and-die-set-40-pc-62831.html	1	16.99	16.99	Yes	
Vice	Maintenance	Harbor Freight	https://www.harborfreight.com/3-in-swivel-vise-with-anvil-61329.html	1	32.99	32.99	No	
Files	Maintenance	Harbor Freight	https://www.harborfreight.com/12-piece-file-and-rasp-set-97070.html	1	11.99	11.99	Yes	
Heat Gun	Maintenance	Harbor Freight	https://www.harborfreight.com/1500-watt-dual-temperature-heat-gun-56434.html	1	14.99	14.99	Yes	
Allen Wrench Set	Maintenance	Harbor Freight	https://www.harborfreight.com/36-piece-sae-metric-hex-key-set-94725.html	1	7.99	7.99	Yes	
Collapsable Stools	Rolls	Harbor Freight	https://www.harborfreight.com/one-step-folding-stool-56185.html	3	8.99	26.97	No	
Tool Box	Rolls	Harbor Freight	https://www.harborfreight.com/22-inch-toolbox-98273.html	1	12.99	12.99	Yes	

Storage Containers	Rolls	Amazon	https://www.amazon.com/Nicesh-Plastic-Large-Storage-Handle/dp/B089R48559/ref=sr_1_23?dchild=1&keywords=Storage+Bin+with+Lid&qid=1601344361&sr=8-23	1	35	35	Yes	For Wheels, Driver Equipment
Vacuum Pump	Layups	Amazon	https://www.amazon.com/ZENY-Single-Stage-Economy-Conditioner-Refrigerant/dp/B012CFTYX4/ref=pd_lpo_263_t_2/147-3480137-4510752?_encoding=UTF8&pd_rd_i=B012CFTYX4&pd_rd_r=d85fcc85-510c-47ef-81a1-7ae8ee62b8e9&pd_rd_w=rx9x1&pd_rd_wg=oCd4U&pf_rd_p=7b36d496-f366-4631-94d3-61b87b52511b&pf_rd_r=6CHBF184TX7ETZG1X8R8&psc=1&refRID=6CHBF184TX7ETZG1X8R8	1	58.99	58.99	Yes	
Epoxy Spreaders	Layups	Amazon	https://www.amazon.com/Astro-4526-Yellow-Plastic-Spreader/dp/B00P3O22Y0/ref=asc_df_B00P3O22Y0/?tag=hyprod-20&linkCode=df0&hvadid=309760780746&hvpos=&hvnetw=g&hvrand=2623953890435092179&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9015206&hvtargid=pla-571965812108&psc=1	1	25	25	Yes	
Popsicle Sticks	Layups	Amazon	https://www.amazon.com/200Pcs-Popsicle-Sticks-Natural-Wooden/dp/B086YVZ99D/ref=asc_df_B086YVZ99D/?tag=hyprod-20&linkCode=df0&hvadid=459725928622&hvpos=&hvnetw=g&hvrand=15426430581337792455&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9015206&hvtargid=pla-945257261175&psc=1	1	4.49	4.49	No	Need something to mix epoxy; could be plastic knives or chop sticks
Mixing Pots	Layups	Amazon	https://www.amazon.com/Disposable-Measuring-Cups-Resin-Multipurpose/dp/B07Q2HQZZB/ref=asc_df_B07Q2HQZZB/?tag=hyprod-	1	8.95	8.95	No	Can be solo cups, but they melt when the epoxy cures

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Scale	Layups	Harbor Freight	https://www.harborfreight.com/digital-scale-95364.html	1	21.99	21.99	Yes	
Hose for Vacuum Pump	Layups	ACP Composite	https://store.acpsales.com/products/18239/neoprene-tubing-	1	12	12	Yes	
Vacuum Fitting	Layups	ACP Composite	https://store.acpsales.com/products/3304/high-temperature-vacuum-connectors-w-twist-pin	1	28	28	Yes	