Materials and Processes in Manufacturing Term Project

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Project Objective

This project will allow you to utilize and practice the various manufacturing processes that have been covered during this semester's course. The processes that will be covered include machining, computer aided manufacturing (CAM), additive manufacturing, casting, and injection molding.

The objective of this project is to create a miniature model of a 1920's era race car. The model will consist of a car body, cockpit, wheels, and axles

Car Body

- The outer shell of the vehicle, including the doors, front fenders, back fenders, and body panels.
- Manufactured through casting silicone into a 3D printed mold that you will design.

Cockpit

- The inner portion of the car that includes the driver/passenger seat, dashboard, and steering wheel.
- Designed and manufactured through additive manufacturing (3D printing).

Wheels

- The wheels support the car and enable movement through rotation
- Fabricated from PLA/PETG and injection molded into metal molds that you will machine using CAM.

Axles

- Cylindrical pieces of tubes connecting the wheels to the car.
- Axles will be made from metal rods, but they will be held in place by 3D printed tubes that will be over-molded into the car body.

Design and Modeling

For this project, you will be creating a model based on a real-world 1920s era race car. This era of car is chosen due to the simplicity of the body shape, making it an ideal contender for 3D modeling and manufacturing.

To begin, you must first select a car. The car that will be used as an example for this guide is the 1931 Bugatti type 51 Grand Prix ('Lord Raglan').

It is ideal to select a car that has simple features, as this will make the modeling process less tedious and ensure ease of manufacture. Additionally, the car body's geometry should gradually decrease in height from the center plane outward toward the sides, where the doors are located. This means that starting from the center plane, and moving towards the side that has the car doors, the height of the car body should have a loping profile. Selecting a car whose geometry differs from these guidelines will cause supports to be generated when 3D printing, which will be difficult to remove, as well as cause a rough surface finish on the final product. Removing the final product from the mold will also prove to be challenging. See **Fig. 1** and **Fig. 2** for examples of acceptable vs. unacceptable car body geometries.

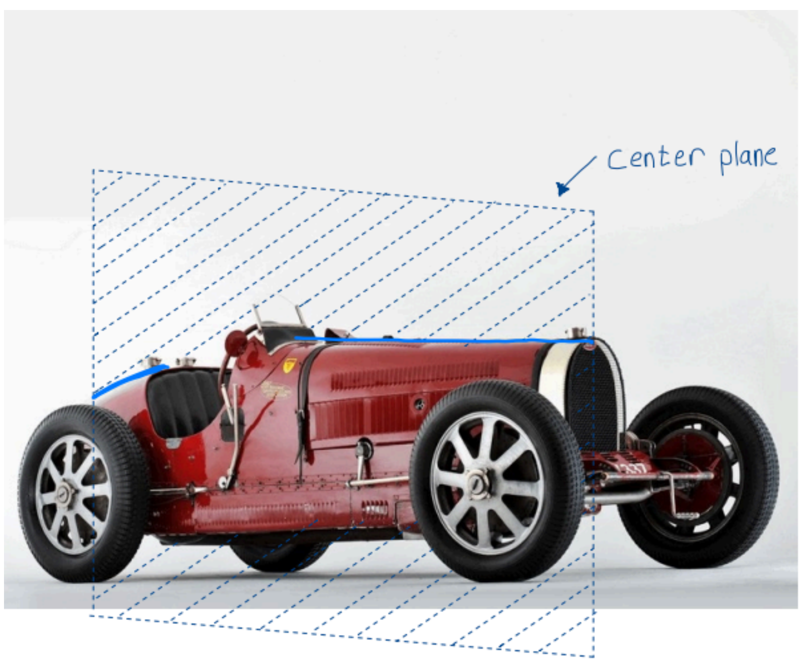


Fig. 1: Diagram of acceptable car geometry - height of the car body is always decreasing from the height located at the center.

Fig. 2: Diagram of unacceptable car geometry - height of the car body increases from the height located at the center in the area circled in yellow.

After selecting a car, you will need to create a CAD model of your car. The models to be created for this project are the car body, wheels, wheel axle holders, and cockpit. You will be using this CAD model to:

1. Create a mold which will enable you to cast your car out of silicone
2. Create a CAM for the wheel mold, which will subsequently be used for injection molding
3. 3D print the cockpit of the car and axle holders to insert into the body of the car

Car Design

A course you have taken or are currently taking is MECE3408: Computer Graphics and Design. In this course, the midterm project was to create a comprehensive scale model of one of many assorted children's toys of modes of transportation, whether it be boat, plane, submarine, or truck. For this project, feel free to apply any methods or techniques that you developed during that experience in order to create your CAD model.

For those who have not taken the course, or have taken the course and would like to see a technique that is proven to be successful in creating a CAD model of a car, here is a high level overview of the methods used in developing this project.

1. First, we find images of your car. The most important is a side profile, as well as preferably a front and back profile. These will serve as the foundation for the sketches that will sculpt the shape of your car. Examples of the photos used for this modeling process are shown below:

Fig. 3: back view of the car

Fig. 4: front view of the car

Fig. 5: side view of the car

2. Import the images into your preferred modeling software. For this demonstration, Fusion 360 was used. If SOLIDWORKS is your preferred software, the same guiding principles apply - you will just use the corresponding SOLIDWORKS functions for each step.
    a. Use the scaling feature to ensure that each view of the car depicts the features of the car at the same size. Superimpose sketches on the primary planes of your CAD workspace, making a rough skeleton of the car, which will allow you to trace sketches and extrude the car body. See **Fig. 6, 7,** and **8** for visuals of this process.

b. This procedure may require some trial and error, so do not expect this component to be perfect. It merely serves as a guide sketch to get the general form of the car.

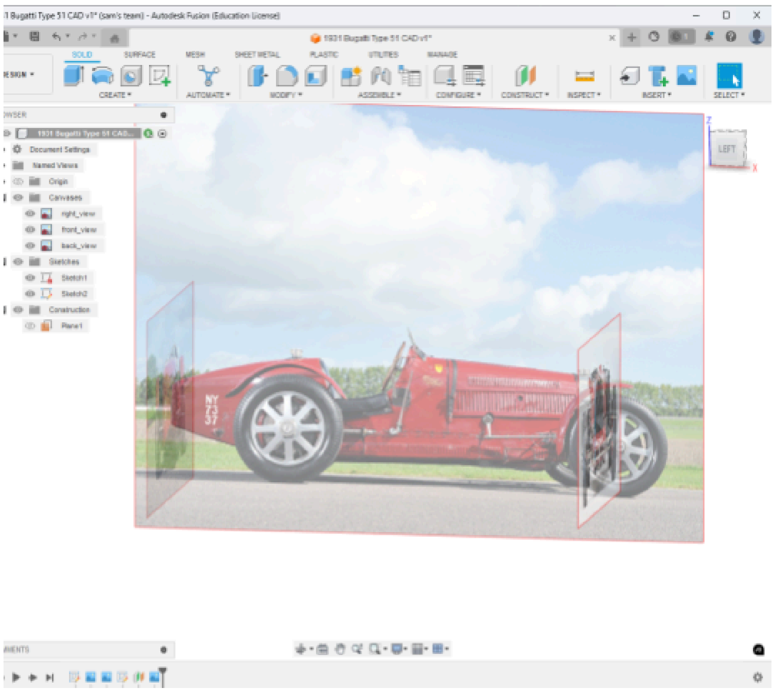


Fig. 6: skeleton of car, created using imported images

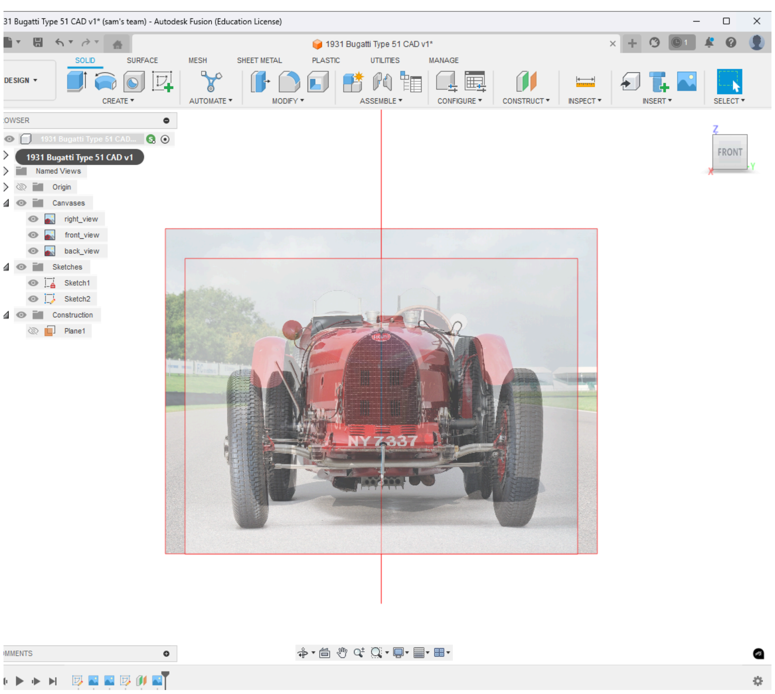


Fig. 7: Front view of skeleton of car

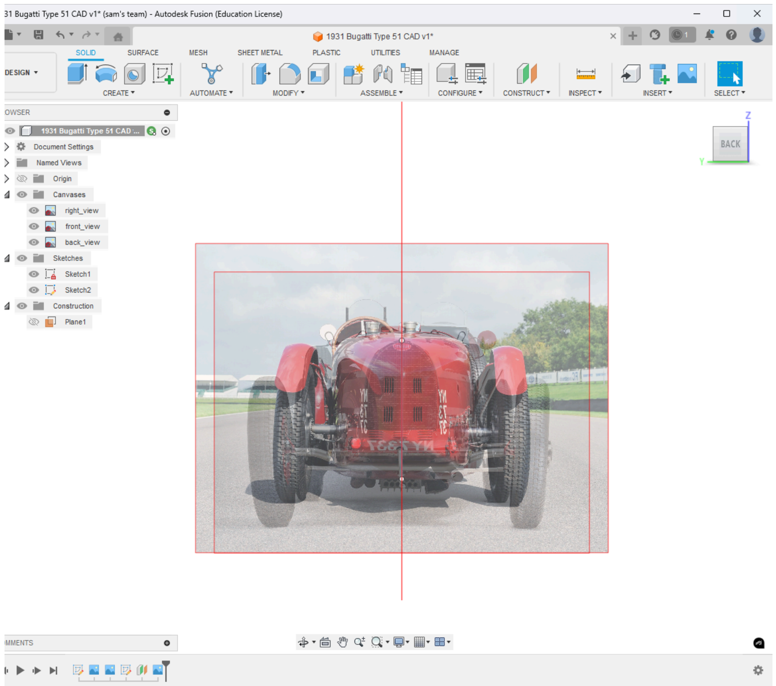


Fig. 8: Back view of skeleton of the car

3. While looking at the right side view of the car, sketch the curves on the car body. This will allow you to use the overall curvature of the car as a guide sketch when extruding later.

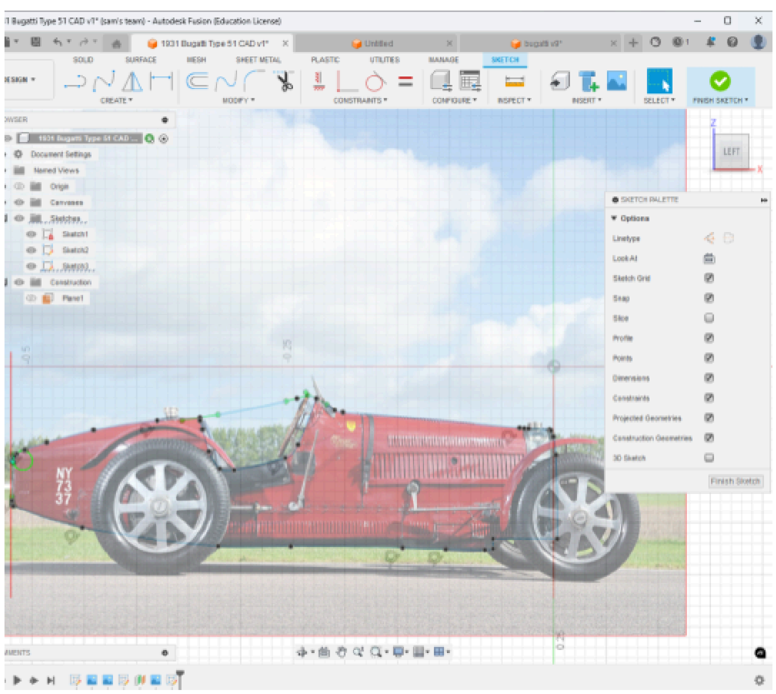


Fig. 9: Side view sketch, using mostly the spline feature

A rough sketch using mainly the spline feature will suffice, but feel free to use any method you are comfortable with. See **Fig. 9** for visuals of this process.

4. For the creation of the car body, we will be using the loft feature. The overall shape of the car is approximated using four cross-sections, which were then connected with the loft tool to generate a smooth form. This step will likely take the longest and will require artistic experimentation to create a realistic car shape. Try adjusting the placement/number of the planes, the geometry of the sketches, and the guide rails.

   When creating the sketches, using the project geometry function in Fusion 360 is very useful, or the convert entities equivalent in SOLIDWORKS. After experimenting with the geometries and placements, a satisfactory example of the cross sections can be seen in **Fig. 10**. At the front, we have a coffin-shaped geometry which defines the engine bay of the car. Then, two identical larger sketches span the region that makes up the cockpit, which will be extruded and designed later. Finally, the end of the car comes to a tapered point, and a slot sketch is utilized. **Fig. 11** shows this superimposed on the image so that the cross sections can be visually mapped to their corresponding portions on the car.

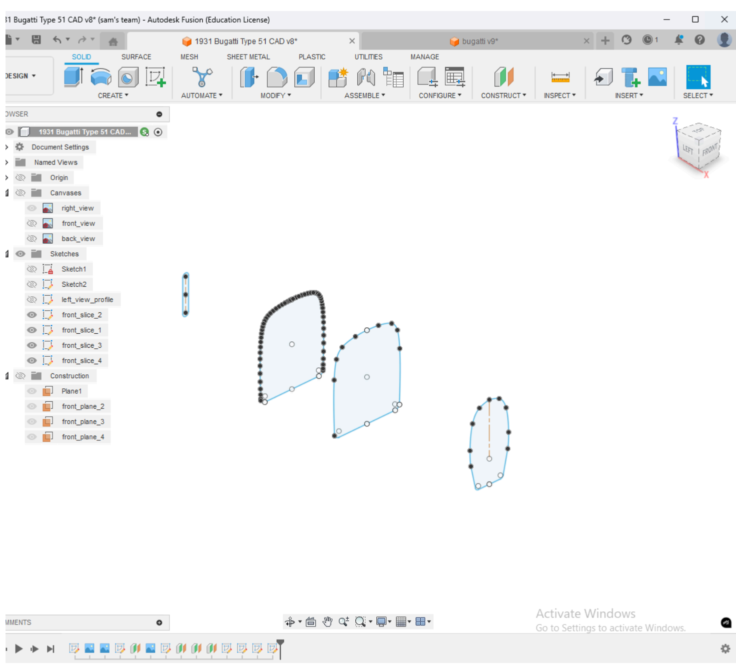


Fig. 10: Four cross sections that best approximate the flow of the car body

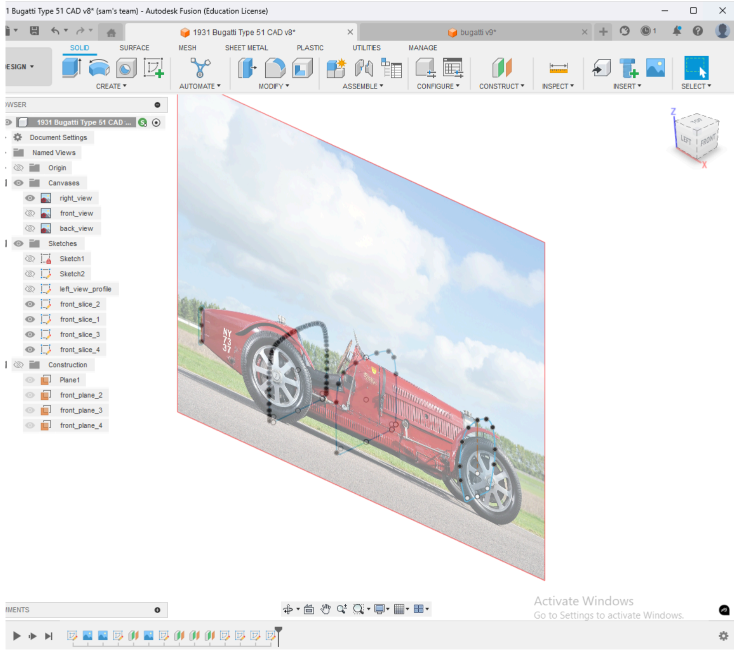


Fig. 11: The four cross sections, superimposed on the photo of the car

5. The loft feature is then utilized in creating the outline of the car. Connect all of the slices together with the loft feature to form the car body. See **Fig. 12** for a visual of this process.

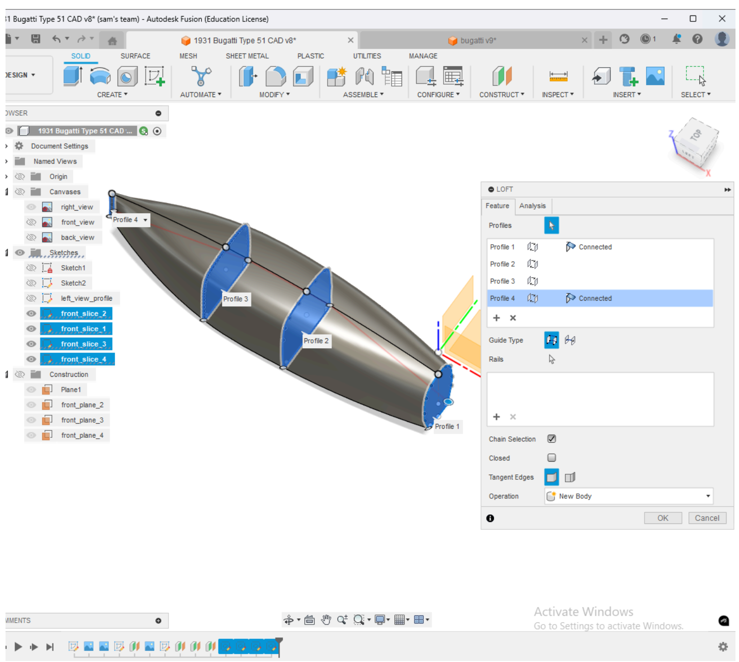


Fig. 12: The loft feature applied on the four cross sections, creating the car body

Cockpit Design

We will initially design the cockpit as part of the car body and later separate it into two distinct pieces.

1. We begin using our left view profile sketch and extruding symmetrically so that a seating cavity is formed (see **Fig.13** for visuals). This creates a canvas on which now you can design your cockpit.

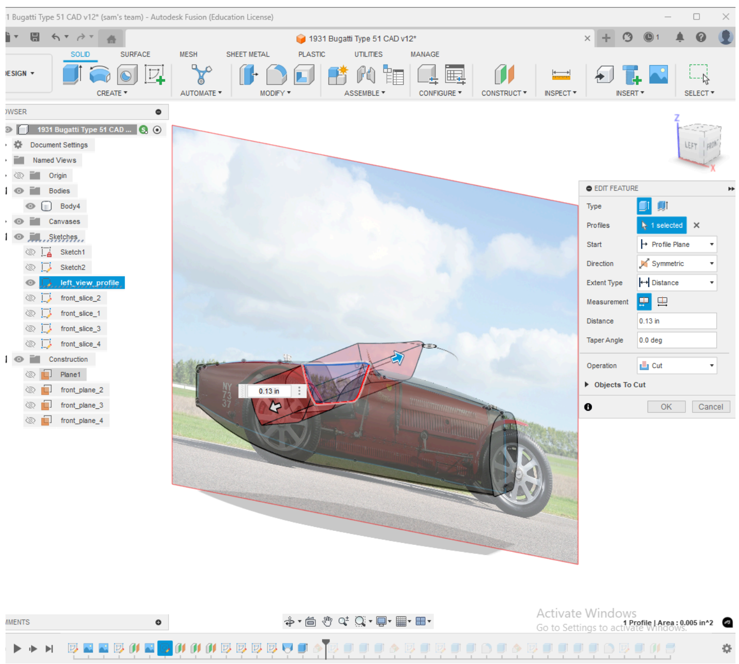


Fig. 13: Symmetrical extrusion forming seating cavity

2. Next, we will design the seat cushion. Using an array of semi circles on a construction plane, we can extrude the back of the cushion. See **Fig. 14** for visuals on this process.

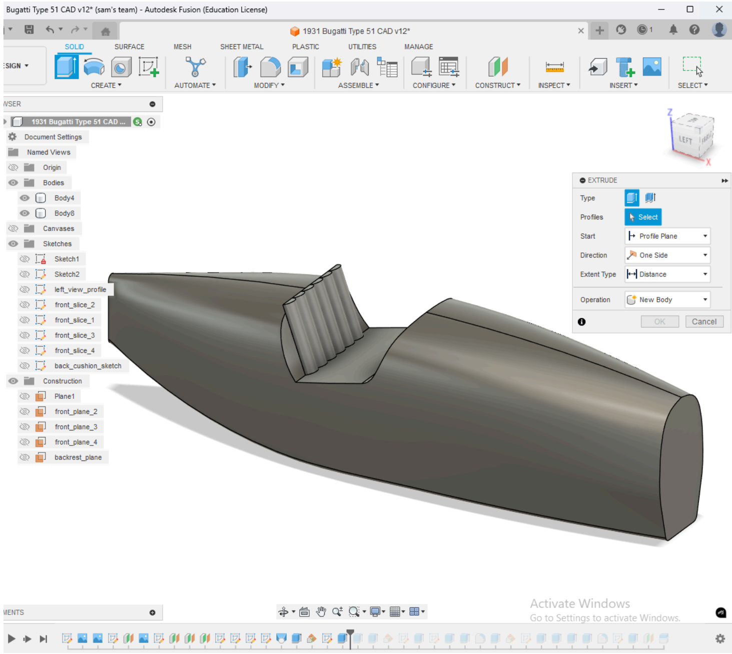


Fig. 14: Creating the seat cushions

3. Some cleanup may then be necessary to make the cushions flush with the car body. Make a sketch of the material that needs to be removed and take an extruded cut.

4. The same can be repeated for the lower portion of the seat. A construction plane with semicircles is extruded to create the bottom of the seat as depicted in **Fig. 15.**

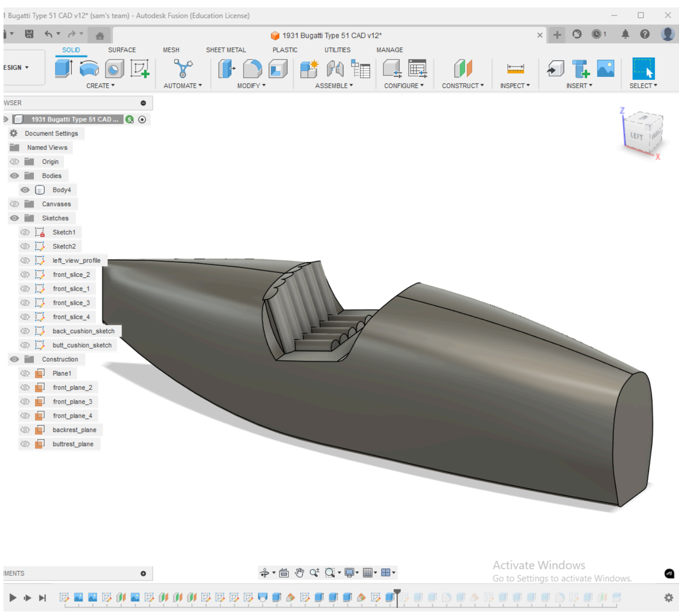


Fig. 15: Extruding the seat cushions outwards

5. Now, let us clear a space for the legs of the driver. A simple rectangular sketch with filleted corners will suffice. Extrude the sketch into the car body to some arbitrary length - this is purely aesthetical. See **Fig. 16** for an example.

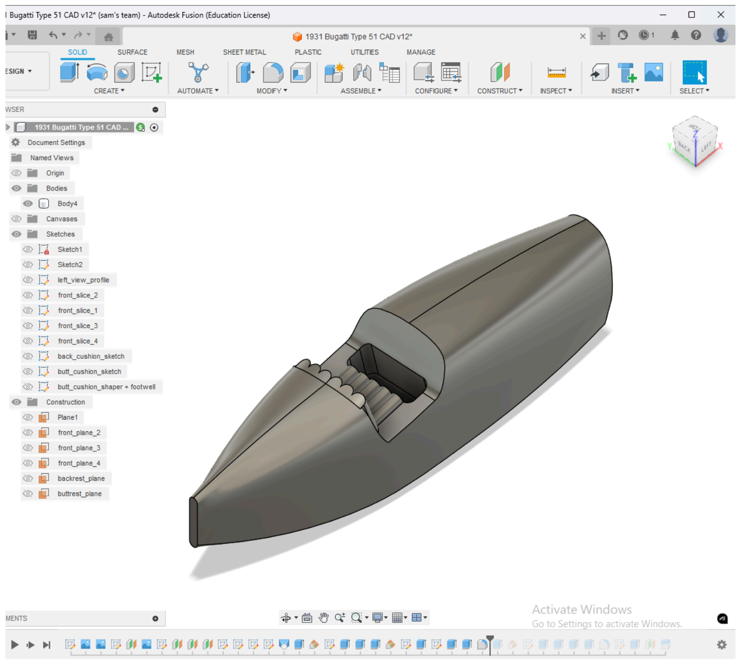


Fig. 16: Extruded leg space

6. Using the plane of the dashboard as a starting point, the steering wheel can be designed. Again, these details are purely aesthetic, so the dimensions and particular design is subject to your tastes and preferences. **Fig. 17** shows a simple steering wheel configuration.

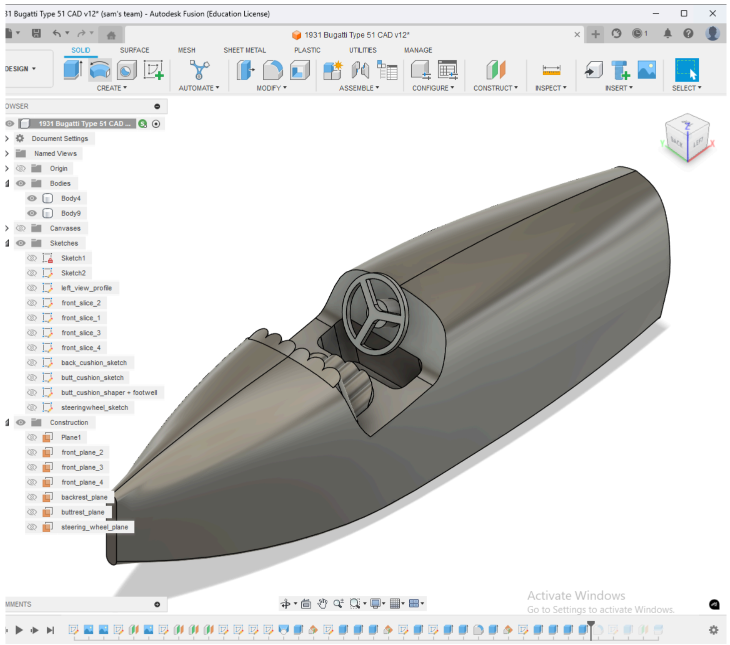


Fig. 17: Steering wheel implementation

7. Finishing touches can now be put on the cockpit, such as fillets on the steering wheel and curves on the lower seat cushion. See **Fig. 18** for visuals.

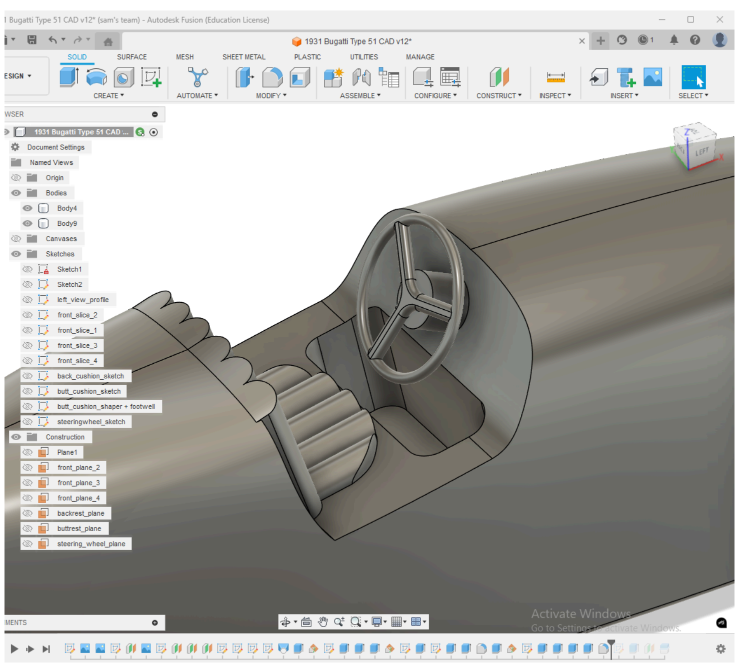


Fig. 18: Finishing touches on cockpit

Next, we will separate the cockpit from the car's fuselage by creating a cockpit pod—an independent interior section that contains the driver's seat, steering wheel, and dashboard.

1. Use a rectangular sketch with filleted corners to create a perimeter for the fuselage 'pod' that will be separately 3D printed and later slid into the car. Offset this sketch by a very very small distance (try 0.0001 in) and save the sketch. Use this to extrude away an 'infinitesimally thin' ring the height of the cockpit to the depth that you want the cockpit to reach into the car body. This will separate the car body from the cockpit 'pod' walls. **Fig. 19** and **20** detail this process.

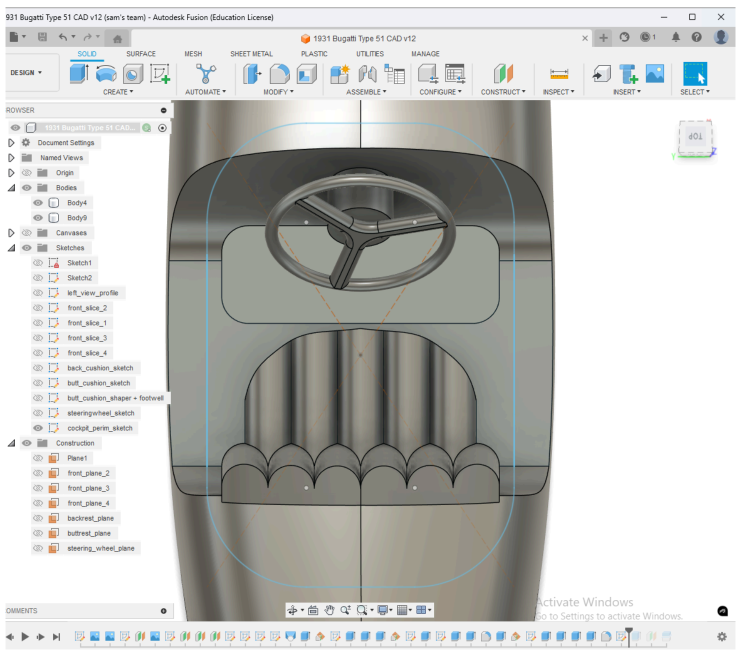


Fig. 19: 'Infinitesimally thin' ring. Please note this figure shows two sketches—an original perimeter and a second offset by 0.0001 inches, creating a nearly invisible separation

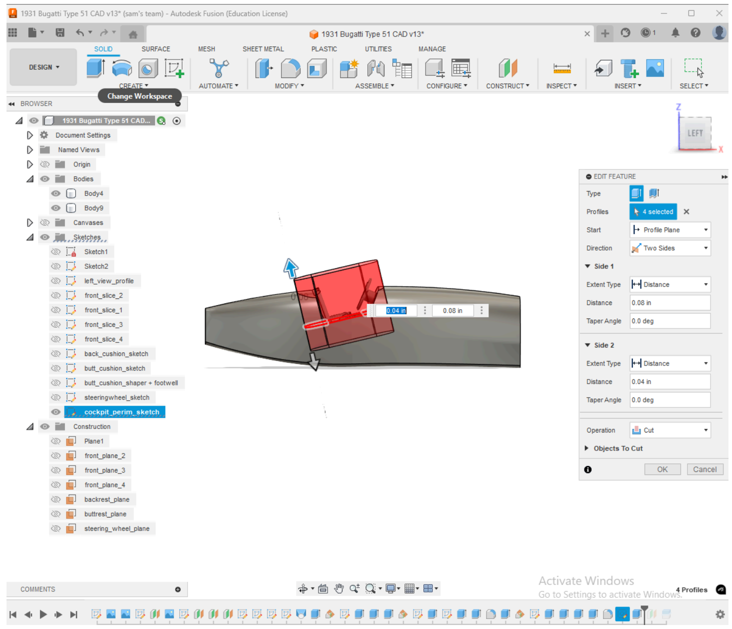


Fig. 20: Extrude the ring to separate the cockpit from the car body walls

2. The cockpit pod's walls are now separated, but the bottom remains connected. To fix this, create a construction plane at the depth of the ring's extension into the car. Use this plane to split the car body, fully detaching the cockpit pod. See **Fig. 21** for reference.

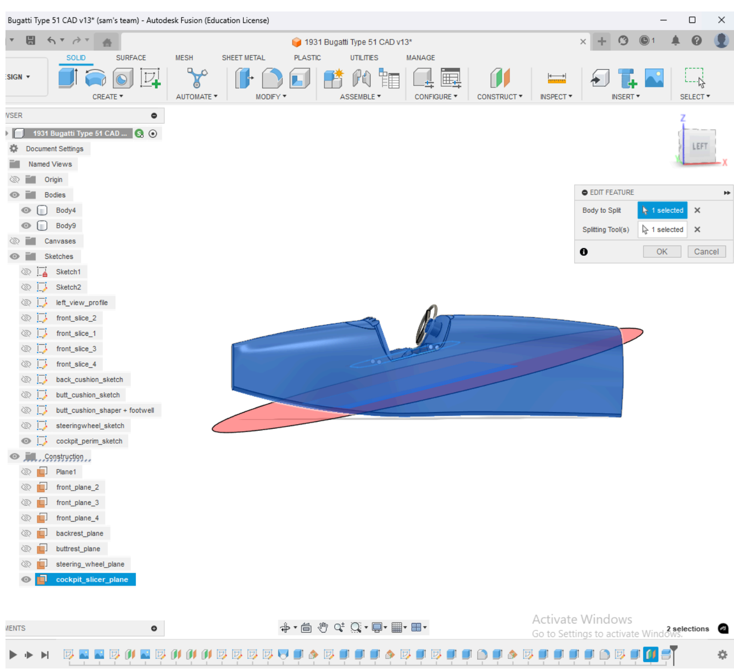


Fig. 21: Slicing the car body at the deepest point of the cockpit 'pod'

3. You can now toggle the cockpit pod for independent viewing, making it easier to isolate for 3D printing. Be sure to reunite the split fuselage using the combine feature so the car body remains a single, continuous piece rather than being divided by the cutting plane. See **Fig. 22** for reference.

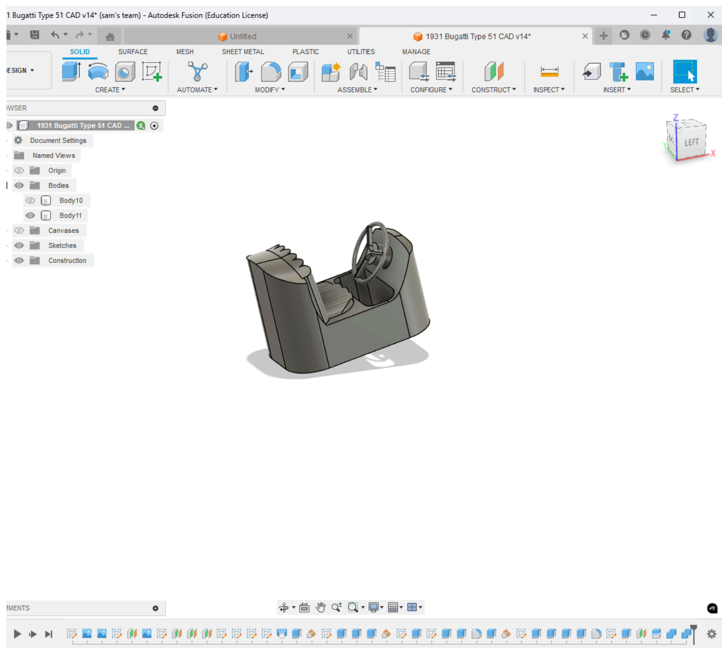


Fig. 22: Finished cockpit ‘pod’

4. Now that the majority of the body is designed, scale the car body up to the final size. Your car must fit in a mold with outer dimensions of 6.25in x 2.25in x 2.25 in. Scale the car to be as large as possible while still fitting inside the dimension constraint. This car was scaled 11x from its original dimensions to a max. length of 5.7in, a max. width of 1.25in, and a max. height of 1.5in. See **Fig. 23** for an example of the united fuselage.

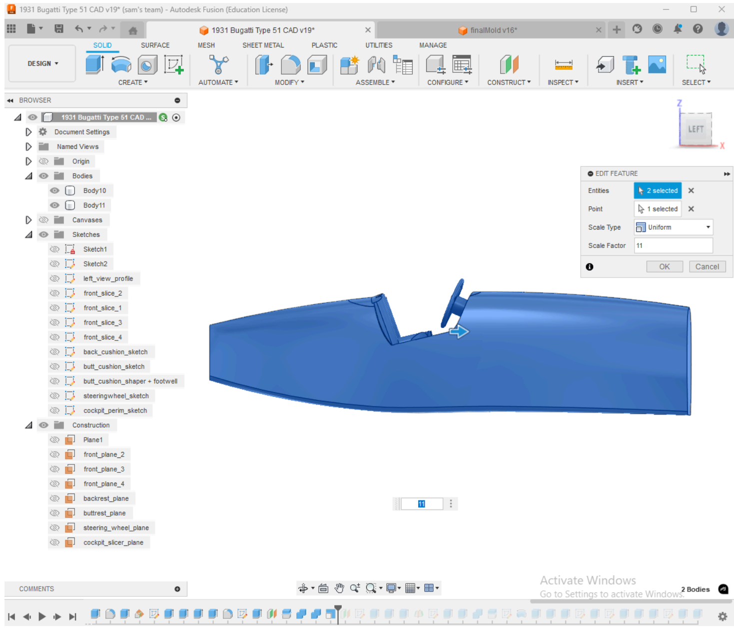


Fig. 23: Finished car body, with split fuselage reunited together using combine feature

Wheel Design

Designing the wheels is a simpler process than designing the car body. Therefore, instead of outlining a detailed step-by-step procedure, constraints will be set on the wheel's critical dimensions and characteristics, while allowing flexibility for artistic interpretation.

Specifically, the wheel must

- be no more than 0.5” wide at its maximum thickness
- be no more than 1.125” in its maximum diameter
- have a central hole for an axle measuring 0.125” in diameter
- have fillets no smaller than a radius of 0.0625” or 1/16”

Fig. 24 serves as a guiding example of a suitable wheel design.

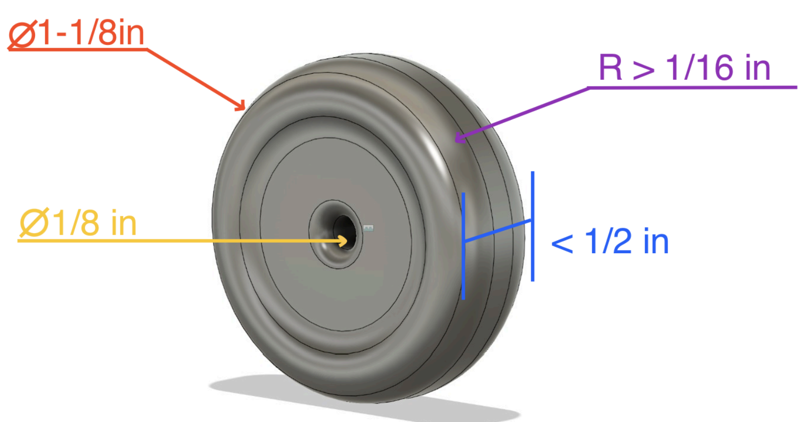


Fig. 24: Sample wheel

Body Mold Design

Now that we have a CAD model of the car, we can work on designing the mold that will be used to shape the car from liquid silicone. To begin, we will start by designing the wheel axle holders.

The wheel axle holder is a tube that will be incorporated into your car body to hold the metal axles for your wheels.

1. Using the side view photo as a reference, start by selecting logical axle positions. For each axle, sketch two concentric circles: a smaller one matching the axle diameter (0.125”) with an added tolerance of ~ +0.02 inches for free rotation, and a larger circle offset by approximately 0.15”. Finally, extrude both circles through the car body. See **Fig. 25** for specifics.

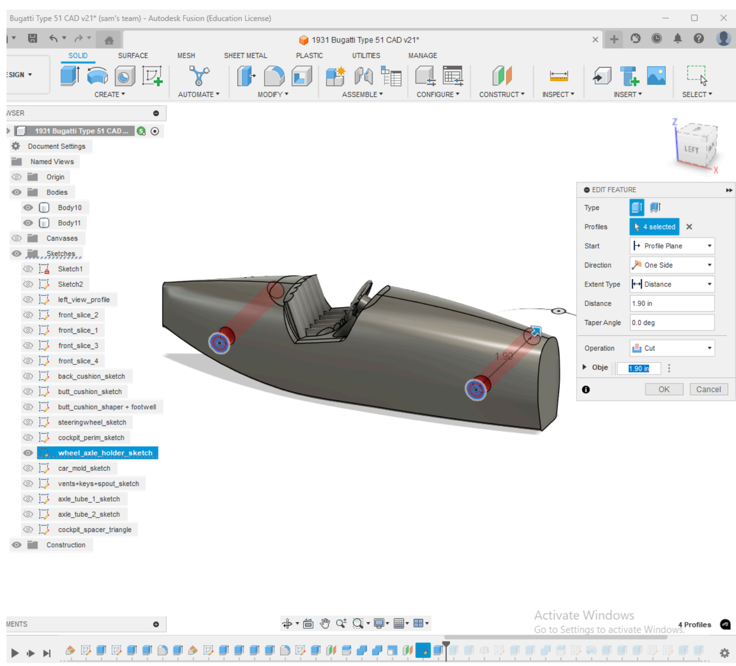


Fig. 25: extrusion of both circles through car body

2. Extrude the outer ring (excluding the 0.125” hole for the axle) through the car body. Make this a new part as opposed to joining it with the fuselage, as this will be 3D printed and the rest of the car will be cast around it. This is shown in **Fig. 26.**

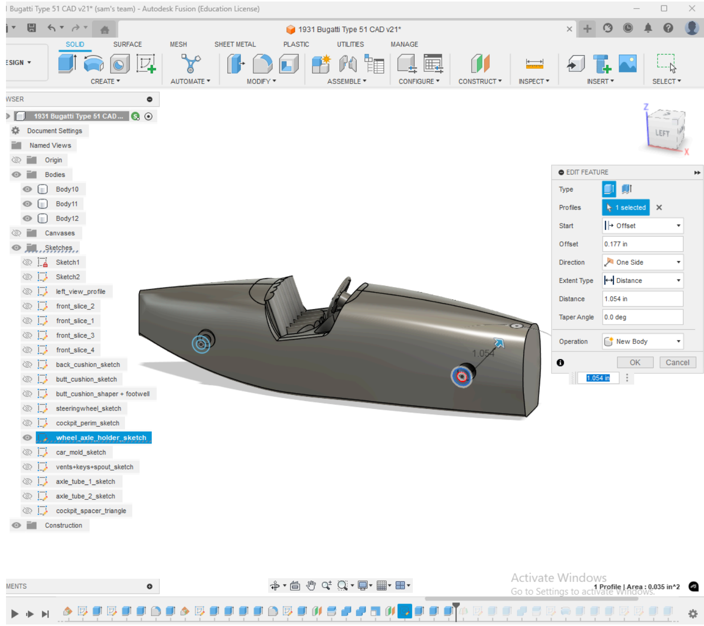


Fig. 26: Extrusion of outer concentric ring to form wheel axle holder

3. Make a rectangular sketch from the midplane of your model. This will form the mold. The dimensions of this should be 6.25” x 2.25”. This will be a standardized size that will make things easier further down the road. Ensure the car is as centered as possible on this sketch, leaving some room around the sides for the addition of features later on. Check **Fig. 27** to see this process.

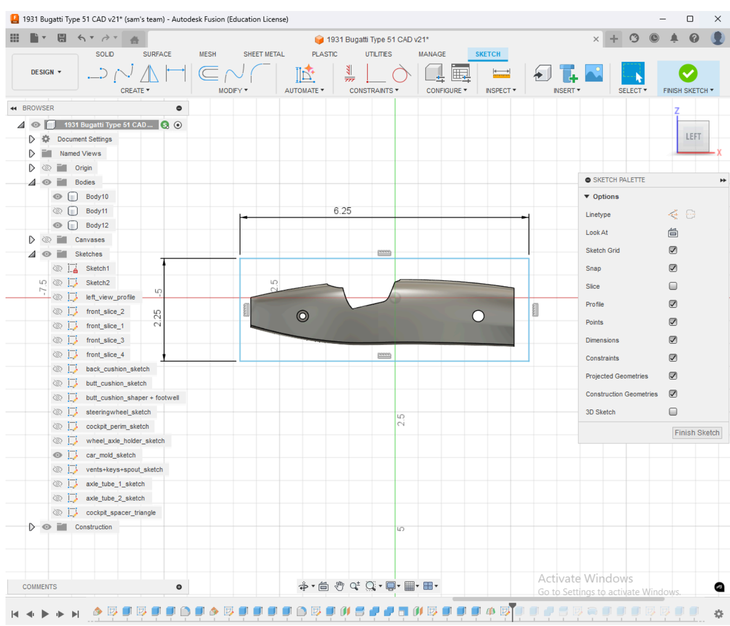


Fig. 27: Rectangular sketch that will later form mold

4. We are very close to making the mold. We need to replace the cockpit 'pod' with a spacer that will hold its place while the silicone is poured. Toggle the cockpit 'pod' off and extrude the bottom of the cockpit cavity upwards. Instead of joining the geometry, make it a new part, so that it can be toggled on and off for later steps, as shown in **Fig. 28.**

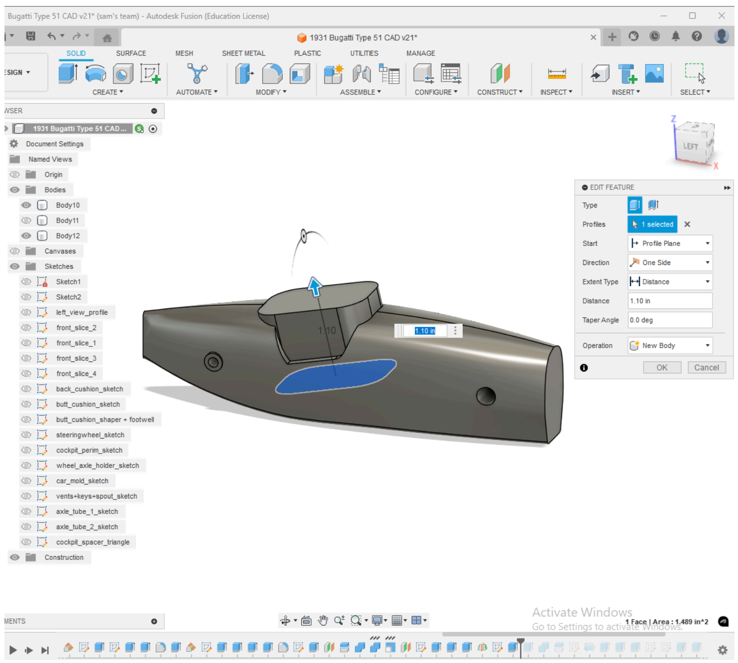


Fig. 28: Extrusion of cockpit 'pod' spacer

5. Extrude the rectangular sketch symmetrically from the center so the box is 2" wide, as shown in **Fig. 29.**

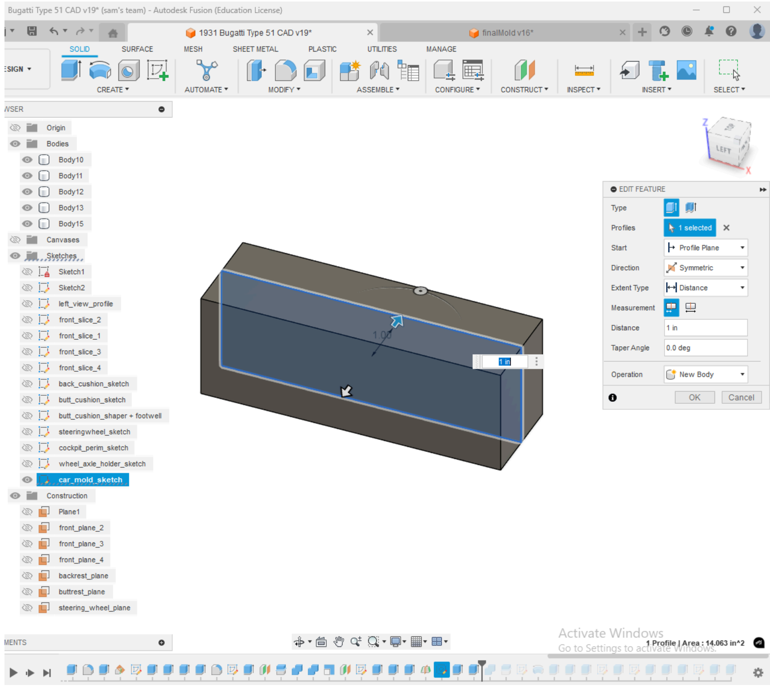


Fig. 29: Symmetrical extrusion of rectangular sketch

6. Use the combine feature selecting the car body, cockpit spacer pod, and wheel axle holders as tool bodies and the rectangular box as the target body. Select cut and ensure that "keep tool bodies" is enabled. This process is highlighted in **Fig. 30.**

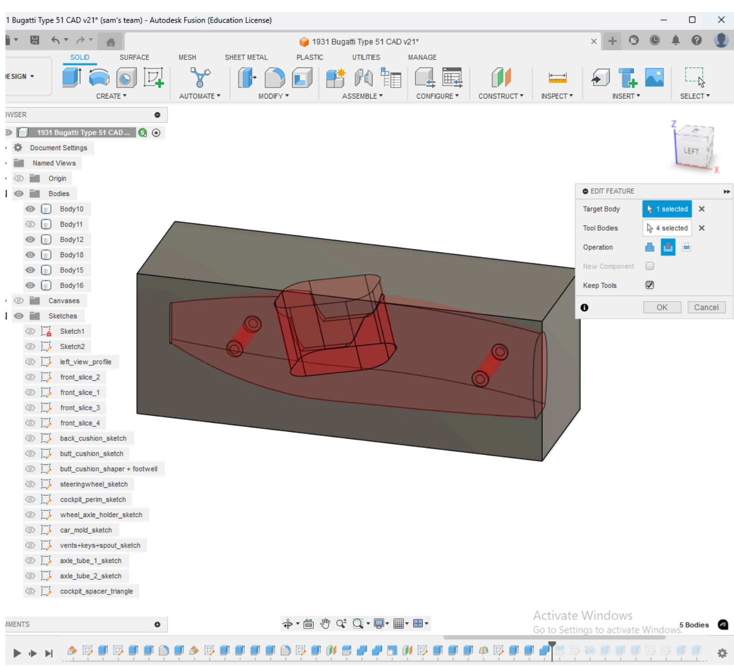


Fig. 30: Using combine feature to create inside of car mold

7. This process hollows out the box, creating the negative space that will be filled with silicone. Next, create a midplane and split the mold in half. Then, on a single sketch, add the keys, spout, and air vents—essential features for proper alignment, material flow, and air escape. Details on these features are provided in the following paragraphs:

Spout: The spout is a funnel-like feature that directs the flow of liquid silicone into the mold. When pouring silicone, gravity controls how the liquid flows and fills the mold. The silicone will naturally seek the lowest areas first, rising to fill the available space. However, the liquid level cannot rise higher than the spout's opening. This is why it is critical to place the spout at the highest point of the mold.

The diameter of the spout should be small to minimize the footprint that it leaves behind. Cutting away a small nib of silicone will leave a less obvious manufacturing footprint than if the spout spans the width of the car. While keeping this in mind, a spout that is too narrow will make filling the mold impossible due to the viscous nature of silicone and surface forces causing the silicone to cling to the narrow walls of the spout.

After an appropriate diameter and placement of the spout is determined, create a sketch of half of the spout, which will then be revolve cut to form the full spout. For this particular application, the largest diameter (top of spout) was 1.32", and the final diameter (bottom of spout) was 0.60", as shown in **Fig. 31.**

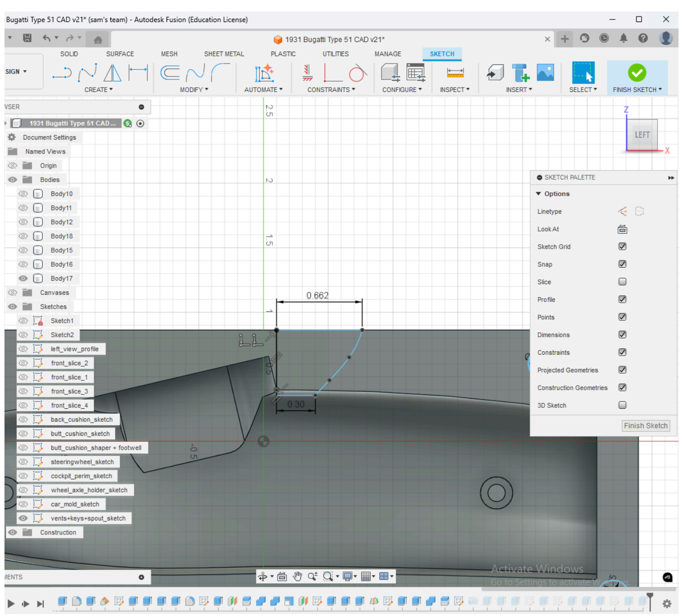


Fig. 31: Example of potential spout sketch

Air vents: As the mold fills with liquid silicone, the air originally within the mold begins to become displaced. While some air may leak through the imperfect seal between the two mold halves, it is not always sufficient, leading to trapped air bubbles. These bubbles can create defects in the final product. In order to mitigate this problem, it is important to add air vents to allow for the air to escape. Bubbles tend to accumulate in sharp angles, where trapped air struggles to escape. To prevent defects, it's essential to place air vents in these regions, ensuring smooth material flow and a complete mold fill.

In order to determine the placement of the air vents, we will use our knowledge and understanding of fluid flow to estimate approximately where the air might get trapped. On the cross section view of the mold, imagine that you are pouring the silicone into the mold and it is filling from the bottom upwards. Visualize where the gas within the mold could get stuck, and cut thin air relief vents into the mold at those points. See **Fig. 32** for a visual explanation.

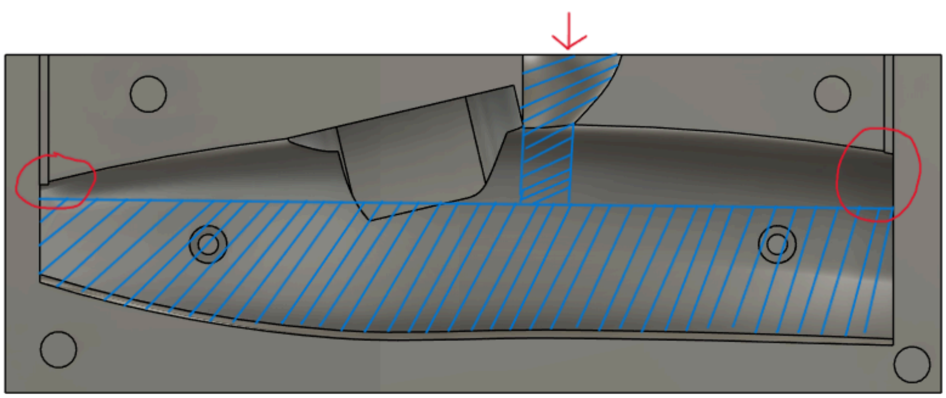


Fig. 32: Cartoon of mold filling with silicone, highlighting air pinch points in red

Keys: These features ensure proper alignment of the two mold halves, allowing their faces to match perfectly when assembled. To achieve this, create four matching circular extrusions and corresponding holes—one in each quadrant of the mold. These alignment keys will help keep the halves properly positioned during the casting process. The finished sketch can be viewed in **Fig. 33.**

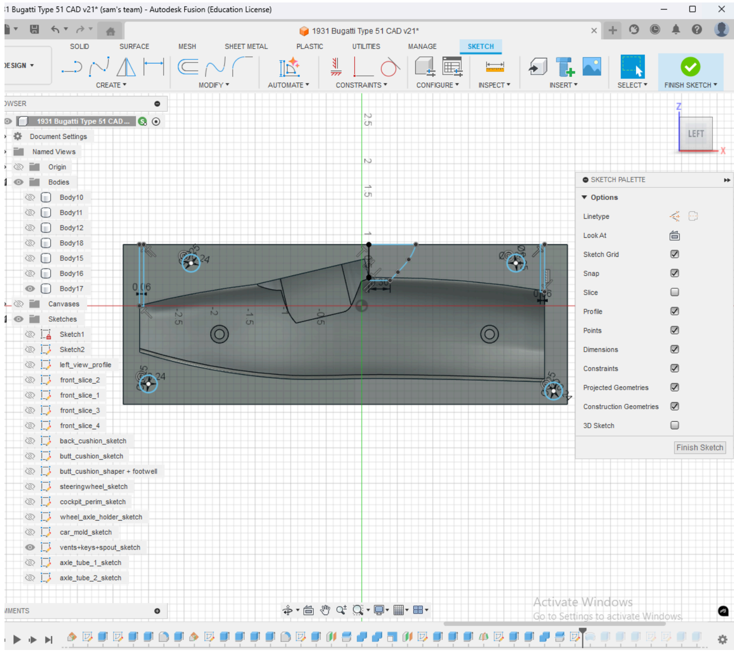


Fig. 33: Finished sketch featuring keys, vents, and spout

8. Extrude the vents symmetrically from the midplane. For the keys, have one half of the mold be ‘male’, and the other half ‘female’. Make the ‘female’ hole diameter larger than the cylinder so that there is tolerance (~0.01 in) due to the nature of 3D printing. Use the revolve cut feature to make the spout. **Fig. 34** shows the ‘male’ mold, and **Fig. 35** shows the ‘female’ mold. You may also consider chamfering the pins for ease of assembly.

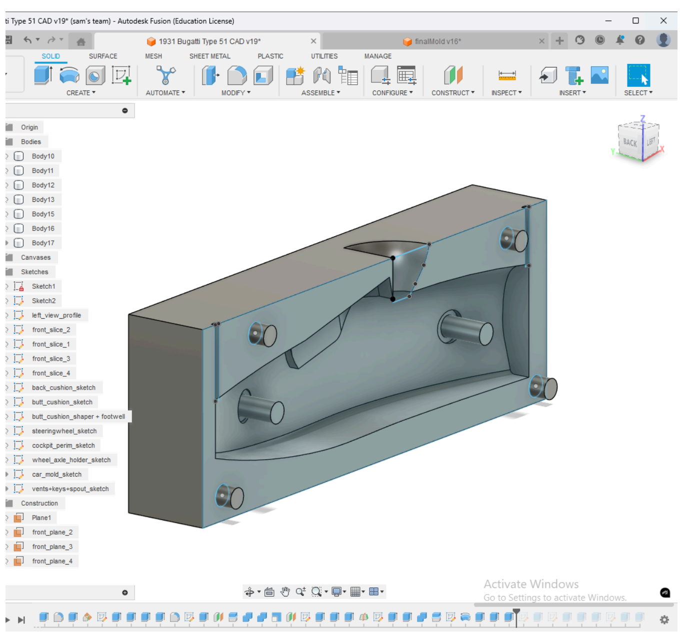


Fig. 34: ‘Male’ half of the mold

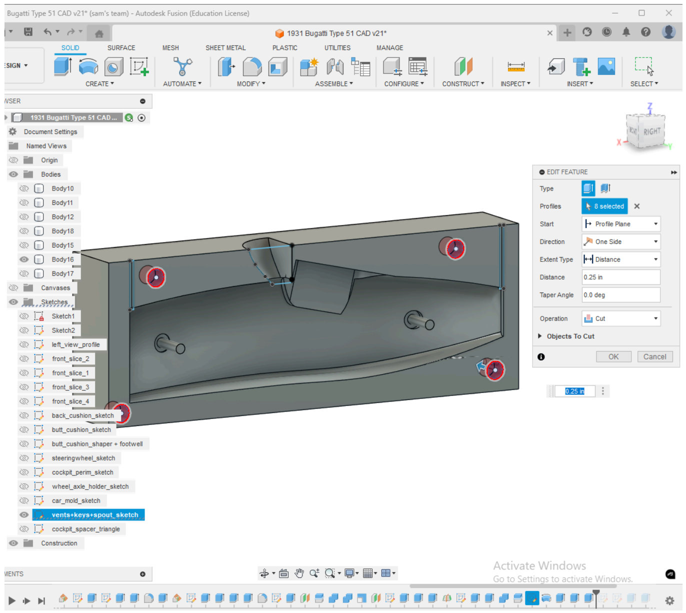


Fig. 35: ‘Female’ half of the mold.

9. Make the axle tube's inner diameter larger by approximately 0.05” to allow them to slide onto the internal mold pins and to fit the diameter of the axle with minimal friction, as shown in **Fig. 36**. This is done because the axle tube was used to create the mold pins, which would create a friction fit in practice - to ensure that the fit is not too tight, a small amount of material should be removed. For the same reason, remove ~ 0.02 inches from the outer diameter to create tolerance for the axle tubes to fit into the mold indents.

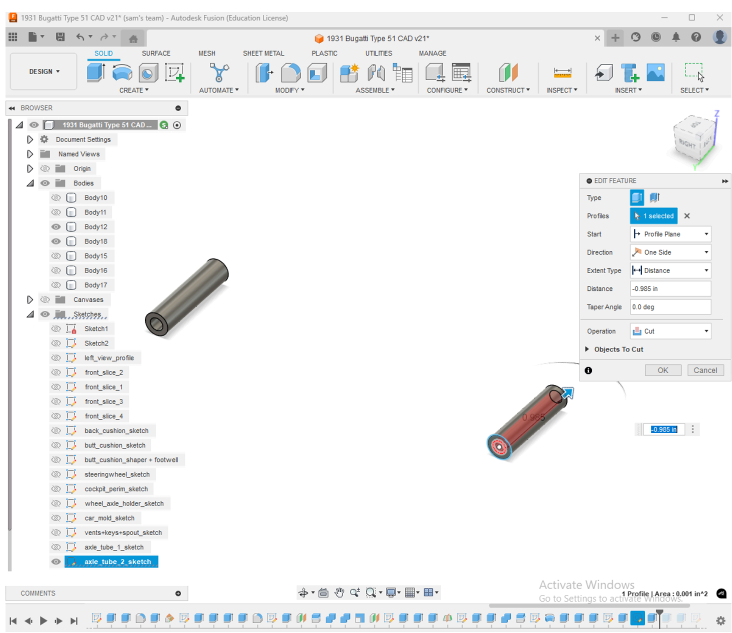


Fig. 36: Decreasing the axle tube inner diameter by approx. 0.05 inches

10. Additionally, shorten the pins that support the wheel axle holder slightly (by about 0.1”, which works well for this application). This helps prevent issues associated with printing long, thin, tall structures. Apply this adjustment to both sides of the mold, as shown in **Fig. 37.**

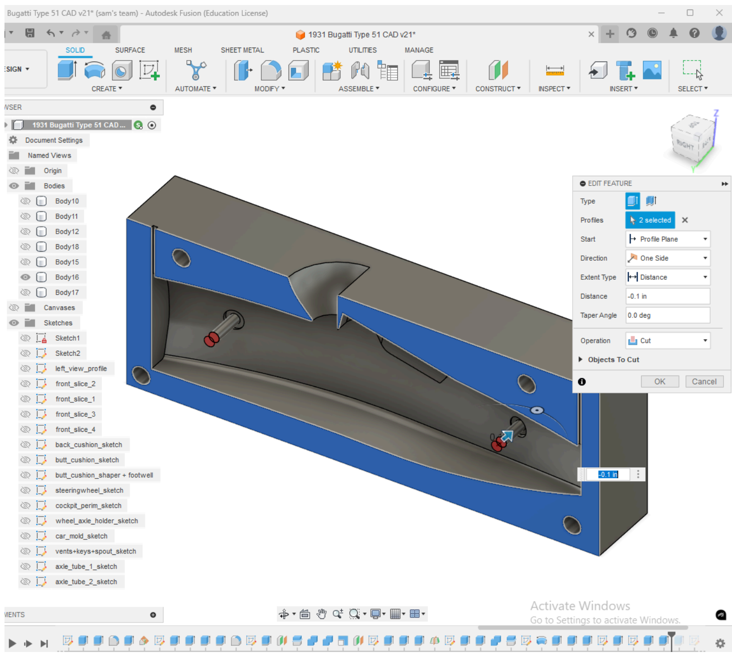


Fig. 37: Shortening of the wheel axle tube support rods

11. In order to secure the cockpit spacer in place while you fill the mold with silicone, make a sketch of a geometric shape on the cockpit spacer's face. A triangle should work nicely. Make sure to make a corresponding recess that is larger (~ 0.01 inch offset) to accommodate the tolerances. Triangle and recess are shown in **Fig. 38** and **39**, respectively.

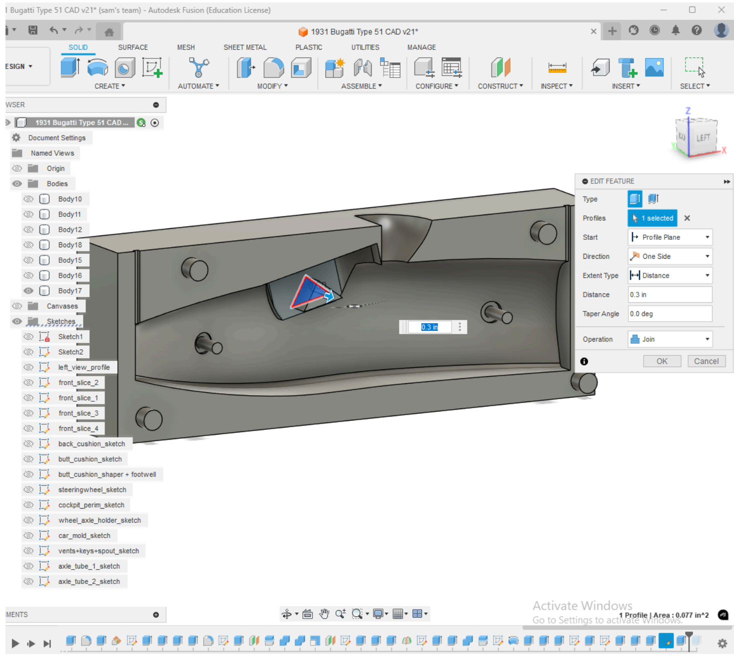


Fig. 38: Creation of triangular extrusion to support cockpit spacer

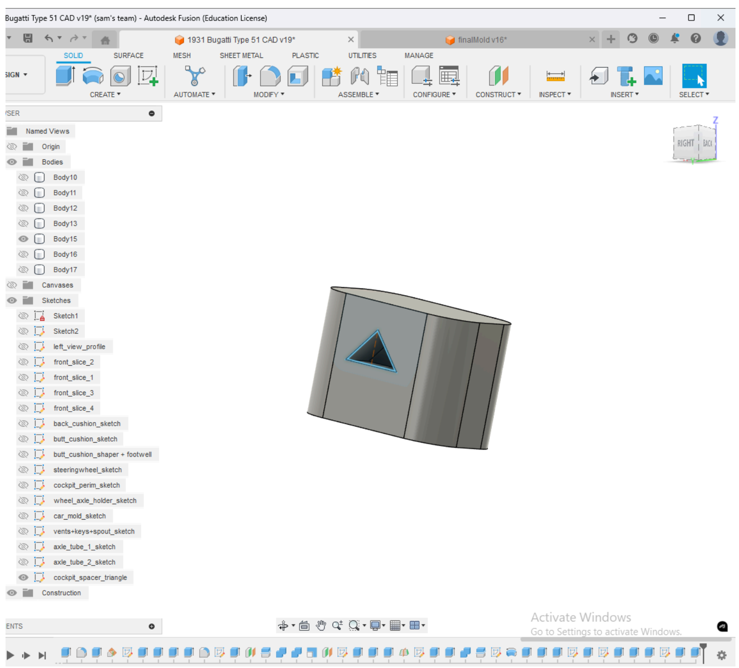
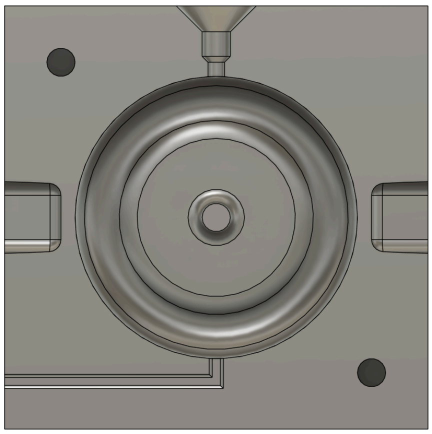


Fig. 39: Triangular recess in cockpit spacer

Wheel Mold Design

Our wheel mold will be used to injection mold the car wheels out of plastic. Different design considerations will need to be made in comparison to the car body mold, as we are dealing with a heated material. This section is less of a step-by-step and more guiding practices, constraints, and considerations. A sample mold can be seen below.



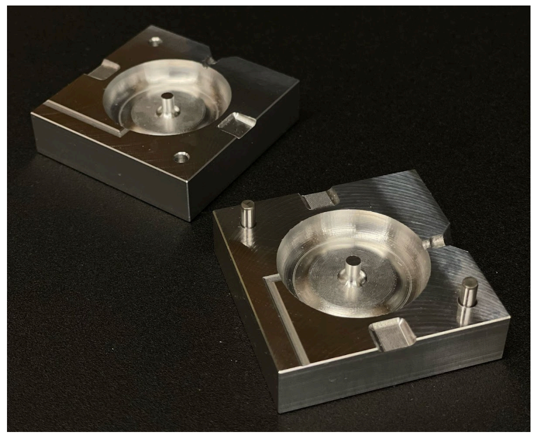


Fig. 40: Sample wheel mold. Left: CAD. Right: machined mold.

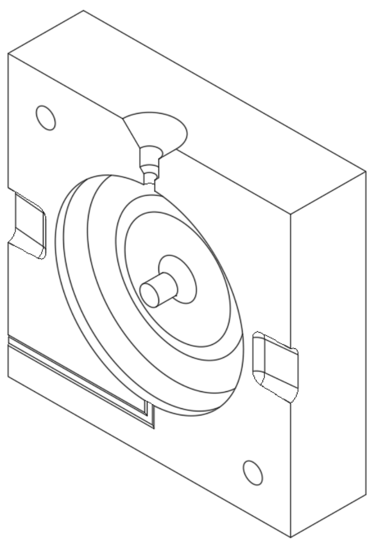


Fig. 41: Sample wheel mold drawing

The following design constraints must be considered:

- The aluminum stock provided will be two pieces sized at 1.875” x 1.875” x 0.500” - one for each mold half.
- The maximum thickness of the wheel must be 0.500” or smaller.
- The maximum wheel diameter must be 1.125” in diameter or smaller.

- All features on the molds must be equal to or larger than a 1/32" radii (note that this is different from the wheel features noted in the wheel design section - this only applies to the additional mold features outside of the cavity for the wheel). The minimum radii is determined by the tools available in the shop, and the smallest 1/16" ball end mill can create a minimum 1/32" radii.
- 0.125" locator pins must be used, as that is the provided stock size.
- The angle of the hole to accept the injection molder nozzle must be 45 degrees.
- The vent must be 0.005" in depth or smaller on each half of the mold.

1. Isolate the CAD model of the wheel in your modeling software. Do not modify or delete the wheel CAD once finalized; it will be used later for injection molding simulations.

2. We need to create the negative space in the mold where your wheel will be made.
    a. Start with two identical square stock blocks that will form the mold halves.
    b. Use the 'combine' feature in Fusion 360
        i. Select the square block as the target body, select the wheel CAD as the tool body, and then use the 'cut' operation to remove material, creating the negative impression of half the wheel in the first mold half. Repeat this process for the other mold half using another square blank.
    c. Save the wheel CAD and tool bodies - they will be needed for injection molding simulations. Note: the mold itself will not be used in this simulation.

3. The video Injection Molding a Spoon - Designing, making, using is a useful resource for understanding the general mold design process. However, instead of using a midplane spline (as shown in the video), you will use the 'combine' feature to cut at the square blanks at the midplane of the wheel.

4. We need to incorporate essential injection molding features into our molds, including an injection nozzle hole, air vents, pry cavities, and alignment features. Descriptions and information are below:

Injection Nozzle Hole: This accommodates the nozzle of the injection molding machine and must be at a 45° taper. This should be placed at the top of your mold and will be opposite to the air vents. Follow the dimensions shown below in **Fig. 42**. Also note that the design of the rest of the spout is not critical and does not need to be the same as is shown below, only the injection nozzle portion must use the given dimensions.

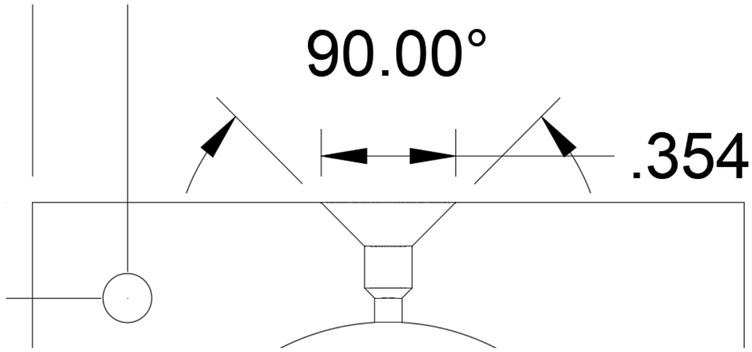


Fig. 42: Dimensions for injection nozzle hole

Air Vents: These allow trapped air to escape as molten plastic fills the mold. They should be on the opposite side of the injection nozzle. These are not dependent on specific dimensions, but must be both large enough for air to escape efficiently and small enough to leave a minimal imprint from any excess plastic that fills it during the injection molding process.

Pry Cavity: These allow you to pry open the mold using flathead screwdrivers, with one each on the left and right sides of the molds. Recommended dimensions can be seen below.

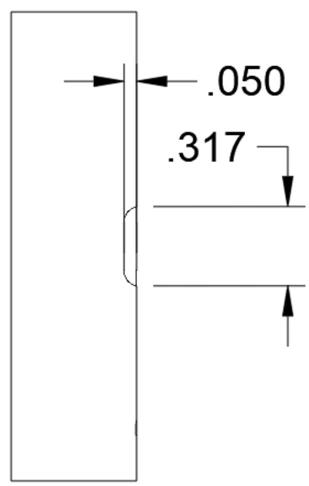


Fig. 42: Dimensions for pry cavities

Alignment Features: These ensure proper alignment of the two mold halves. Unlike the car body mold, this mold will use two 0.125” dowel pins for alignment on opposing diagonal positions. You will need to create holes in both mold halves to fit 0.125” diameter dowel pins using a #30 diameter drill bit tip at a depth of 0.221” with “drill tip through bottom” enabled on bottom height of the drilling operation. This will ensure the holes are a slip fit for a secure hold, allowing them to stay attached to the mold when taking the two halves apart.

Manufacturing

You should now have all of the designs required to start the manufacturing process of your car.

3D Printing

The car body mold, cockpit, and wheel axle holders will be 3D printed. Please submit these print requests as you normally would to the teaching lab as described [here](). If you would like to print elsewhere, you are also free to do so.

Silicone Casting

The car body will be made from [Mold Star 30]() silicone. This is a two-part silicone that hardens when mixed together. Once mixed, it will begin to harden in 45 minutes, and will fully cure in 6 hours.

The casting process will consist of clamping down the body mold, weighing and mixing the two-part silicone, degassing the silicone mixture, pouring the liquid silicone into the mold, and allowing it to cure. This must be done in a particular method to ensure the silicone hardens correctly and that there are minimal air bubbles in the final product. [Sign up times]() will be provided to learn about and perform this process with a teaching lab staff member. Be sure to bring your 3D printed mold, cockpit spacer, and wheel axle holders to your session.

CAM

The wheel molds will require the use of computer aided manufacturing (CAM) and will be made from aluminum stock provided to you. You will utilize Fusion 360 to CAM your toolpaths for machining the mold halves. A step by step tutorial video made by Jorge Casas is provided to instruct you on this. Once your CAM is done, you will set up an appointment with a TA to have your CAM approved for machining. Any advanced setups or questions will be directed to lab staff for approval. Machining of this mold may only begin after CAM has been approved. It is also highly encouraged that you simulate injection molding in Fusion 360 before creating your CAM to ensure your mold design is viable. A great video resource on this can be found here: Will It Fill? -- Inexpensive Mold Flow Analysis in Fusion 360.

Machining

Machining of the wheel molds will be done on the Tormach mills in the teaching lab. You will be provided with pre-squared material and locator pins/keys. Once the CAM has been approved, any student team member trained on these mills can sign up for a machining slot to machine their wheel mold. Students not yet trained in the machine shop will not be trained for this course and must have a trained team member machine the mold.

Injection Molding

The wheels will be formed through injection molding plastic into the molds that you have machined. A manual desktop injection molding machine will be utilized. Sign up times will be provided to learn about this process with a teaching lab staff member, after which you may complete the injection molding of your four wheels at any time during daily operating hours.

Assembly

Once all components have been manufactured, your car can be assembled. Your wheel axle holders have been molded into the car body. Cut down two pieces of axle stock (available in the teaching lab for your use) to fit the width of the car and insert them through the axle holders. Use CA glue to glue your wheels to the ends of the axles. Use CA glue to attach your cockpit to the car body. Your car is now finished - congratulations! You have just applied the manufacturing methods learned in the classroom to real life applications.