Final Design Report

Loco-Motives

Hill Climb Event - MCEN 3025

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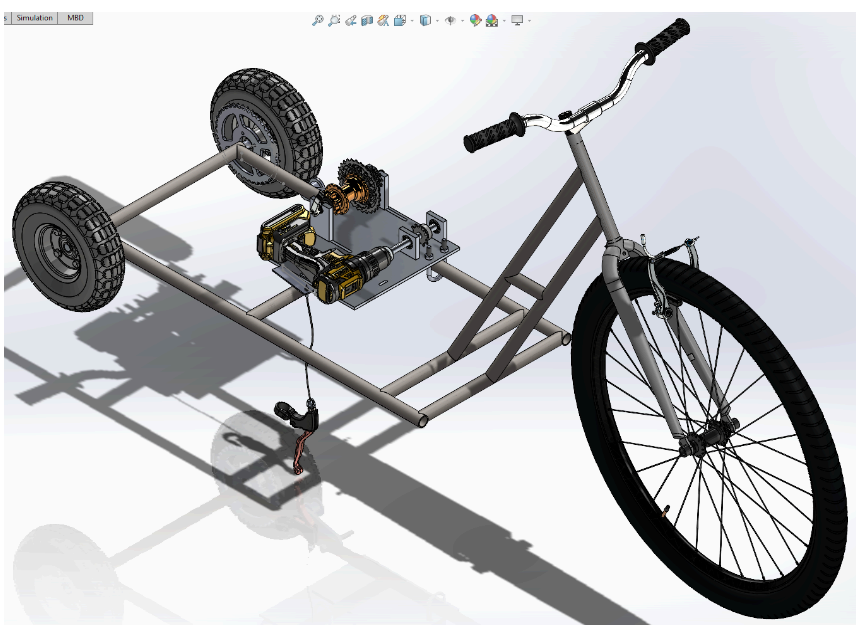
May 8, 2024



Introduction

The purpose of this project is to build a functional vehicle that is powered by an 18V hand held drill while meeting all of the design requirements set at the beginning of the course. Some of these requirements include the total weight of the vehicle must be under fifty pounds, the vehicle must have a free wheel, the vehicle must have at least three wheels, the vehicle must have a braking system, and it must have some sort of trigger actuation. The one monetary requirement of the project was to remain under a two hundred dollar budget. Our manufacturing requirement for this project was to manufacture at least two custom components for our vehicle. Every component that we purchased from fasteners to the steel for our frame had to be factored into this budget. These design requirements forced us to consider every component that we created and ensure that we engineered them so that the final product would fit within them. We were allowed to use one half of a commercial bike frame, either the front fork and wheel assembly or the rear triangle and free wheel assembly. This meant that the rest of our frame would have to be custom designed and manufactured from the metal of our choice purchased online.

Along with the overall design requirements we had to choose a competition to design our bike around, we chose the hill climb. The objective of this competition is to load our bike with as much weight as possible and drive it up a hill. This created a whole new set of design considerations that we now had to build our bike around. Our minimum payload would have to be two hundred and twenty pounds and from there on we can load it with as much weight as we can carry. This motivated us to try and design our bike to have as much torque as possible so that it would be able to carry as heavy a load as possible. The drill that we were given alone would never be able to produce enough torque to carry as much weight as we needed it to to compete in the hill climb. We had to think of every possible way to increase our output torque at the wheels. We had to draw on skills that we have learned throughout our career as engineers at CU to design our bike to find solutions to problems like increasing the torque. We decided to use a dual stage drivetrain to increase our gear ratio and thus increase the torque at the wheels and increase the RPMs at the drill. We had to ensure our frame would be able to withstand the load we apply to it, so we used hand calculations along with digital softwares such as finite element analysis to test where our weakest points would be. We then redesigned our vehicle and ensured that those areas were reinforced and would not cause our bike to fail.

Design

Embarking on the path to engineer a vehicle tailored for the hill climb challenge, we set out to maximize load capacity and torque output. We aimed to create a mechanical combination of strength and reliability, drawing upon the nature of a modified "big wheel" concept and the nimbleness of a large bike front tire coupled with smaller, thicker rear wheels. This section details the journey from our earliest sketches to the final assembly, showcasing the thought process, design evolution, and engineering that fueled our creation.

Conceptualization and Initial Design Thoughts

First, we'll look into the inception of our vehicle's design. Inspired by the classic "big wheel" tricycle, our aim was to craft a machine that could carry substantial weight and traverse steep inclines without forfeiting the essential torque needed for the hill climb competition.

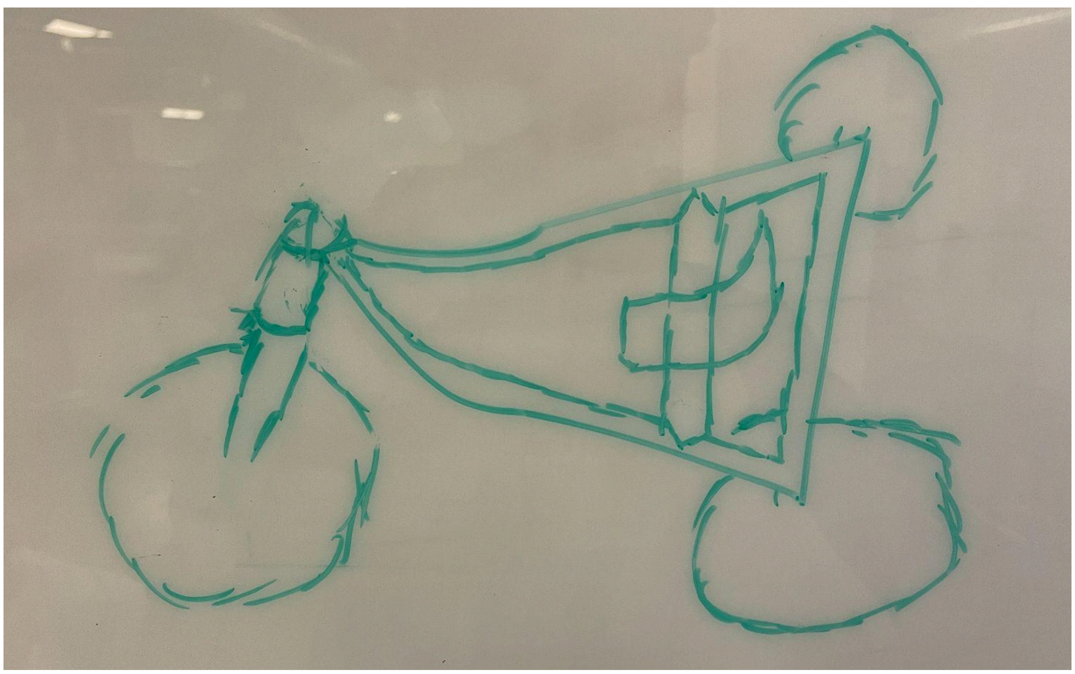


Figure 1. Initial concept sketch of the design, illustrating the modified 'big wheel' configuration for enhanced load capacity and torque optimization.

The larger bike front tire was selected for its superior contact patch and ability to absorb irregularities of the terrain, thus providing stability and control. The rear wheels, being smaller and wider, were designed to distribute weight effectively while allowing for a more compact and powerful drive system. This foundational concept set up a baseline so we could pursue a vehicle fitted for endurance and power.

The Drill Plate Design and Mechanics

Next, the report will focus on the drill plate — a central component of our design. We chose to incorporate a freewheel at the drive shaft, accepting that energy loss was a trade-off we could afford with the nature of the challenger we selected. The non-stop spinning of the chain was a small price to pay for the mechanical simplicity and reliability that would come in handy during the hill climb.

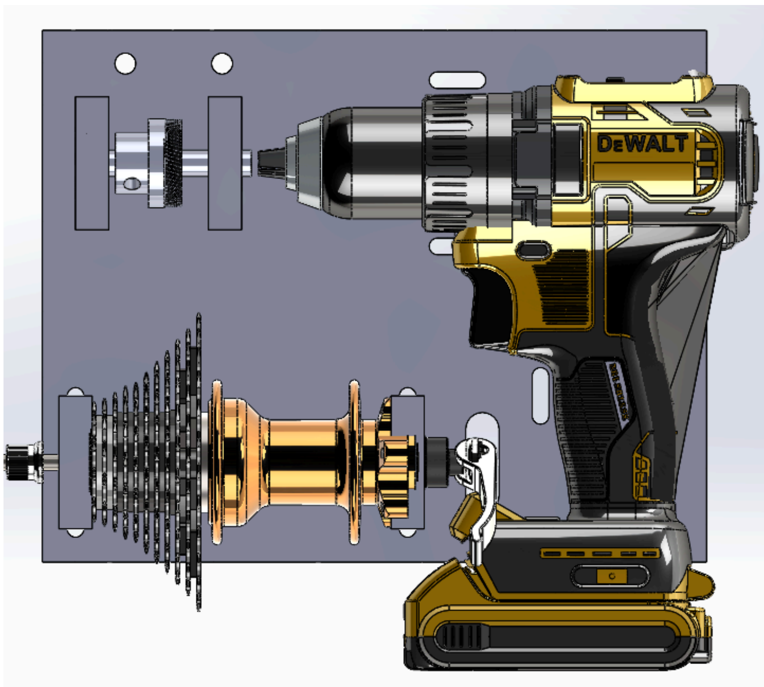


Figure 2. The drill plate with integrated hub, designed to emulate a gearbox and maximize torque output from the drill to the largest ring, and then from the smallest ring to the driven wheel's sprocket.

The addition of a hub onto the drill plate served a dual purpose. Firstly, it mimicked the functionality of a gearbox, crucial for amplifying our torque output where it mattered most. By connecting the drill's sprocket to the largest ring of the hub and then channeling it through to the smallest ring to our rear wheel's sprocket, we achieved a gear reduction that substantially increased torque, giving us the edge necessary for steep inclines.

Final Assembly and Design Synthesis

Finally, the complete assembly of our creation is the culmination of the planning and collaboration that went into every decision and design iteration.

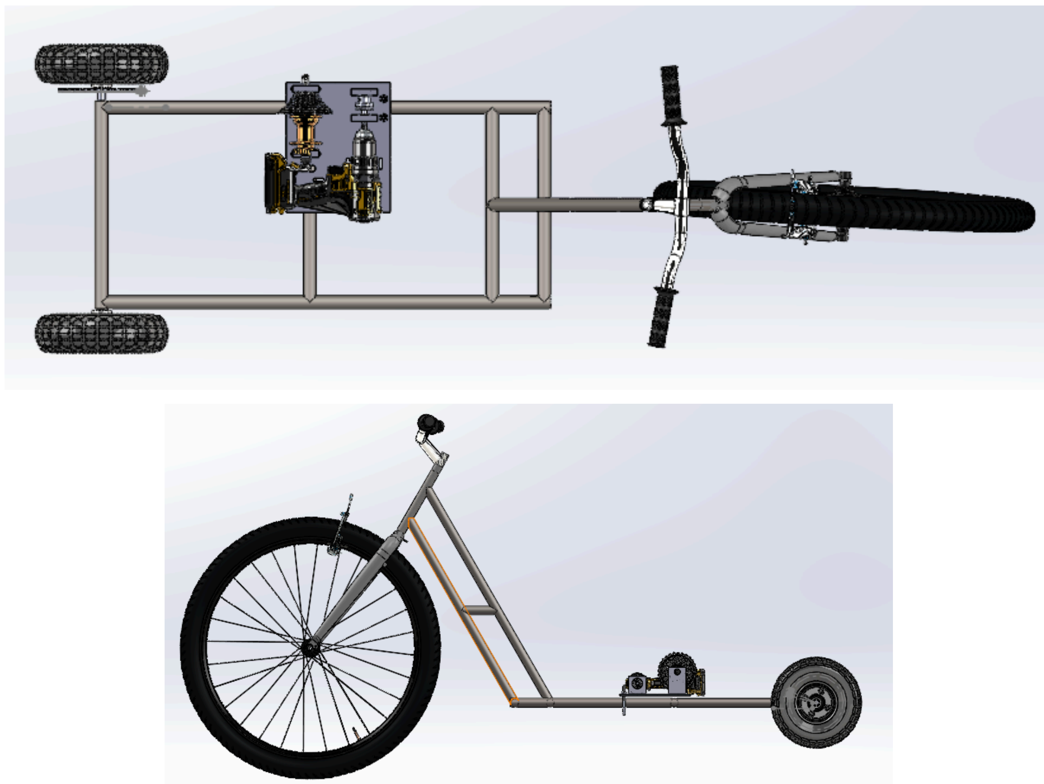


Figure 3 & 4. Comprehensive CAD drawing of the final design, capturing the intricate assembly and engineering precision that brings our vision to life

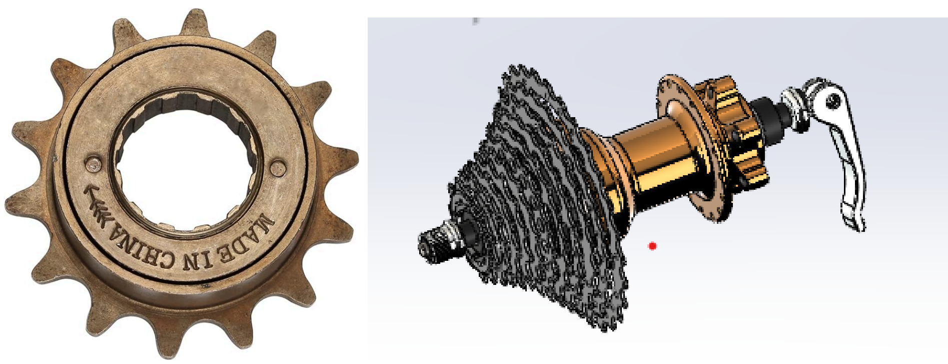
Our assembly is where the individual aspects of our design are collected into a functional whole. In the final assembly, we developed our hand brake system on the front wheel, decided the placement of the drill trigger to be to the handlebar for actuation, and the specialized design of the rear axle. Opting for a fixed axle, we strategically deliver power exclusively to the back left wheel, enhancing traction and removing the need for a differential component. This focused application of power, paired with the selective engagement of our brakes, ensures a balanced vehicle.

Results

We originally expected our hill climb challenge vehicle to weigh 39 pounds, but it actually ended up weighing about 41 pounds, well under the 50-pound maximum. With this slight increase in weight, the results from our project were better than expected. Initially, through FEA calculations we thought the vehicle could carry around 600 pounds, but during actual testing, it impressively managed to pull 947 pounds. This performance, which was almost 60% higher than our original estimate, showed that our design was not only strong but also effective, confirming that our engineering choices were right on track.

Component Analysis

Three of our most critical components are housed on our drill plate, and they are our freewheel sprocket assembly, our second drive train stage, and our extended drill trigger mechanism. The drive train, and specifically the components mounted on the drill plate, are especially important to our success in this challenge because they convert drill power to driving power.



Figures 5 and 6. Our freewheel sprocket (left) and bike cassette used as an intermediate gearset

The freewheel sprocket assembly is a critical component because it allows the drill's rotation to be put into the chain drive and also allows the vehicle to coast when the throttle is not engaged. The assembly is composed of the threaded freewheel sprocket, a keyed freewheel sprocket adapter, the key, and the keyed drive shaft. These components work together to transmit the drill's rotational power from shaft to key to freewheel adapter to the teeth of the freewheel sprocket which mesh with our first chain. The ratcheting mechanism inside the freewheel sprocket allows the drill to push the gear in the drive direction when powered on, but also prevents backdrive of the drill when coasting. We elected to put this component on the drive shaft as opposed to on the driven wheel because of a couple main reasons. The first reason is simplicity. Due to our challenge being hill climb, we aimed to maximize our gear ratio in every aspect of design. Mounting the freewheel sprocket to a larger sprocket attached to our rear wheel while also attaching the wheel to our axle and maintaining proper freedom of motion immediately proved to be a tedious task to accomplish. Instead of overcoming those obstacles which would have required us to manufacture multiple custom components, we decided to mount the freewheel sprocket directly on the drive shaft. We did this knowing that because the drive shaft had the highest RPM, it would also have the lowest torque, and therefore the lowest stress on our adapter components. We also knew that putting the freewheel in this location would mean that our chain would continuously rotate while our vehicle was coasting. We decided this was not a significant problem because in the hill climb challenge, our throttle will be engaged for almost the entirety of the run anyway, minimizing coasting time and with it the time that the chain spins unnecessarily.

The second critical component of our design is the second stage of our transmission. Inspired by the previous transmission design of our TA, Daniel, we sought to maximize our gear ratio while staying within the confines of our allotted drill plate space. The second stage of our transmission is composed of a bike cassette mounted on two additional hub blocks. The first chain connects the freewheel sprocket to the largest sprocket on the cassette, while the second connects the smallest cassette sprocket to our large, driven-wheel-mounted sprocket. This component is critical because it allows us to maximize the torque produced by our driven wheel, increasing the amount of weight our vehicle can haul. Its existence alone boosts our potential to perform well in the hill climb.

Our third critical component, the extended drill trigger mechanism, was especially crucial for us being in the hill climb challenge. The mechanism itself extends the internal wires of the drill that connect the battery, trigger, and drill so that the trigger can be moved out of the drill and attached to the handlebars. This was useful for us in hill climb because we planned on using our team as weight for the challenge, meaning many of us would be standing on the vehicle for extended periods. We knew that if we fell off the vehicle we would be disqualified, so decreasing operating movement was a priority. We knew that reaching down to actuate the drill trigger with four or more members on the vehicle would be not only impractical but detrimental to our performance. Extending the trigger allowed for all team members to pack onto the vehicle while no movement or rearranging was necessary for the throttle to be activated. Wiring the trigger directly also allowed us to avoid less reliable trigger actuation methods (like brake lines) which failed during competition for some teams. When designing this component, we first safely measured the current through the lines we would extend, then chose an acceptable voltage drop percentage, calculated the length of wire needed to reach the handlebars, and then calculated the VDI (voltage drop index), which we referenced to choose the necessary wire gauge to solder on.

Next we will demonstrate the application of failure analysis techniques on the key used to connect the ½” drive shaft and threaded freewheel adapter. The key is 1” long and its face is ⅛” on both sides, making it a square key. It is made from 1015 Steel. We assume that the drill will be transmitting 50% of its 515 in-lb maximum torque, or 257.5 in-lb, to the drive shaft at any given moment. Using the key force equation we can calculate the force applied on the key.

$$F = \frac{2T}{d} = \frac{2(257.5\ in\cdot lb)}{0.5\ in} = 1030\ lb$$

Next, we calculate the normal stress on the key.

$$\sigma_x = \frac{2F}{lh} = \frac{2(1030\ lb)}{(1\ in)(0.125\ in)} = 16480\ psi$$

Then, we calculate the shear stress on the key.

$$\tau_{xy} = \frac{F}{wl} = \frac{1030\ lb}{(0.125\ in)(1\ in)} = 8240\ psi$$

We can then calculate von Mises effective stress at the key’s midpoint where both shear and normal stress act.

$$\sigma' = \sqrt{(\sigma_x)^2 + 3(\tau_{xy})^2} = \sqrt{(16480\ psi)^2 + 3(8240\ psi)^2} = 21801\ psi$$

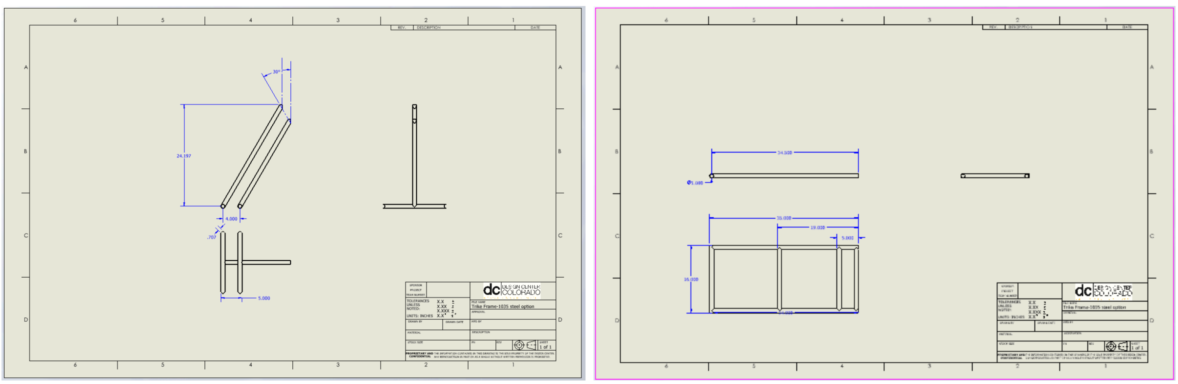
Finally, we can calculate the factor of safety by applying 1015 Steel’s 47 ksi yield strength.

$$N = \frac{\sigma_y}{\sigma'} = \frac{47000\ psi}{21801\ psi} = 2.2$$

Because the factor of safety is greater than one, the key should not fail during normal use.

Fabrication

Starting the fabrication process to fit the guidelines we had many customs parts to fabricate, including building our own custom frame. Beginning with simple sketches we decided to go to a classic “big wheel trike” frame. Taking our drawings to solidworks we were able to build a frame with the correct weight requirements and test strength using FEA analysis. Next was to order the frame members. From Stock Car Steel we ordered 1” OD with a wall thickness of .065”. We chose a Drawn Over Mandrel tubing 1020. DOM is commonly used in manufacturing of race cars and motorcycle frames and easy to weld. We cut the tubing to our member lengths and copped the necessary members for seamless welding spots. We secured each member before adding the weld beads to be certain that the measurements were correct. Below are the drawings of the frame used to fabricate.



Figures 7 and 8. Frame weldment drawings

Along with the frame the drill plate was also custom made for our vehicle. The drill plate was made from 6061 aluminum which we obtained from the machine shop. We started again with simple sketches that would be easy enough to mount on our frame but also room that the chain coming off the plate had a clear path to our drive wheel. Definitely not our biggest component, but the one that took the most time completing, especially the drawing. The plate is most of our drive train. Encompassing the drill, the free sprocket, cassette, and pillow blocks with bearings. Without specific tolerances surely the drive train would fail. After many iterations of drawings we were finally able to submit the final drawing to the machine shop to create. The machine shop used a water jet to fabricate. Below is the drawing for the drill plate.

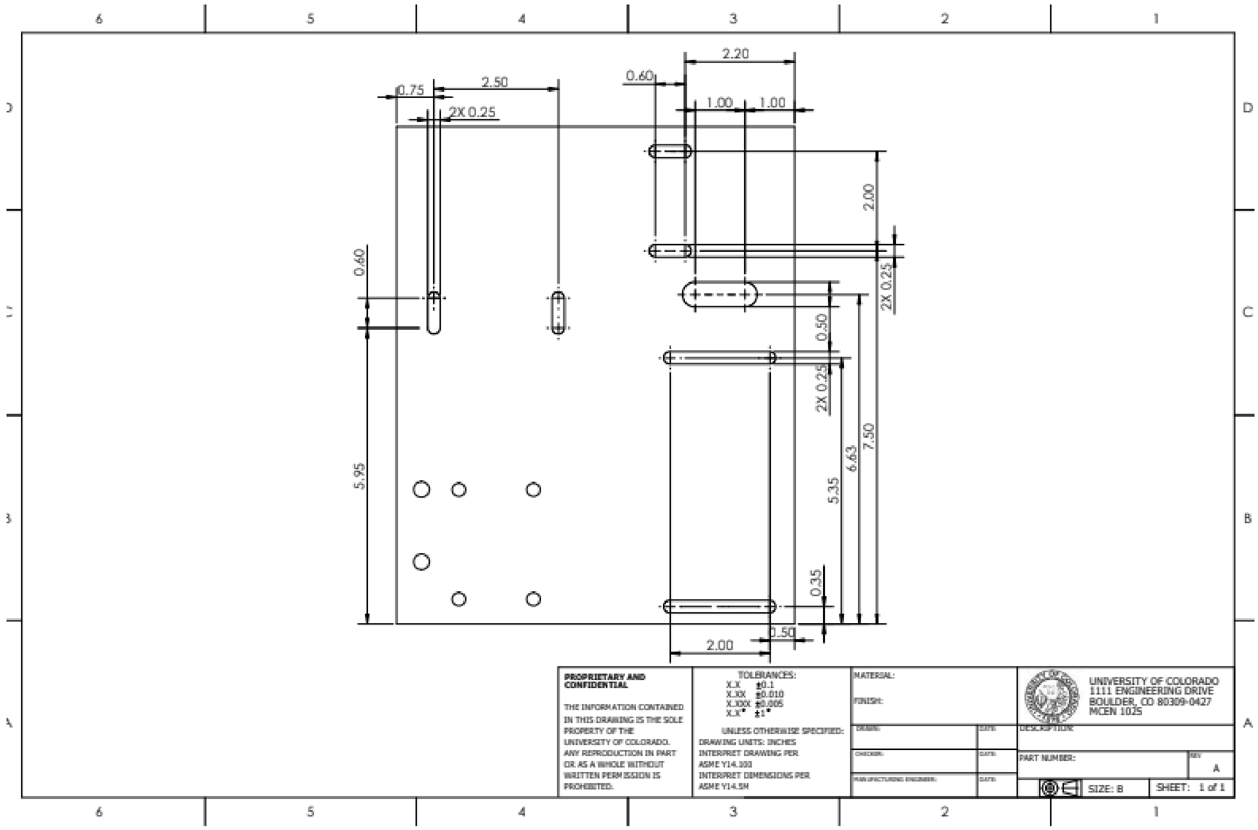


Figure 9. Drill plate manufacturing drawing

Design Iterations and Fabrication

During design and fabrication, our team had large and small scale iterations. Our major iteration was our drivetrain. During design, we iterated multiple designs of how the drivetrain would fulfill the freewheel requirement. Originally, our idea was to have the freewheel connected to the rear axle. Figure 11 however, we also thought of having the freewheel located at the drill shaft. Both ideas were presented to IdeaForge engineers, and they recommended freewheel at the drill shaft. In our original rear-axle freewheel design, we had accounted for welding a sprocket onto the rear-axle, which would be rotating. IdeaForge engineers recommended against this design as welding may cause warping, which may cause failure and unsafe component conditions. While the freewheel at the rear axle could have gone through more iterations to avoid welding, our team found a freewheel properly sized for our drill shaft and compatible with our bike chain. For this reason, we chose the drill shaft freewheel to avoid the over-complicated solution.

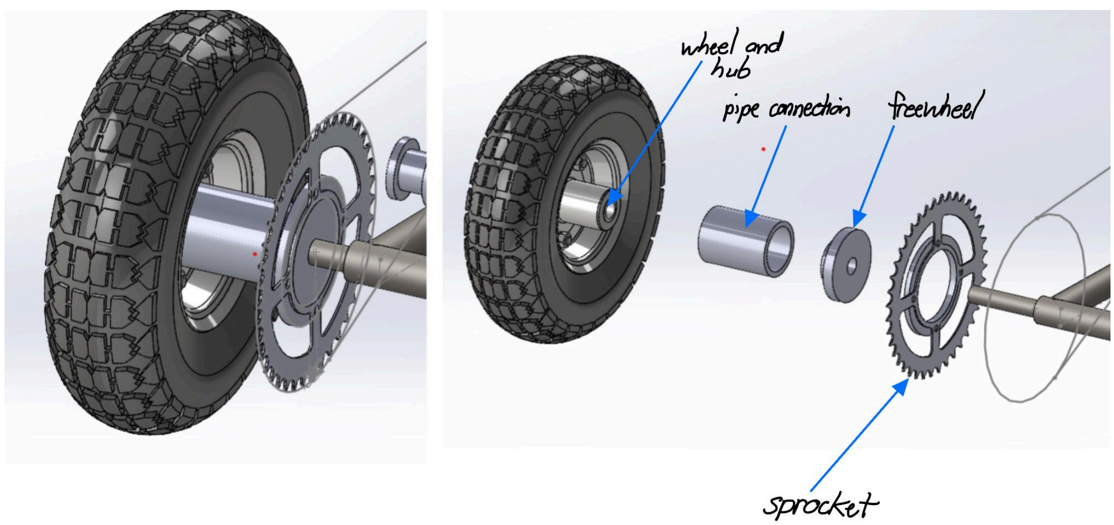


Figure 10: CAD Model of Rear Axle Freewheel Concept

One of the main components that we did not account for were a lack of standing blocks for riders and the placement of the drivetrain in terms of the rider. We realized this during our initial design review with the IdeaForge engineers. Our testing category is hill climb, therefore, they asked how we were going to load any extra weight. Additionally, they pointed out that our drivetrain was in the middle of the bike rider area. We decided to attack these issues after the fabrication of the frame and drivetrain. During the fabrication of our frame, we realized we had a relatively long base, therefore, once our assembly was complete enough to test, we were able to load up to five team members standing on the frame without causing frame or drivetrain damage for a similar amount of time to our race time. For this reason, we decided against a drivetrain cover and weight carriers.

While we ran into a few issues in the design process, our team thrived during the fabrication process. We collectively jumped at opportunities to use the mill, lathe, tube bender, and welder. Each team member took ownership of different parts and manufactured them well.

Our team learned valuable lessons during this project. First, we learned to be as thorough as possible during the design process in order to catch some of the easy mistakes that come up later. Second, we learned what tasks we do and do not enjoy doing. We were all anxious to get to the manufacturing process as it was our strength but we also learned how to improve as process and design engineers. Thirdly, we learned many lessons in design for manufacturing by having multiple iterations of component drawings.

During testing, we mainly had issues with our drivetrain and axle components. Upon initial assembly and testing, we had issues getting the chain line between the single sprocket and the hub proper in order to avoid rubbing on the pillow block closest to the single sprocket. Additionally, during testing, the frame deflected downward enough that caused the chain to become slightly loose. We fixed this with our designed system of shifting the drill plate away from the rear axle and retightening. Although we designed for chain tensioning and utilized our systems, the problem seemed to persist. Fortunately, it was a minor enough problem that our first three race-day runs had no chain issues, however, during our test with a maximum weight, the frame deflected enough downward that the chain became too loose and fell off the largest sprocket.

If we could make large iterations to our project, we would definitely change either the placement of the drivetrain or the overall frame shape in order to maximize rider area and safety. Additionally, we would design placement of weight carriers much earlier in the design process. Lastly, we would have gotten some of the manufacturing done slightly earlier to avoid machine wait time.

Timeline

S.O.C. = Start of Class E.O.C. = End of Class

PM Log - Comp D Bike - LocoMotives - Hill Climb/Tug-a-War

PROJECT DETAILS					
STATUS	**PRIORITY**	**DEADLINE**	**TASK NAME**	**ASSIGNEE**	**DESCRIPTION**
CLASS DELIVERABLES					
Complete	Low	1/29/24	Team Intro	Team	Initial project ideas
Complete	Low	2/8/24	Project Planning Document	Will (Project Manager)	Bulleted list of all tasks, timeline, team member assignments, team roles, chosen race course
Complete	Low	2/12/24	Concept Sketches	Team	Create and submit vehicle concept sketches with explanatory notes, backed by research. Include
Complete	Medium	2/23/24	CAD Complete	Team	
Complete	Low	2/26/24	Informal deisgn review	Team	
Complete	Low	3/3/24	Restructure of CAD	Team	
Complete	High	3/4/24	Design Review	Team	Attend lab sessions for team work, with additional meetings as needed. Presentations will cover vehicle
Complete	Low	3/6/24	Restructure of CAD	Max (CAD Engineer)	
Complete	Low	3/15/24	Design Review Reflection	Will (Project Manager)	
Complete	Medium	4/12/24	Power train complete	Luke (Manufacturing Engineer)	Drill plate complete, back axle complete
Complete	Low	4/15/24	Hardware Demo	Team	Manufacture custom parts, assemble with related components, and demonstrate machining quality and
Complete	Medium	4/17/24	Frame Manufacturing	Luke (Manufacturing Engineer)	
Complete	Medium	4/19/24	Vehicle Complete	Team	Frame,Power train integation, seating
Complete	Low	4/23/24	Vehicle testing/tweaking	Team	
Complete	High	4/30/24	Run off	Team	Vehicles near Idea Forge to be judged pre-race for mechanical design, race happens rain or shine.
In Progress	High	5/8/24	Final Report	Will (Project Manager)	Final report outlines design process, analysis, testing, failures, and future recommendations.
In Progress	Low	5/9/24	Peer Review	Team	

Figure 11. High-level project timeline

We were able to keep most of the dates that were set. Along the design process was where we were set back a few days. The drive train design took some time to finalize as well as puzzling out how to mount the back axle to frame. However, after establishing how we would accomplish those tasks we were able to order the components to start manufacturing without significant problems.

Bill of Materials and Costs

Part #	Component	For Subassembly	Relevant Measurement(s)	Unit Price	Quantity	Total Price
SCS-DOM	Tubing	Frame	1035 steel 1" w/ .065 Wall Thickness	$0.46	194”	$90.00
285760894195	Freewheel Sprocket	Drill Plate	12T	$9.99	1	$9.99
	Gear at rear wheel	Rear Axle	48T	$24.95	1	$24.95
	Drill Plate	Drill Plate		Provided		$0.00
	Bike Chain	Drill Plate		Salvaged	2	$0.00
	Fork	Front Wheel		Salvaged	1	$0.00
	Handle Bar	Front Wheel		Salvaged	1	$0.00
	Brake line	Front Wheel		Salvaged	1	$0.00
	Brake Calipers	Front Wheel		Salvaged	1	$0.00
	Bike Wheel 18in	Front Wheel		Salvaged	1	$0.00
30900	Pneumatic Tire	Rear Axle		$8.99	2	$17.98
	Seat	Frame		salvaged	1	$0.00
U20300.062.3600	Rear Axle	Rear Axle	36" 5/8in Steel rod	$29.99	1	$12.00
	Bike cassette+hub	Drill Plate		Salvaged	1	$0.00
UBH1372	U-Bolts	Drill Plate		$2.11	1	$4.28
91253A533	Screws	Pillow Blocks		$10.00	1	$10.00
5972K101	Bearings	Pillow Blocks		$2.12	4	$8.48
	Master links	Chain		$0.40	20	$8.00
	Freewheel Adapter	Drill Plate	1/2" ID, 1.375"x24TPI RH	$11.25	1	$11.25
Total -->						$196.93

Figure 12. Bill of Materials

Our initial budget was mapped out based on the parts that we thought we were going to purchase and use on our vehicle. Over the course of the semester our vehicle was redesigned many times and that meant that the parts we were planning on purchasing also had to change. We knew that the bulk of our budget was going to be spent on steel tubing to build our frame and we did not want to go with a cheap option and have our frame be a point of failure. We estimated that cost to be around one hundred dollars so we only had one hundred more to purchase the rest of our components. We underestimated the cost of a bicycle chainring which ended up costing us around twenty five dollars. We also did not consider the cost of shipping at the beginning of our project which ended up costing us around fifty extra dollars on top of our final budget. However we were able to salvage many of our parts which cut down on our costs. Besides a few parts that we ordered that were unable to be used due to design problems we stayed within our budget in the end.

Advice

General Advice

- Start meeting up with your group and planning out your design as soon as possible. This will allow you to order steel and other materials before other teams and get into the machine shop before it gets busy later in the semester.
- Having a well organized schedule at the beginning of the semester with prioritized tasks will help you stay on track. This will also help you to make adjustments to your design if anything goes wrong or changes since the high priority tasks will be done first.
- Run your ideas by the TAs and the guys in the machine shop before ordering parts so that you avoid spending money on materials that you can't use.
- Finish your drill plate and pillow block design first, these are the two most essential parts of the bike and the pillow blocks take a few hours to manufacture.
- Save all of your CAD models, drawings and screenshots for later use in the project report and personal portfolios.

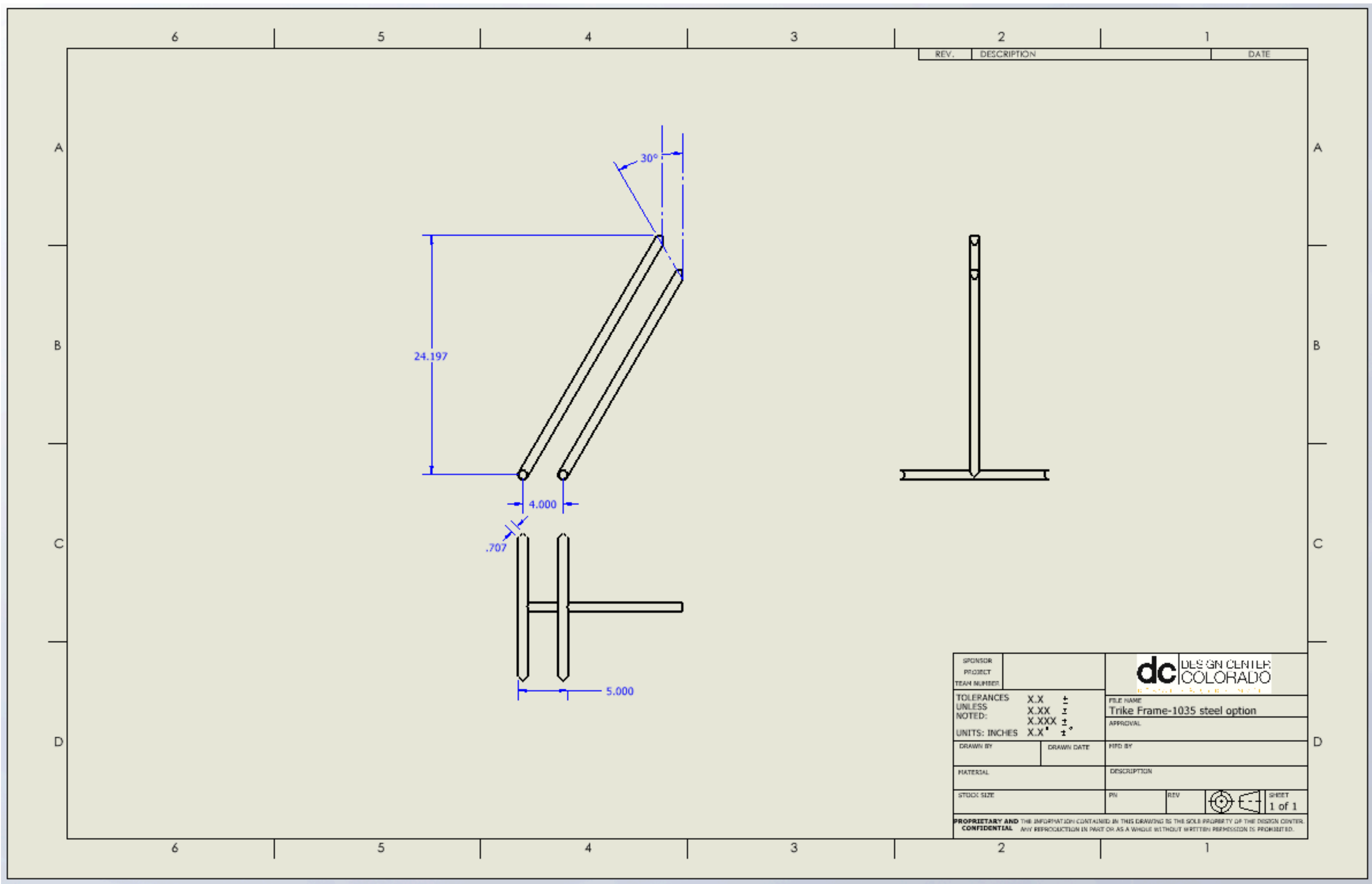
Hill-Climb-Focused

- Don't worry so much about frame strength but about how much space on the frame there is for people to stand/weights to sit.
- If you are having trouble figuring out your freewheel system you can do the freewheel at the drill using a freewheel sprocket and a threaded freewheel sprocket adapter
- Do a two-stage transmission, this will allow you to increase your gear ratio without having to use oversized chainrings.
- Design the vehicle so that most of the weight will be distributed to the back wheels or your driven wheel to gain the most traction.
- Pull the trigger out of your drill, it's awesome and a simple throttle solution
- Make sure that your chain tensioning system is sound, without proper chain tensioning the bike will not run.

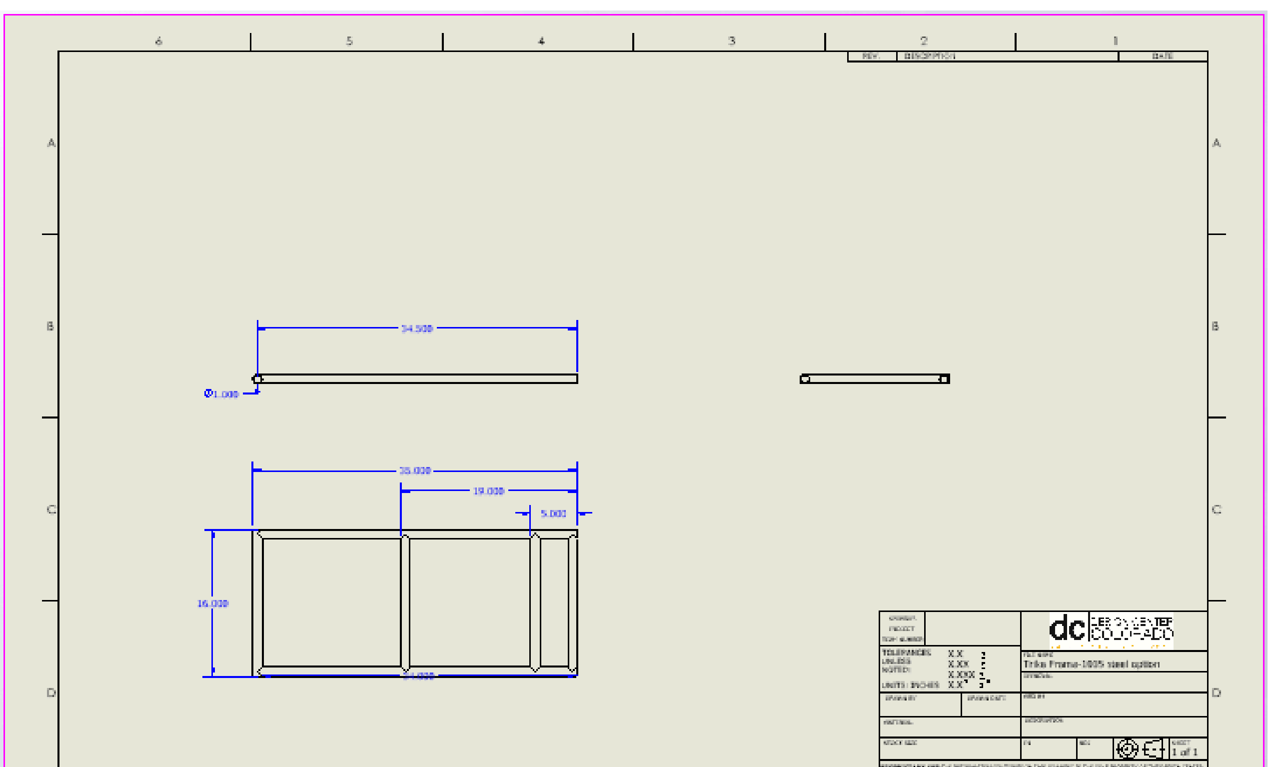
Most of the advice on this list will probably be followed by only a few teams, but we think that most teams will heed the advice to focus on drill plate and pillow blocks first and to start meeting with their teams early. Probably the most important advice on the list is to keep a well organized schedule and order steel early, but doing this depends on the whole group's willingness to put in significant effort early in the semester.

Appendix of Drawings

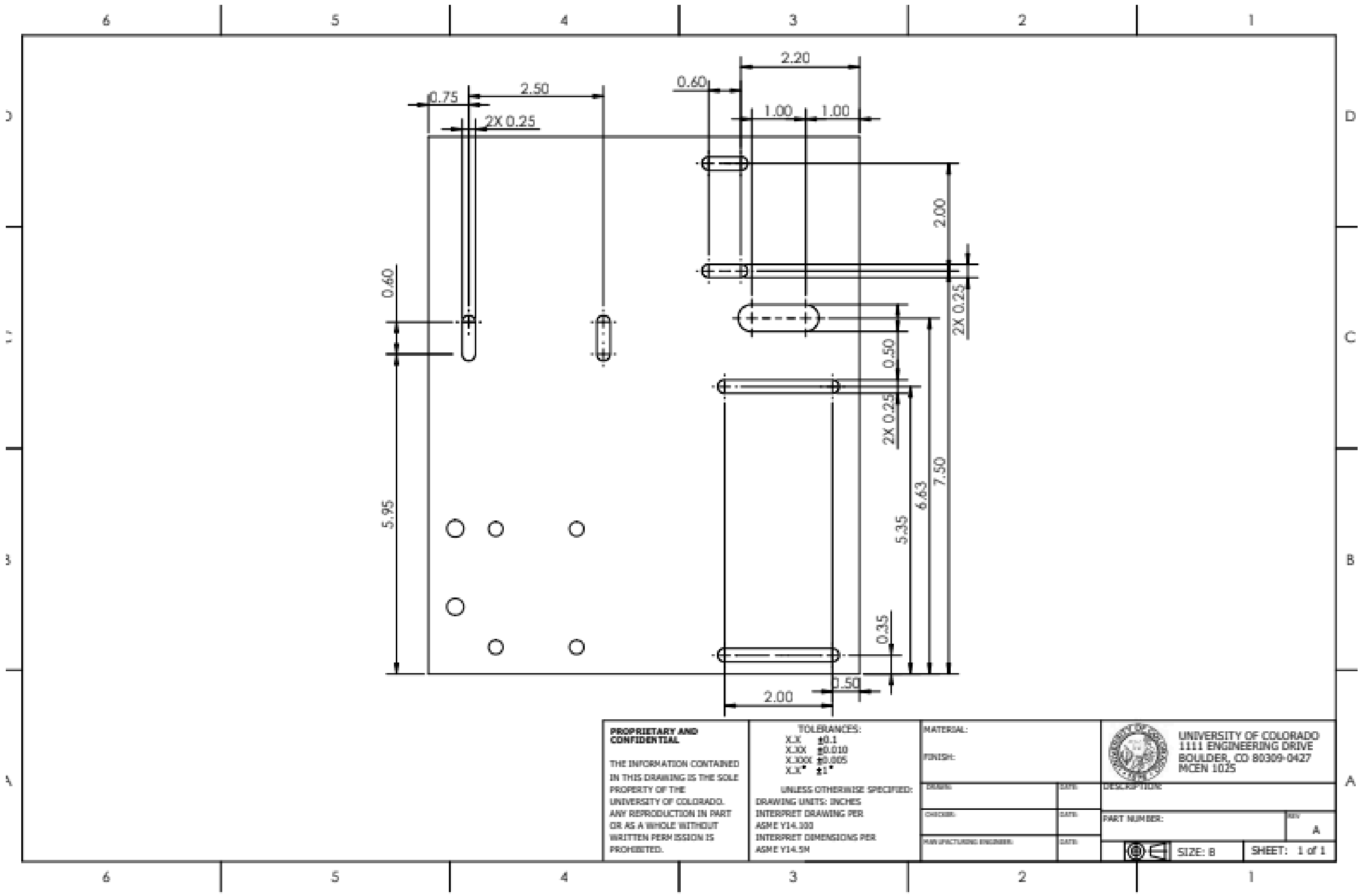
Include an exploded view of your vehicle.
- Include engineering drawings for all parts. Use the ones you presented to the machine shop if that is easiest.



Forward frame assembly weldments (Figure 7).



Above, the main frame assembly weldments (Figure 8).



Final, machine-shop approved drill plate drawing (Figure 9).