2021 Bearcat Baja Steering

A Baccalaureate thesis submitted to the
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Bachelor of Science

in Mechanical Engineering Technology

by

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Before I begin, I want to thank the people who helped me make it to where I am today. This thank you is to my parents who have been extremely supportive of me throughout my college career, and I would not have been able to make it through college without their constant support along the way. Thank you Mom and Dad for everything.

I also want to give a big thank you to everyone who helped to make this project possible. These people are Dave Conrad, Nick Plataniotis, Brian Yockey, and Jordon Graff, for giving advice and a helping hand during the fabrication process. I also want to thank Professor Allen Arthur for his guidance and input on the project to help make it the best it can be. And last but not least, to my team for their support and help throughout the project. These people are Zachary Fenger, Nathan Winninger, and Henry Hemmelgarn.

ABSTRACT

SAE Baja is a collegiate design challenge for university students to design a 4-wheel, all-terrain, single-seat off-road vehicle from conception to reality. Once completed, the car will compete against over a hundred other universities with their own vehicles. This collegiate design series is just one of many projects available to Mechanical Engineering Technology students at the university.

The students each work together as a team on the Baja vehicle, with each student taking on the design and fabrication of one aspect of the vehicle, such as steering. This aspect was my chosen portion of the 2021 Baja car.

This report discusses in detail the background research done, design challenges for the 2021 car, fabrication, and testing. Work on the vehicle began in the Fall 2020 semester in Senior Design I. It was during this time that background research was made, and customer surveys were taken to receive feedback on the desired features of the car. Then during Senior Design II concept models were made and finished and an FEA analysis of various components were done. Fabrication of the car began in Spring 2021 in Senior Design III, coming to an end with the completion of the steering assembly in early April 2021. While there were some bumps along the way, the project was able to be completed on time and under budget, with almost all of my design goals being achieved.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

Each year students from around the world design and build single seat all-terrain vehicles as part of the SAE BAJA competition. SAE describes the goal of the challenge on their website: "engineering students are tasked with designing and building a single-seat, all-terrain sporting vehicle that is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle that serves a recreational user market." (1) The vehicles are designed under the premise that they are for a "customer" - a fictitious utility vehicle supplier that will produce 4,000 units annually. Pleasing a "customer", keeping costs low and designing with a known production quantity is part of the challenge of this competition.

RESEARCH

BACKGROUND AND SCOPE OF THE PROBLEM

SAE updates the rules and regulations of the competition yearly to prevent teams from submitting the same vehicle multiple years in a row. Historically, the SAE specified the design of a two-wheel drive vehicle, but this year SAE is now requiring a four-wheel drive vehicle. SAE also has historically changed their rules regarding components such as the frame and fuel tanks to improve safety. In 2018 teams needed to switch the fuel tanks and splash pan configurations from past years to meet SAE's new safety guidelines. (2) Along with SAE's required changes, each year teams have different points of emphasis that they consider when designing their vehicle with a goal to improve in specific areas compared to previous years. In 2018 the team from UC designed the frame prioritizing the improvement of driver ergonomics, maintenance access and weight reduction from past years. Other components experienced less progression such as steering. In 2017 the UC team's goal for steering was for a design with effective and precise maneuverability that will meet SAE criteria. (3) This is an example of a goal that carries over from year to year. The competition rules and regulations change yearly but the same general challenge remains the same.

Impact of the Problem

The groups most impacted by this project are the end user and the "company" we are designing the vehicle for. The vehicle must be designed with a "customer" in mind that wants to produce 4,000 units annually. This impacts how our team will evaluate costs associated with the project. Since this design would then be sold by the "customer" to an end user, the comfort and performance need to be considered. As an off-road vehicle the safety of the end-user is the highest priority by both SAE and the design team.

Our team will also take our design to competition where the vehicle be put through a series of tests. Our team members will be operating the vehicle and will be impacted by the ergonomics, safety, and performance as well.

Magnitude of the Problem

The magnitude of the problem is the challenge to build an economical, safe, and durable vehicle. With 4,000 units expected annually, material and manufacturing costs must be kept to a minimum. Safety is also a significant concern because of the extreme terrain, and accidents like rollovers might happen, so the driver must be protected. There are also the engineering challenges such as acceleration, handling, and performance on rugged and off-road terrain. (1)

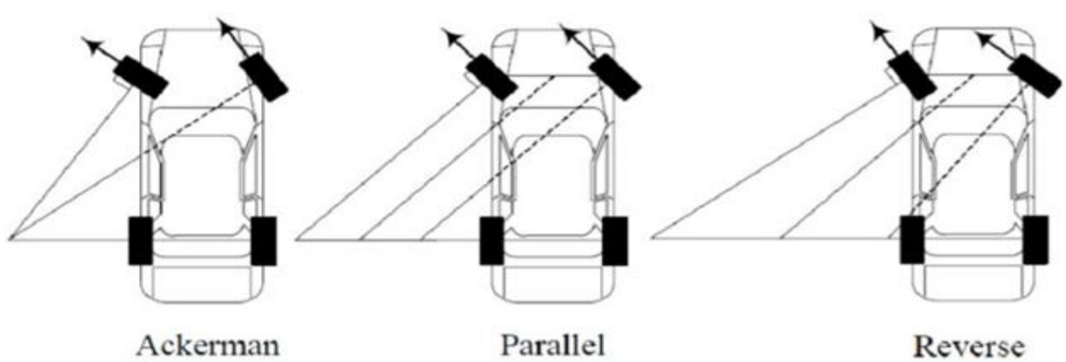
How the Problem is Currently Being Addressed

The latest University of Cincinnati (UC) Baja design was done in 2020. The off-road capability, safety, and comfortability played a large role in the design of the 2020 UC Baja design. To address these 3 areas, the 2020 UC Baja team chose the parallel method of steering, 4-wheel drive drivetrain, and a frame to support the front differential while providing the end user with enough leg room.

The 2020 UC Baja design looked at how to address the off-road capability, safety, and comfortability through the following ways. The parallel method of steering was used in the 2020 UC Baja design. (4) The parallel method is well balanced and will prove to be highly effective in extreme terrain. 4-wheel drive was an added feature that the 2020 UC Baja team added to the design from previous years. (4) The 4-wheel drive feature will greatly improve traction and the friction force that the car will be able to provide on the driving surfaces thus allowing significantly better off-road capabilities. The 2020 UC Baja design included spacing and brackets to hold the additional differential in the front of the vehicle. (4) This design will allow the end user the proper safety and comfortability when driving with the 4-wheel drive feature. The design from 2020 will be a starting point for our team and we will build off what was started in 2020.

CURRENT STATE OF THE ART

There are three different types of steering geometry. These steering geometries are Ackerman, Parallel, and Reverse Ackerman. When a car goes through a turn, the wheel on the inside of the turn travels a shorter distance than the wheel on the outside of the turn. To compensate, the inside wheel must be angled into the turn further than the outside wheel, so that the wheels are tangential to the center of the turn. This condition is known as Ackerman, which is demonstrated in the image below.



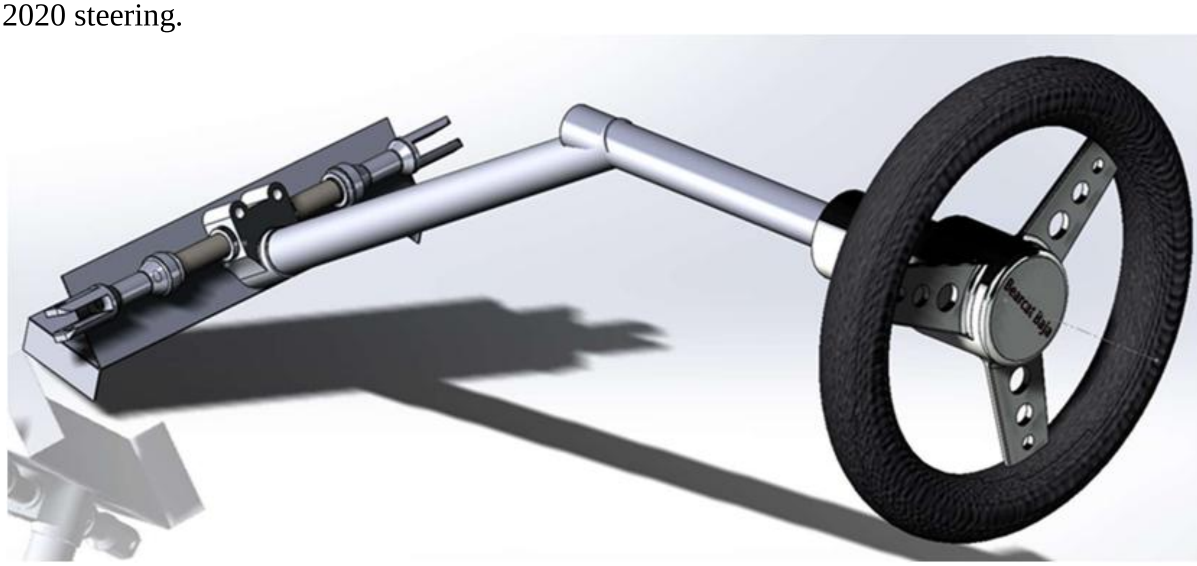
The other condition is parallel, where the wheels stay parallel to each other throughout the turn. The other is Reverse Ackerman, which is the opposite of Ackerman, so the inside wheel is angled less than the outside wheel. For an off-road vehicle like the Baja car that will be going through low speed maneuvering, Ackerman steering will be the best choice as it prevents the tires from slipping sideways in a turn, since the wheels will ideally be aligned with the center of the turn.

Additional research was done on previous cars built by the Baja team. The Baja team has tried several different designs for their steering system over the years. The designs for the 2013, 2017, and 2020 were examined to better understand previous designs and the advantages and disadvantages with each design.

2013 Baja:
The 2013 Baja used a 6.4:1 steering ratio. This allowed for more precise movement of the wheels and better performance on maneuverability exercises, but it also has the drawback of requiring additional effort when turning the steering wheel. Using a lower steering ratio helps to cut costs, but in the end, the team recommends using a higher steering ratio, between 8.0:1 and 10.0:1. This particular steering design also required the use of a rack spacer, as the selected steering rack was not wide enough.

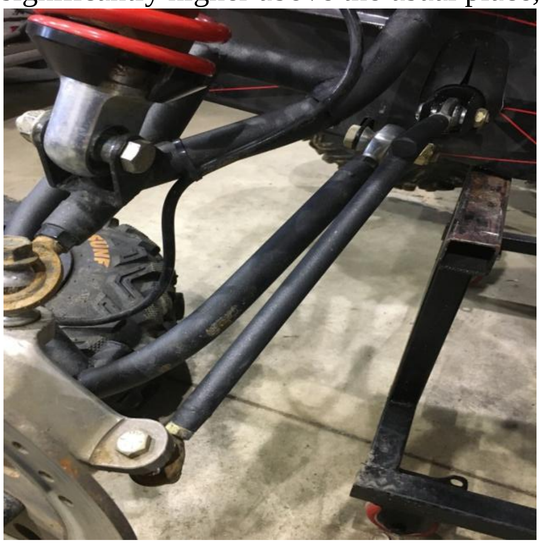
2017 Baja:
For the 2017 Baja, the team also chose a rack and pinion system and a steering ratio of 6.4:1. Another design change was increasing the steering angle, which allows for evacuation of the Baja vehicle much easier. The team also reduced the traditional two-U joint design that allowed for more play to a single U-joint design, which allows increased control and lifespan. The 6.4:1 ratio, while cheaper, also requires the driver to exert more force on the steering wheel, and also allows for more steering rotation.

2020 Baja:
The 2020 car was designed and partially constructed, which construction was halted in early 2020 due to the COVID-19 pandemic. It was then up to the 2021 team that would evaluate and finish the 2020 vehicle. The 2020 designer Bradley Bendel left only a partial 3D model with a planned steering ratio of 12:1 with parallel steering. Below is the initial 3D model for 2020 steering.



A significant change required for the 2020 vehicle is the requirement of a 4-wheel drive system. Additionally, due to the front suspension the location of the tie rod connection to the wheel is much higher than normal, which combined with making room for a driveshaft and differential, results in the steering rack needing to be placed much higher than traditionally placed.

Below to the left is the 2019 car, with the tie rod connection point traditionally very close to the center of the wheel. Then to the right is the higher location of the tie rod connection as seen on the now completed 2021 car. As mentioned previously, the tie rod connection is significantly higher above the usual place, creating an additional design constraint.




END USER

The end user for the 2021 Bearcat Baja senior design is the drivers of the Baja vehicle. This will include the drivers using the Baja vehicle for the SAE Baja competition and the drivers that will be purchasing the Baja vehicle from the fictitious company for recreational use. Safety will be the biggest priority in our design while also designing the Baja vehicle to be reliable, ergonomic, durable, and have exceptional off-road capabilities. The vehicle will be designed with a specific customer in mind. This customer is a fictitious company that plans on purchasing 4,000 units per year and will sell directly to their own customers. The design of the vehicle must be able to facilitate this production quantity. These users would be mostly concerned with the overall performance of the vehicle. The speed, agility and comfort would all be areas prioritized by these users. Since the 10 HP Briggs and Stratton engine we will be using is not exceptionally powerful it is likely the people purchasing it from the fictitious company would be less experienced drivers wanting to look for a less powerful and more user-friendly vehicle. The user buying a vehicle from the fictitious company could be anyone so the vehicle will need to accommodate as many people as possible.

CONCLUSIONS AND SUMMARY OF RESEARCH

Based on past designs, it seems that a midrange steering ratio, and as suggested by the 2013 report, between 8:1 and 10:1. The higher angled steering rack also proved to be a successful design. However, one key technology missing from older Baja cars that the 2021 car requires is a design for 4-wheel drive. The gearbox for a 4-wheel drive system will be in the space normally occupied by the steering system, so a new design that can still meet what made previous cars successful will be a requirement.

QUALITY FUNCTION DEPLOYMENT

In order to get a better understanding of customer wants and desires, a survey was created on all aspects of the Baja car. For customer feedback on steering, questions were asked on the survey about the turning radius, tightness of the steering, and effort to turn steering wheel.

CUSTOMER FEATURES

Below is the list of the customer features for the 2021 car determined during the quality function deployment. Relevant features to steering are maneuvers easily, turns with small radius, and steers tightly.

- Meets Safety Requirements
- Maintains a High Level of Reliability
- Climbs Steep Grade
- Maintains a High Level of Reliability
- Maneuvers Easily
- Is Cost Efficient
- Illuminates Path
- Turns with Small Radius
- Steers Tightly
- Cushions Driver

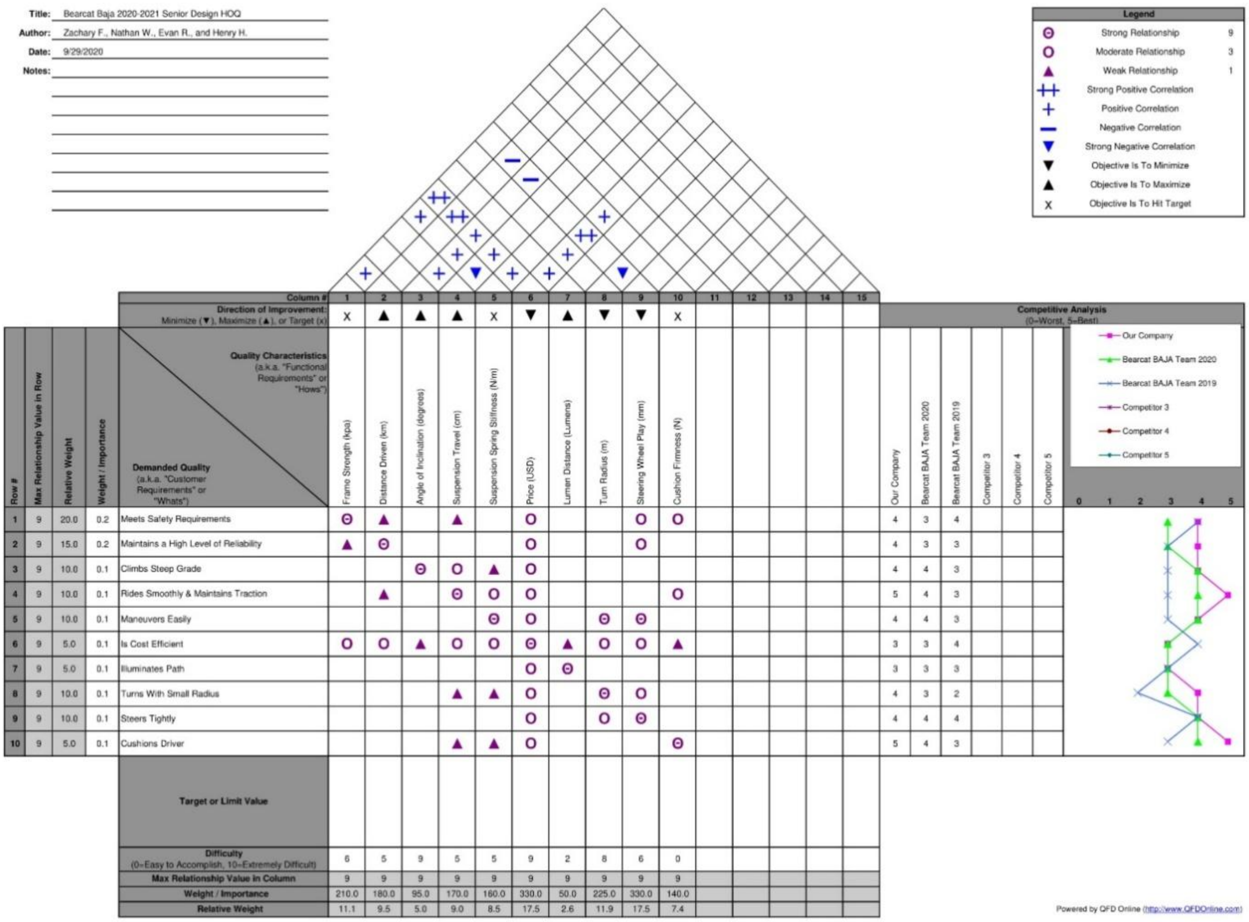
ENGINEERING CHARACTERISTICS

Below are the engineering characteristics that describe how each customer feature will be achieved.

- Frame Strength (kpa)
- Distance Driven (km)
- Angle of Inclination (degrees)
- Suspension Travel (cm)
- Suspension Spring Stiffness (N/m)
- Price (USD)
- Lumen Distance (Lumens)
- Turn Radius (m)
- Steering Wheel Play (mm)
- Cushion Firmness (N)

HOUSE OF QUALITY

Previous year's designs were evaluated for comparison with our planned vehicle, and the quality and characteristics were compared with each other.



PRODUCT OBJECTIVES

Below are the weighted product objectives as seen in the House of Quality.

Meets Safety Requirements (20%)

- Meet and exceed rules from the SAE Baja 2020 and 2021 rule booklet.

Maintains a High Level of Reliability (15%)

- Will focus on the quality of parts purchased and manufactured.

Climbs Steep Grade (10%)

- Ensure a low center of gravity, have good traction, and have high suspension travel.

Maneuvers Easily (10%)

- Small turn radius, tightness in steering system

Is Cost Efficient (5%)

- Will make as many parts as possible using the resources at the Victory Parkway Campus.

Illuminates Path (5%)

- Light bars will be installed to illuminate in front of the vehicle to help guide the operator and to make the vehicle visible to others.

Turns with Small Radius (10%)

- Shorter wheelbase and higher degree of wheel rotation.

Steers Tightly (10%)

- Will ensure bushings and tie rod ends are good quality and that the knuckles will be within a tight tolerance.

Cushions Driver (5%)

- A cushion will be placed on the driver's seat to maximize comfort.

From the customer survey, all three steering related questions rated quite highly and equally, averaging about 4/5 importance. Similarly, the product objectives for steering were also weighted equally, taking 10% of the total weight of design considerations of the car.

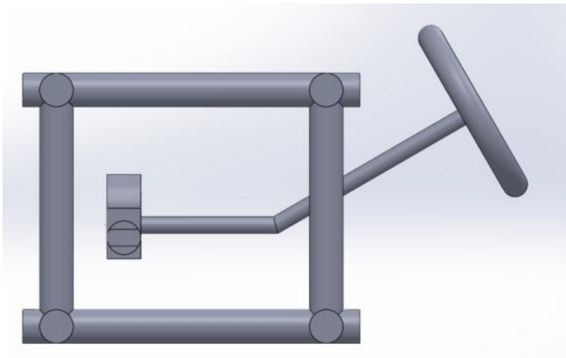
DESIGN

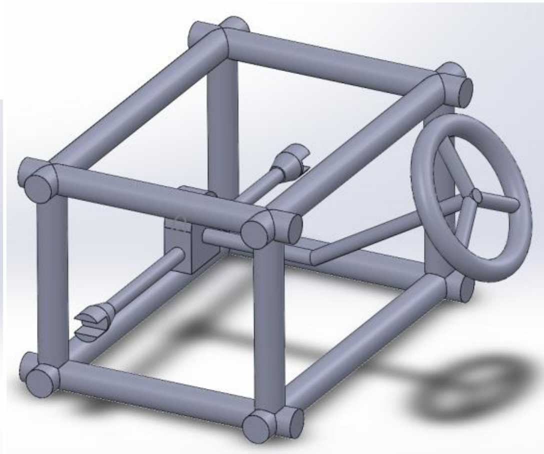
Concepts Drawings

Three possible solutions have been created to solve this year’s Baja challenge, taking into account customer feedback, research into previous year’s designs, and design constraints of the current Baja car.

<u>Concept 1</u>

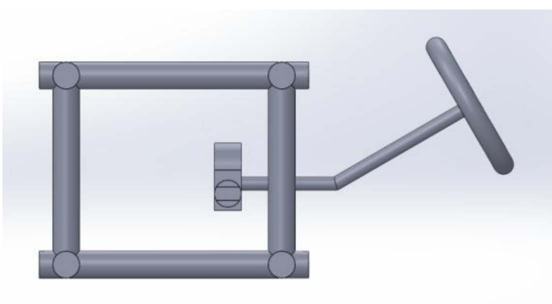
The first concept as seen below on the next page places the steering rack near the front of the car. The pipe frame is a rough representation of the current frame at the Victory Parkway campus. Depending on how the actual car is designed when accounting for the gas and brake pedals, front gearbox, foot room, and tie rod mounting locations on the suspension, this particular design placement may be necessary. However, this location is somewhat less desirable as in the event of a crash, the steering rods are more likely to break. The steering column will also only use one U-Joint. This will help increase steering tightness, but the steering wheel angle will be lower.

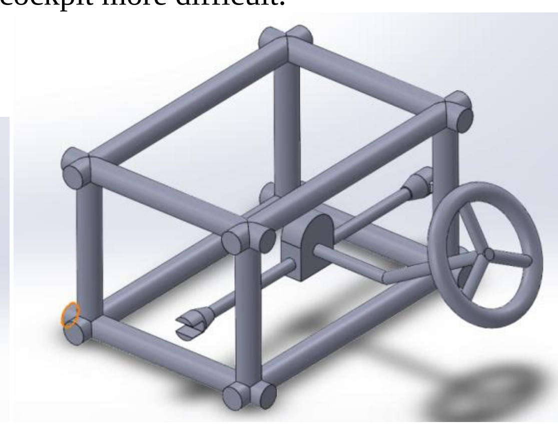




Concept 2

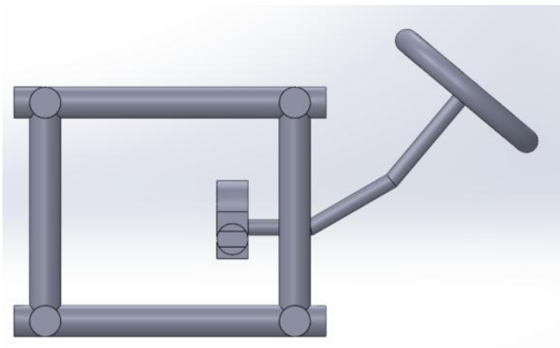
This second design places the steering rack and pinion closer to the driver, where it is much safer from damage in a crash. This design also uses just one U-Joint to help increase steering tightness. Similar to the first concept, the lower angle steering wheel may be less comfortable for drivers, and may make egress from the cockpit more difficult.

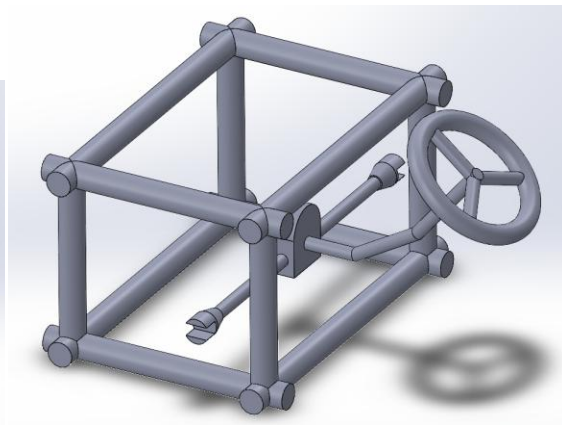




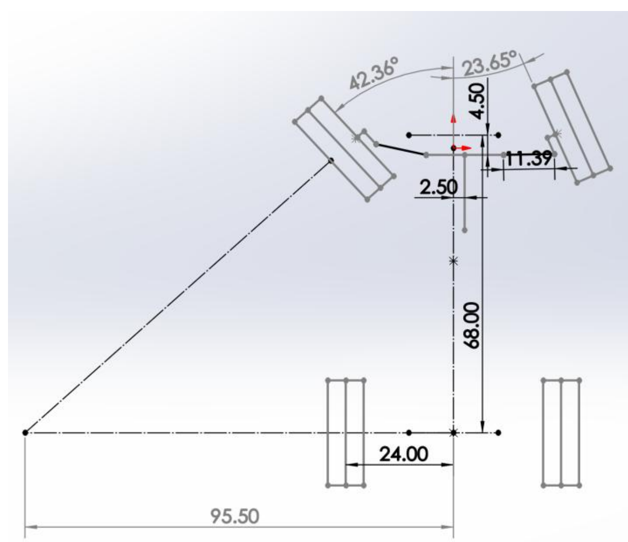
Concept 3

Like the second concept, the steering rack is towards the driver where it will be safe from damage in a crash. However, this design uses two U-Joints to allow for a larger angled steering wheel. As noted in the 2013 design, such a design allows for easier egress from the vehicle.





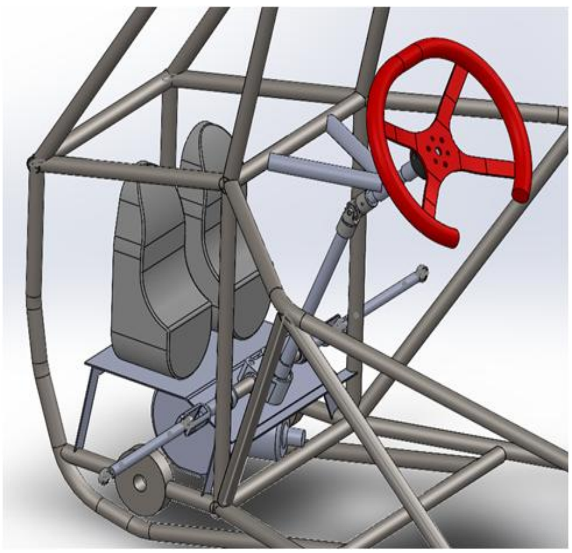
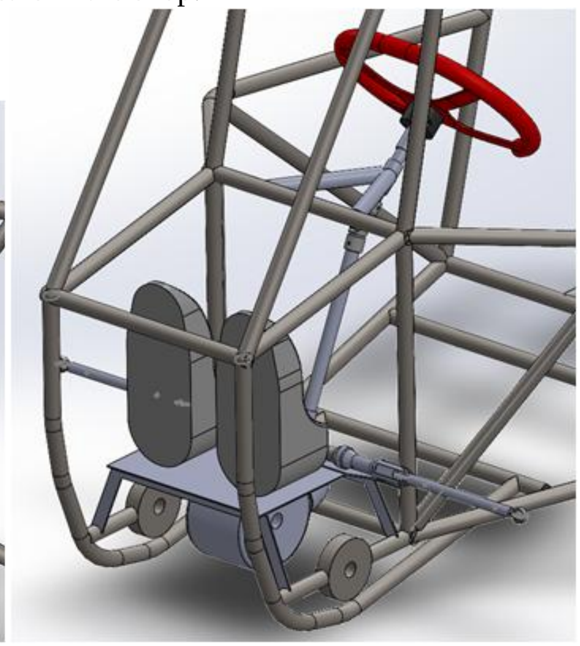
Ultimately, the exact design will depend on various other design factors, such as the front drivetrain placement and gas and brake pedal placement. Placement of the steering rack may be forced to a certain location depending on how other components of the vehicle are designed.



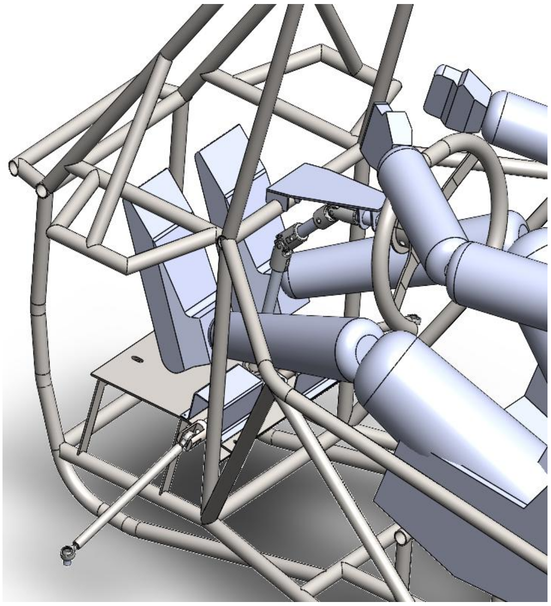
Next, the steering geometry that will give the Ackermann condition and an acceptable turning radius must be designed. Design variables include wheel base, width of the wheels, rack travel distance, rack width, and the distance of the steering rack from the centerline of the front wheels. Variables such as the wheel base and width of the wheels are determined from suspension requirements, and the rack travel distance is based on the selected steering rack. So the two variables that can easily be changed is the location of the steering rack and the width of the rack, which is determined by the rack extension design. To the right is the SolidWorks sketch that shows the final steering geometry. As can be seen in the sketch, the inside wheel turns a greater degree than the outside wheel, giving the Ackermann condition. Additionally, the turning radius comes to about 8 feet.

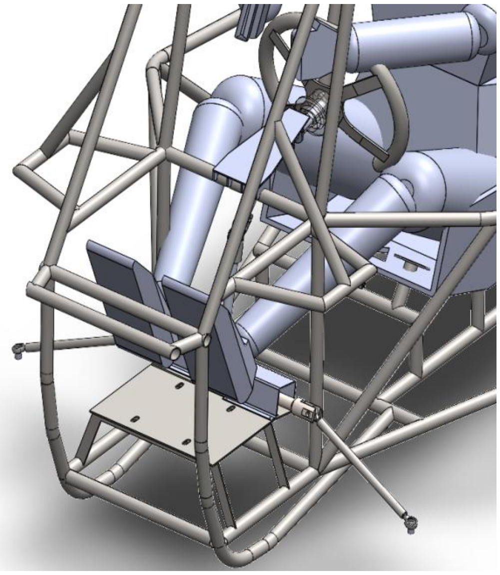
Now that the correct steering geometry had been achieved, CAD modeling could begin. The biggest design consideration was the front differential and location of the tie rod mounts as discussed earlier. Since in the future the front differential would need to be installed and receive maintenance, a removable assembly for the floorboard where the driver's feet would rest was also designed for easier access.

Below is the initial CAD design completed at the end of the Fall semester. As can be seen in the image, the floorboard lets the driver's feet rest above the differential. It was still at this time that a single U-joint was used for the steering column. This causes the steering wheel to be angled much further back than ideal, especially when taking into consideration the near-vertical angle of the current 2017 and 2019 cars in the shop.

After fabrication began, additional changes were identified, and the final CAD model is shown below. A more robust mount for steering was designed, and the shaft size of the steering column was adjusted for easier manufacturing. Additionally, an extra U-Joint was added to bring the steering wheel to a more comfortable angle for the driver, and sheet metal guards were added to protect against pinch points on the steering rack. To assist with easier deconstruction and assembly, roll pins with metal wire strung through were used so the steering column could still be taken apart but still be secured in place. Roll pins were chosen over set screws, as set screws can slip and come loose during operation, resulting in loss of steering.





As seen above, the biggest changes are to the angle of the steering wheel, now very close to vertical, as well as two U-joints. Sheet metal covers protect the driver from pinch points on the steering rack, and a more robust support for the steering wheel column was designed.

DESIGN ALTERNATIVES AND SELECTION

Ultimately, concept 3 was chosen for the final steering design. This decision was primarily due to the location of the mounting points for the tie rods on the suspension. Ideally, the tie rods would be as collinear with the steering rack as possible to reduce the amount of steering force lost from the driver to the suspension mounting point. The two U-joint design also allowed the steering wheel to achieve a much more comfortable vertical angle for the driver.

ENGINEERING CALCULATIONS

The steering column, tie rods, and rack extension are all prone to breaking, so an FEA was used to ensure that the part would still hold up under more extreme scenarios.

<u>List of equations</u>

Torque Equation:

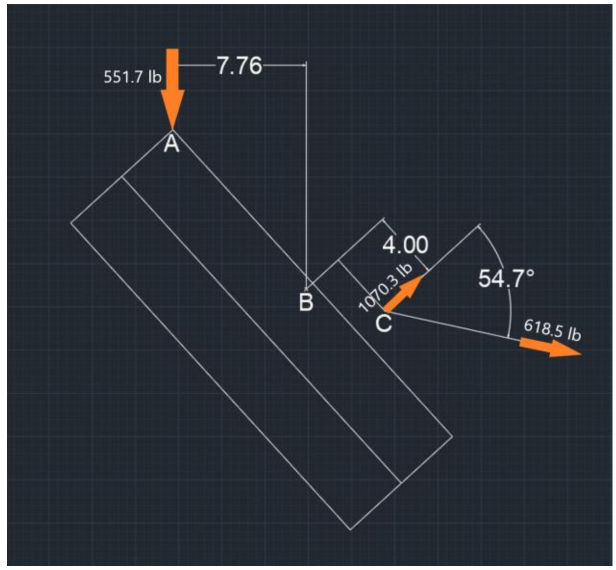
$$\tau = F * D$$

Conservation of Momentum Equation:

$$m_1 v_1 = m_2 v_2 + Ft$$

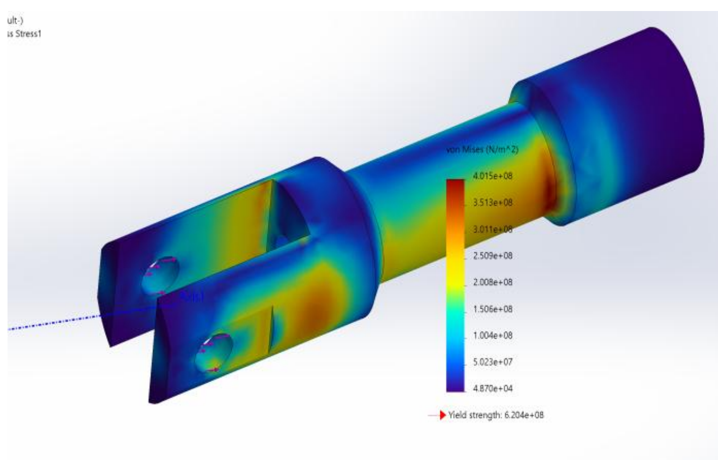
Rack Extension

The 2017 senior design report simulated an impact of the front wheel resulting in a change of velocity of 35 mph to 30 mph in 0.25 seconds. For the 2021 car, the same impact was simulated. An estimate for the mass of the car was based off the 2019 car for a total weight of 600 pounds; 350 pounds for the car and 250 pounds for the driver.



During an impact, the mass of the vehicle stays the same. With the assumptions made with the changes in velocity and time, the conservation of momentum equation can be used. Since mass stays constant, $m_1 = m_2$, $V_1 = 35$ mph, $V_2 = 30$ mph, and $t = 0.25$ seconds. This leaves force as the only unknown, which can be solved for. This force is what will act on the front tire, and will be translated from the wheel to the tie rod and to then to the rack extension.

After solving the equation, the amount of force was found to be 551.7 pounds of force, which is represented by the red arrow at point A. This creates a torque of 4281.2 lb.in. around point B, which consequently creates a force of 1070.3 lb. at point C. Based on the steering geometry, the tie rod would be at an angle of 54.7 degrees from the force at point C. Using a vector triangle with the 1070.3 lb and 54.7 degrees, a 618.5 lb force was calculated. This 618.5 pound force will be exerted along the axis of the tie rod, and will be exerted from the tie rods to the rack extension. It is this force that will be used for the simulation on the rack extension.

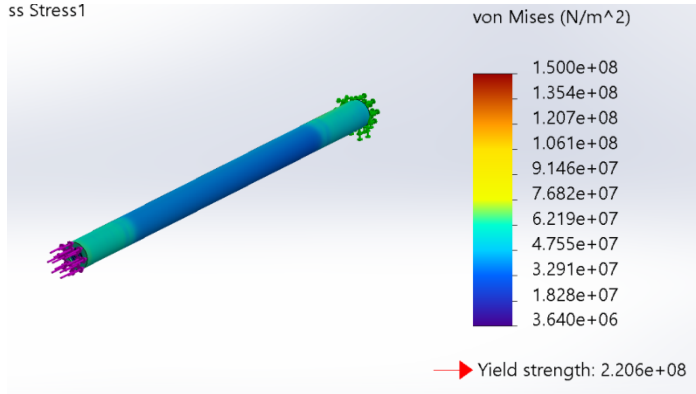


The simulation results for a plain carbon steel material is shown to the right, although it should be noted that it is from a simulation based on earlier steering geometry calculation, which resulted in a 1,420 pound force being applied. In the simulation, the force is applied at the angle the tie rod would be in the test scenario, and is applied on the two holes for the heim joint. The fixed location is on the opposite end of the rack extension where the rack is in contact with the rack extension.

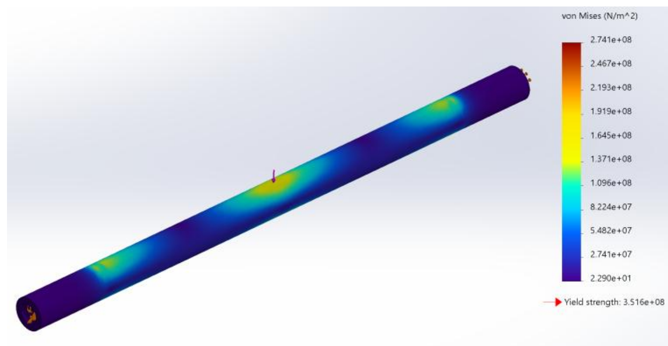
Since the new force was less than the original simulated force, new simulations were not run. In the original simulation, a factor of safety of 1.5 was observed, so the design was considered acceptable. Steel was chosen over aluminum to achieve better strength while only adding a little more weight to the rack extensions, an acceptable tradeoff.

Tie Rods

From the earlier force analysis on the rack extension, the 681.5 pound force is also what will be exerted on the tie rod. Two different tests were simulated. The first was the force in-line with the axis of the tie rod, which is the force the tie rod exerts on the rack extension. The factor of safety was 1.5 for a plain carbon steel. This factor of safety was again from the previous simulation, and since the new force is much smaller than the old force, new simulations were not run.

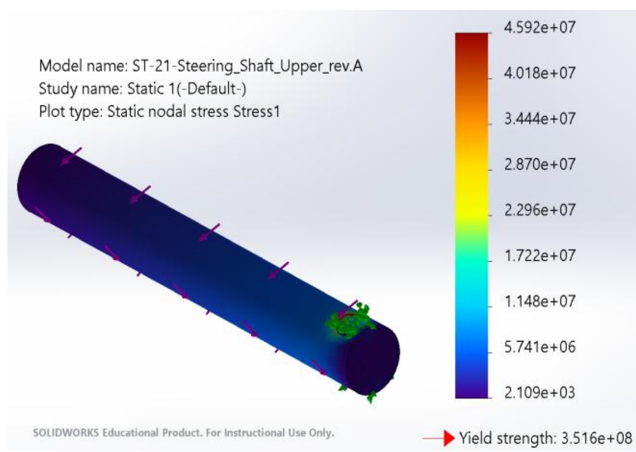


The second simulation was a force applied to the center of the tie rod. This would simulate an accidental bump or collision with the environment, experiencing the same change of momentum. Thus, the 551.7 lb was applied, achieving a factor of safety of 1.3. This factor of safety is on the low side, and tie rods are one of the items most likely to bend and break, so an extra set of tie rods will be made.



Steering Column

For the steering column, the consideration is the torque applied by the driver. A driver applying 100 lb of force with two arms was assumed, for a total torque on a 12 in. steering wheel of 50 ft.lb of torque. Due to the design of the steering column, ¾" ground rod was used, which the material ordered from McMaster was O1 Tool Steel.

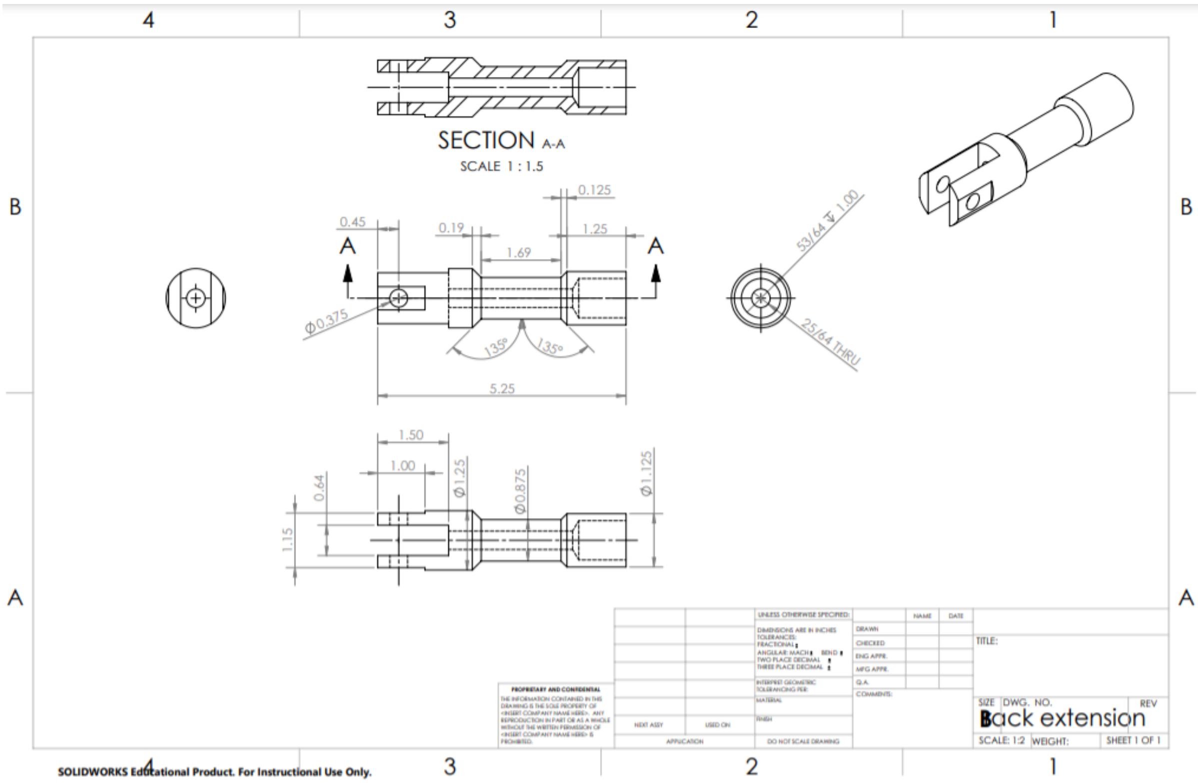


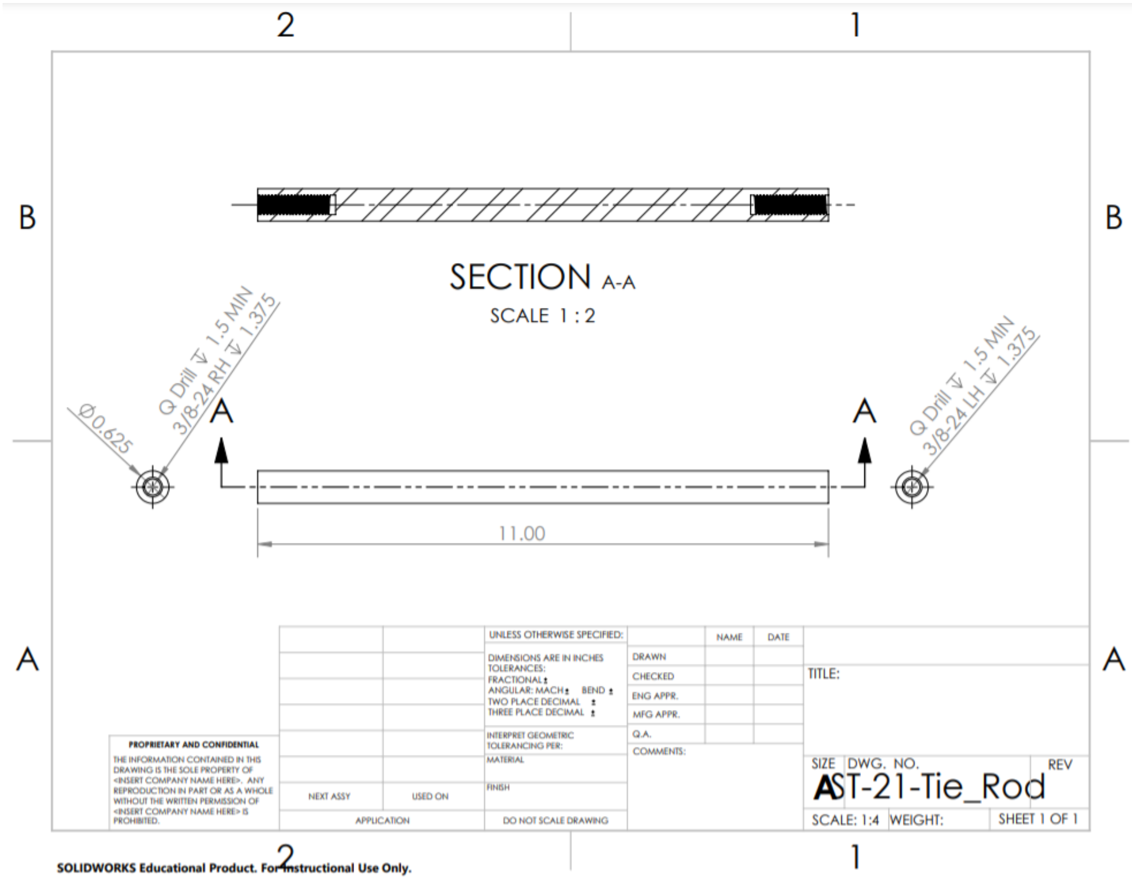
In the unlikely event that the wheels become locked in place and the driver is trying to turn the steering wheel, the fixed points would be the holes used by the roll pins. As can be seen by the image of the simulation results, there is very little stress on one of the steering column parts, with a factor of safety of 7.7, so there is very little concern of the steering column breaking.

Material Selection

FEA simulations were run using plain carbon steel for parts whose material had yet to be determined, which would be the rack extension and tie rods. The rack extension with plain carbon steel was able to hold up under the applied 1,420 pounds of force exerted, and the tie rods were also able to resist buckling and bending under the applied forces. Thus, plain carbon steel was deemed an adequate material to use for the construction of these components. The steering column was also able to easily resist the torsion applied, so there is no concern of breakage from the purchased material from McMaster.

MANUFACTURING DRAWINGS




SECTION A-A
SCALE 1 : 2
Ø0.625
Q Drill ↧ 1.5 MIN
3/8-24 RH ↧ 1.375
Q Drill ↧ 1.5 MIN
3/8-24 LH ↧ 1.375
A
A
11.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE DWG. NO. REV
A ST-21-Tie_Rod
SCALE: 1:4 WEIGHT: SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
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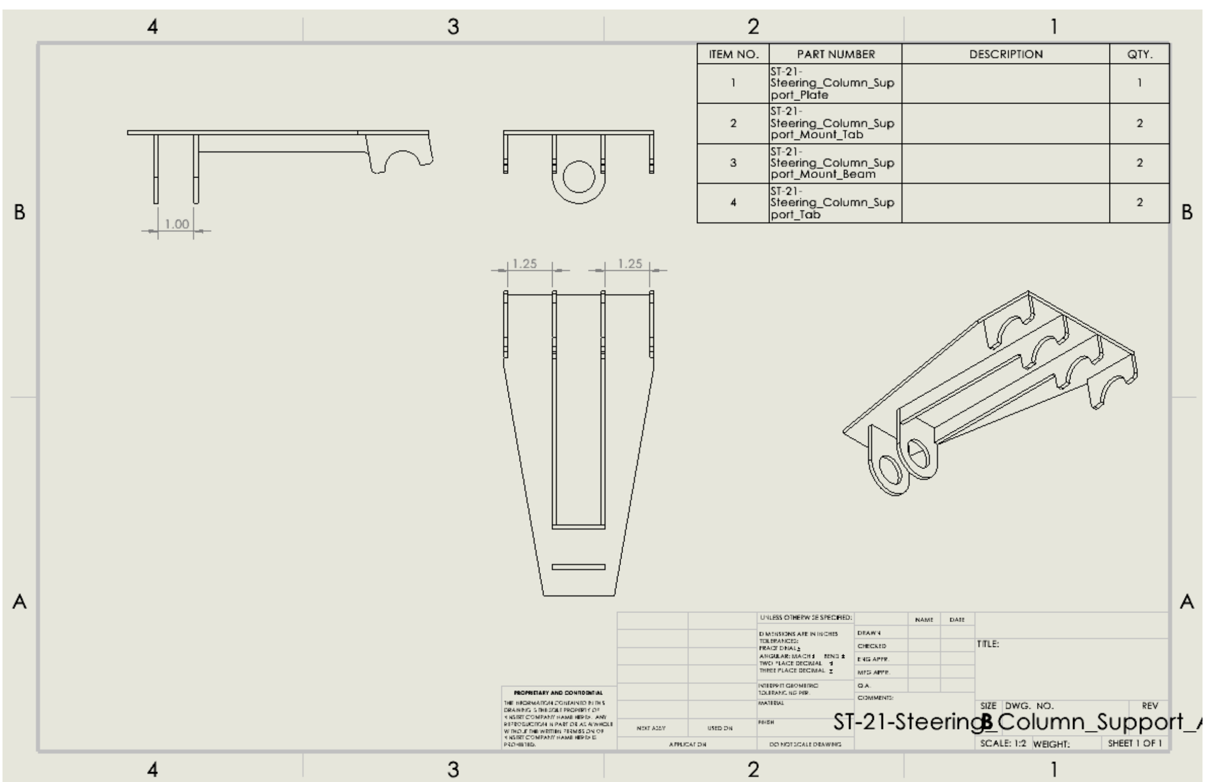
ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | ST-21-Steering_Column_Support_Plate | | 1
2 | ST-21-Steering_Column_Support_Mount_Tab | | 2
3 | ST-21-Steering_Column_Support_Mount_Beam | | 2
4 | ST-21-Steering_Column_Support_Tab | | 2
1.00
1.25
1.25
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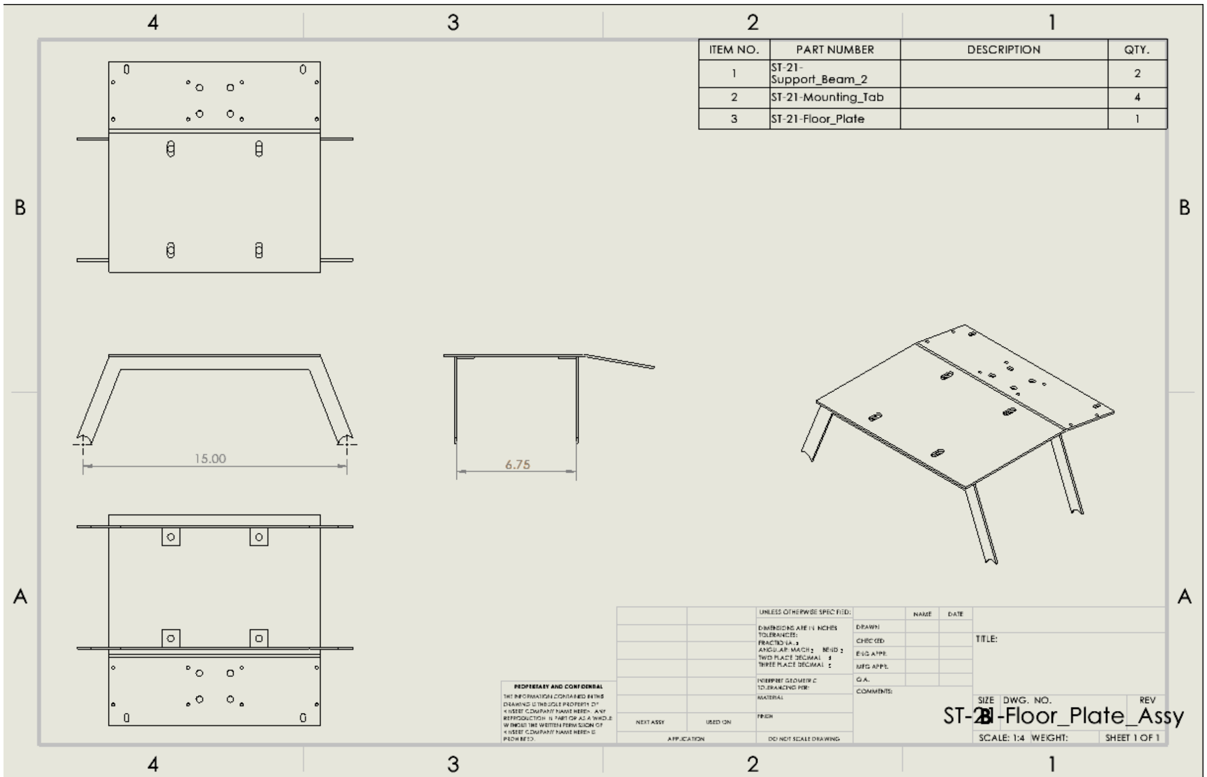
SIZE DWG. NO. REV
B ST-21-Steering_Column_Support_A
SCALE: 1:2 WEIGHT: SHEET 1 OF 1


ITEM NO.
PART NUMBER
DESCRIPTION
QTY.
1 ST-21-Support_Beam_2 2
2 ST-21-Mounting_Tab 4
3 ST-21-Floor_Plate 1
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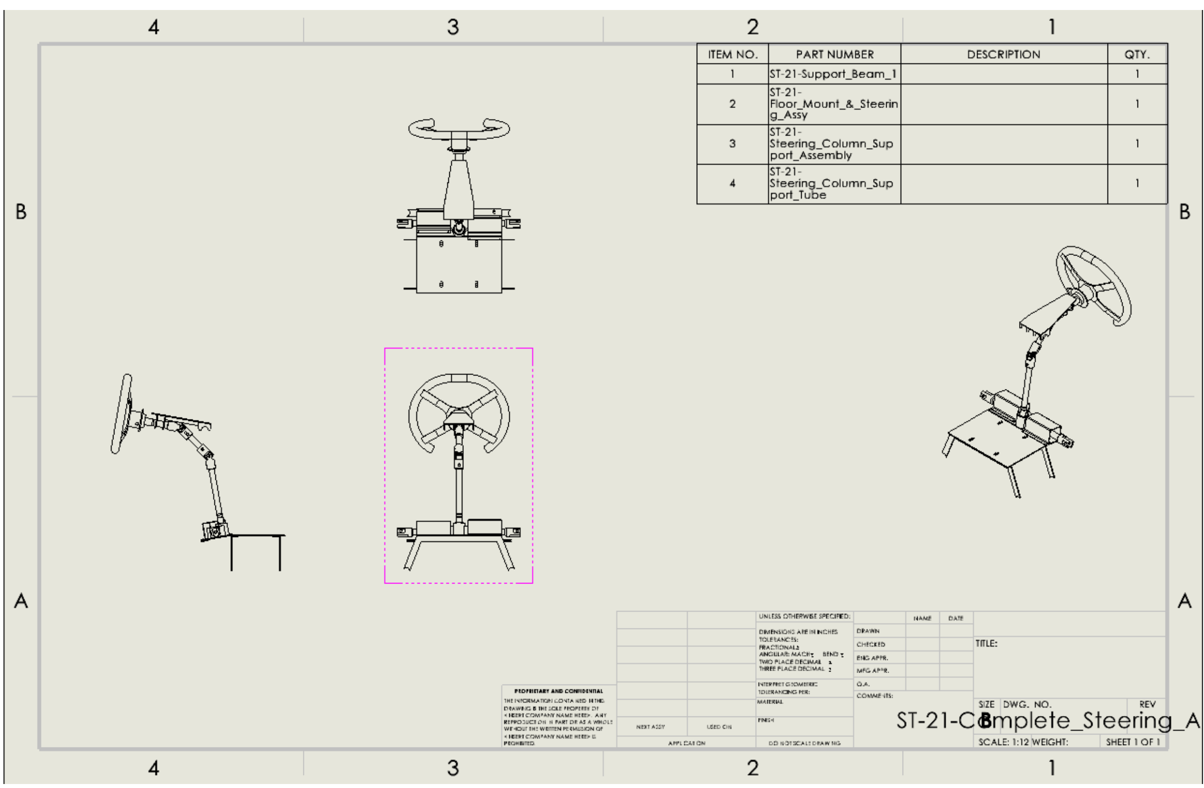
6.75
TITLE:
SIZE DWG. NO.
REV
ST-21-Floor_Plate_Assy
SCALE: 1:4 WEIGHT:
SHEET 1 OF 1


ITEM NO.
PART NUMBER
DESCRIPTION
QTY.
1 ST-21-Support_Beam_1 1
2 ST-21-Floor_Mount_&_Steering_Assy 1
3 ST-21-Steering_Column_Support_Assembly 1
4 ST-21-Steering_Column_Support_Tube 1
TITLE:
SIZE DWG. NO.
REV
SCALE: 1:12 WEIGHT:
SHEET 1 OF 1

BILL OF MATERIAL

A list of all parts used in the steering assembly, not including hardware found in the shop.

Bearcat Baja 2021 Bill of Materials			
Part Number	Description	Qty.	Vendor
ST-21-Support_Beam_1	Floor Mount Support	1	Bearcat Baja
ST-21-Support_Beam_2	Floor Mount Support	2	Bearcat Baja
ST-21-Mounting_Tab	Floor Mount Support	4	Bearcat Baja
ST-21-Floor_Plate	Cover plate for driver's feet	1	Bearcat Baja
ST-21-Steering_Cover	Protection from R&P	2	Bearcat Baja
ST-21-R&P	Rack and Pinion Assembly	1	Stilletto
ST-21-Rack_Extension		2	Bearcat Baja
c42-403-a	5/16 Spline for R&P	1	Stilletto
ST-21-Steering_Shaft_Lower_rev.A	Steering Column Shaft	1	Bearcat Baja
2456K17	35 Degree U-Joint	2	McMaster Carr
ST-21-Steering_Shaft_Middle_rev.A	Steering Column Shaft	1	Bearcat Baja
ST-21-Steering_Shaft_Upper_rev.A	Steering Column Shaft	1	Bearcat Baja
ALL53205	Quick Release	1	AllStar Performance
ALL53204	Spline for ALL53205	1	AllStar Performance
ST-21-Steering_Wheel		1	Bearcat Baja
98296A948	3/8" Roll Pin	4	McMaster Carr
ST-21-Steering_Column_Support_Plate	Steering Column Support	1	Bearcat Baja
ST-21-Steering_Column_Support_Mount_Tab	Steering Column Support	2	Bearcat Baja
ST-21-Steering_Column_Support_Mount_Beam	Steering Column Support	2	Bearcat Baja
ST-21-Steering_Column_Support_Mount_Tube	Steering Column Support	1	Bearcat Baja
60645K141	3/8-24 Heim Joint	4	McMaster Carr
ST-21-Tie_Rod		2	Bearcat Baja
94205K78	U-Joint Cover: 1.36" ID, 2.14" Long	2	McMaster Carr
6436K16	2-Piece .75 in ID Lock Collar	1	McMaster Carr

BUILD AND TEST

Manufacturing began mid-January due to COVID-19 restrictions in place by the University. It was at this time final design changes were made and fabrication could begin. Once shop hours were opened, fabrication of the other parts was able to be completed.

DISCUSSION OF THE MANUFACTURING PROCESSES UTILIZED

Machines such as the vertical mill, lathe, CNC plasma cutter, sheet metal bender, and TIG welding were all utilized in the fabrication of the steering assembly.

The vertical mill was used to drill the holes for the roll pins on the steering shafts and U-joints, as well as finishing the rack extensions. The lathe also proved to be extremely useful, with a significant portion of machining time spent using the lathe. Using the lathe to machine tap the threads on the tie rods was a significant time saver, and resulted in much higher quality threads than if they were tapped by hand.

The CNC plasma cutter was also a valuable tool for fabrication. The parts for the steering mount and floor plate were all plasma cut using a DXF made in AutoCAD.

TIG welding was used to then weld the plasma cut parts together, which included the floor and steering mounts. A year previously I had learned how to TIG weld at 1819 Innovation Hub, but did not get the chance to practice since. This project was a good opportunity to get much needed practice with TIG welding. Due to an unexpected design change a new steering mount needed to be made, which I was able to weld together much faster and better due to the additional practice.

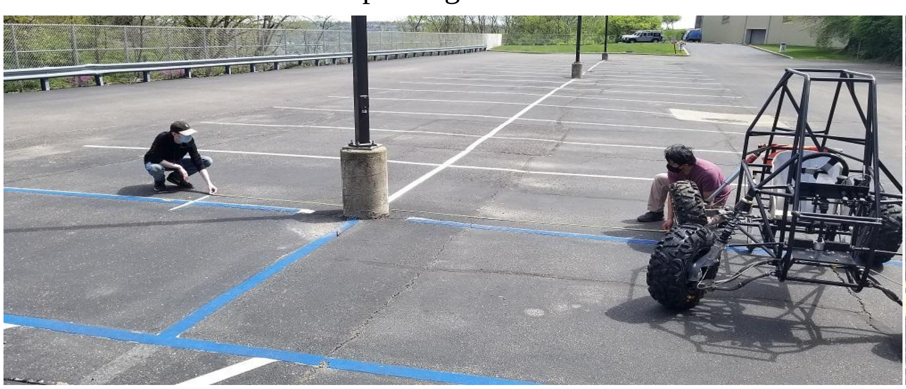
Below is the final steering assembly. Sheet metal covers were fabricated using the plasma cutter and sheet metal bender to cover the steering rack and protect the driver from any projectiles. Boots over the U-joints also kept any pinch points under cover, and metal wires through the roll pins will help keep them secure in the steering column.

TEST PROCEDURE AND CRITERIA

From the quality function deployment, the desired steering traits are: small turning radius, low effort to turn steering wheel, and steering tightness. To test the turning radius, a live test will be performed to evaluate the actual turning radius. At the time of the turning radius test, the difficulty in turning the steering wheel can also be evaluated. The tightness of the steering can be evaluated by seeing how much the steering wheel needs to be turned before the wheels turn in response to driver input. Last but not least, the overall driver experience must be comfortable in the cockpit, so there must be adequate space for the driver's feet, and the steering wheel should be a comfortable distance from the seat.

The best way to check for Ackermann steering and the turning radius is to do a live test. First, the toe must be adjusted so that the wheels are in alignment, which can be adjusted by loosening or tightening the tie rods, which is possible because of the left and right hand taps. To check the toe, the distance from the center of the left and right wheel is measured on both sides of the wheel, while also ensuring the steering rack is centered and fixed. The two pictures below show the wheels turned all the way left and right. As can be seen from the pictures, the inside wheel turns much further than the outside wheel, which is desirable since it is the Ackermann condition.


To test the turning radius, the car was actually put through a turn on the pavement. Chalk was used to mark the starting point of the rear wheel, and the car was pushed with the steering wheel turned all the way to the right and brought around 180^o. Then the diameter the car turned could be measured, and consequently, the turning radius. The image below shows how the team used chalk and the parking lines in the lot outside the lab to test the turning radius.




Taking into account the additional distance from the rear wheel to the center of the car, the turning radius came to about 9'-11".

TEST RESULTS AND FINDINGS

First off, when all the steering components were finally put together with the suspension components so the wheels could be turned, it was discovered that the steering rack was installed upside-down, a huge design oversight; when the steering wheel was turned to the right, the wheels turned to the left. This was able to be quickly corrected, however. The centerline of the steering rack was kept the same, so new holes were drilled in the floorplate, and a new steering mount was constructed, resulting in a slight shift forward of the steering column and steering wheel. These changes were able to be completed quickly, within one working day, so progress on the project was not significantly impacted.

Once the steering flaw was corrected, testing revealed many things about the overall steering design. From the turning radius test, it was revealed that the turning radius was much larger than anticipated, from a designed turning radius of 8 feet to an actual turning radius of 9.9 feet.

There are many potential reasons why the designed turning radius was not achieved. The location of the steering rack is important, and when combined with the removable floor plate assembly where the steering rack is mounted and the slight shifting of parts during final welding, the steering rack did shift forward towards the driver slightly. Additionally, the location of the tie rod mounting points may not have been in the exact location when the steering geometry was designed. The suspension was also not perfectly mirrored, which would also mean that the tie rods would not be a mirror of each other. It was likely a combination of all these factors that led to the expected turning radius not being achieved. As can be seen from the photo on the right, the tie rods are not mirrored to each other when the wheels are straight,

On the other hand, it is quite easy to turn the steering wheel, and the steering is also very responsive to driver input. As can be seen from the images below, the overall driver experience is very comfortable. There is plenty of space for the driver's feet, despite initial concerns of discomfort with the bulky steering rack guards. However, I did end up moving the adjustable pedals all the way back, as it was simply not comfortable with the pedals being that close, combined with the intrusion of the steering rack covers. A few other Bearcat Baja organization members also sat in the cockpit and noted that it was comfortable, so overall, the driver comfort test was a success. The images below show how well the driver can fit into the vehicle. There is plenty of foot room, and the steering wheel is a comfortable distance from the driver's body.

PROJECT MANAGEMENT

BUDGET, PROPOSED/ACTUAL

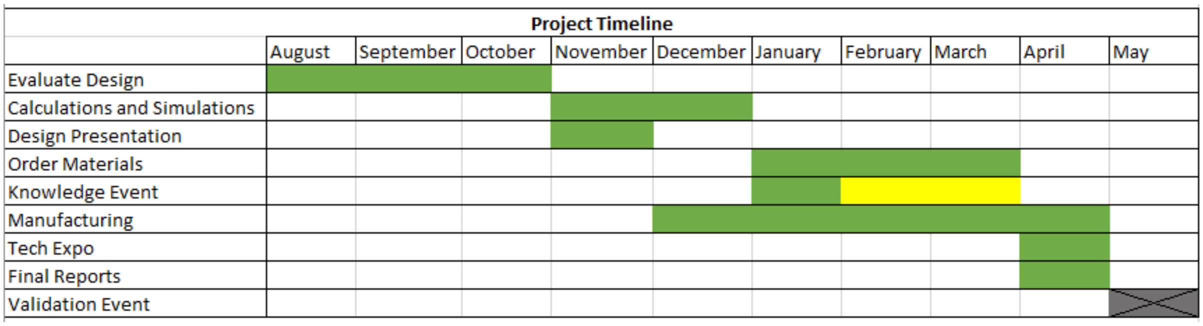
For the 2021 year, $750 was allocated for purchasing required steering components. Below is the materials that were purchased for steering. An old rack and pinion was reused from an old car, which resulted in significant cost savings. In the end, the project came in under budget, as only $507.60 was spent of the allocated $750.

Baja 2021 Steering BOM

Item	Qty. Req.	Unit Price	Total Price	Vendor	Part#
35 Degree U-Joint	2	$ 93.21	$ 186.42	McMaster Carr	2456K17
Heim Joints	4	$ 4.07	$ 16.28	McMaster Carr	60645K14
3/4"-16 Hex Nut	1	$ 13.90	$ 13.90	McMaster Carr	95462A540
.75 inch ground rod	1	$ 23.58	$ 23.58	McMaster Carr	8893K19
2-Piece .75 in ID Lock Collar	1	$ 6.00	$ 6.00	McMaster Carr	6436K16
3/4"-16 Ball Joint Rod End	1	$ 13.31	$ 13.31	McMaster Carr	60645K18
Quick Release Hub	1	$ 89.99	$ 89.99	AllStar Performance	ALL52304
Quick Release Shaft	1	$ 21.99	$ 21.99	AllStar Performance	ALL52305
DUAL LOCK SPLINED COUPLER 5/8-36 SPLINE, 5/8" BORE	1	$ 33.99	$ 33.99	Stiletto	C42-403-A
U-Joint Cover: 1.36" ID, 2.14" Long	2	$ 19.77	$ 39.54	McMaster Carr	94205K78
Roll Pin, 3/8" DIA, 1.5" long	1	$ 9.84	$ 9.84	McMaster Carr	98296A949
3/8-24 RH Ball Joint	2	$ 13.19	$ 26.38	McMaster Carr	4483T4
3/8-24 LH Ball Joint	2	$ 13.19	$ 26.38	McMaster Carr	4483T4
Total			**$ 507.60**		

SCHEDULE, PROPOSED /ACTUAL

Below is the proposed schedule for the project.



Overall, the project ran pretty closely on schedule. CAD modeling wrapped up at the end of the Fall semester, although final design changes were made at the beginning of the Spring semester. SAE presentations and documentation also ended up taking a larger than expected portion of time, but nothing too significant to throw the project off schedule. Due to university restrictions because of COVID-19, manufacturing got a late start near the end of January. Shop hours also opened late and with less open hours than ideal, but with the request for additional shops hours during the day the project was able to be completed on time.

SUSTAINABILITY AND MATERIAL USAGE

The biggest expense, the rack and pinion, was recycled from a previous vehicle, so a significant cost savings was achieved. Additionally, sheet metal used for the floor and steering mount assemblies was used from previous Baja projects, so cost savings on material for this year was also achieved. A more thorough inventory of parts could have also allowed for more efficient use of previously purchased parts, such as the heim joints or old tie rods, could have saved some material. However, since those items are quite prone to breaking and bending during operation, it is not a complete waste of material. Additionally, an old quick release for the steering wheel could have been used, but purchasing the same style quick release as the 2019 car simplified the steering column design.

CONCLUSIONS

Overall, I was able to closely meet my project objectives. My design goal was to build my steering around the new design challenge of a 4-wheel drive system, which I believe can be achieved, although the driveline system has yet to be completed. I was able to achieve most of my product objectives such as steering tightness and the effort required to turn the steering wheel. However, the turning radius was larger than anticipated, which the location of the steering rack and suspension are all potential factors that contributed to this objective not being met.

Even though the project got a late start due to COVID-19 restrictions, the project was still able to be completed by the end of the semester on time and under budget.

Design Recommendations

The biggest design recommendation would be to design a fixed mounting location for the steering rack. With the current design, the steering rack is mounted on the floor plate, which is removable, so every time the floor plate is taken off and put back on, there is no guarantee that the steering rack will be in the same place, which will affect steering. This, along with the shifting of the floor plate supports welded to the frame shifting during the final welding, resulted in the steering rack location moving from its original, intended location. Thus I would advise future designs to stick with the fixed designs found on the other Baja vehicles.

It should also again be stated that the steering rack must be oriented correctly to avoid reverse steering input, a mistake I discovered midway through fabrication. Just to clarify, the spline with the gear must be oriented above the rack. If in doubt, an examination of the other vehicles will clarify the correct orientation of the steering rack.

The roll pins used to secure the steering column, while successful, did add additional complexity and manufacturing time. As far as I am aware, previous Baja designs have not yet used roll pins to secure the steering column, so the likelihood of the roll pins coming loose during operation is unknown. This design decision will be a good way to test the viability of roll pins, and if need be, the steering column can be welded together.

In the future it may be advisable to acquire a higher ratio steering rack. Initially, a 12:1 steering ratio was planned, although due to budget considerations and the availability of a steering rack from an older car, it was not used. Since many older reports recommend a higher steering ratio, including the 2020 report, it may be useful, budget allowing, to use one for testing and comparison with other cars.

One final recommendation would be to use the same AllStar quick release for all future designs. The quick release in particular is the AllStar Performance part ALL52304. This part includes both the quick release and spline. This will allow for quick swapping of steering wheels while on the track, or for reuse in future projects. Once a few quick releases are acquired, the only part needed in the future will be the AllStar part ALL52305. As of the end of April 2021, there is currently one ALL52305 part in storage, a surplus due to a mistake in ordering.

Contact Information

Should a future student be reviewing my report for their research, please do not hesitate to get in touch with me with any questions or clarification. I am always open. You can contact me at:

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WORKS CITED

Works Cited

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5. **Biteman, Brooks.** *Baja SAE Frame Design.* Cincinnati : University of Cincinnati College of Engineering and Applied Science, 2013.

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APPENDIX A

Photos of construction of the Baja car and steering