2019 University of Cincinnati SAE Baja Rear Suspension

A Baccalaureate thesis submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

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April 2019

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ABSTRACT

The Society of Automotive Engineers (SAE) holds a Baja competition each year for universities worldwide to compete in. The class of 2019 had 10 seniors interested in Baja for their design projects. With the amount of interest in the project; and an unsafe 2018 car to work with, it was decided to start fresh and build a new car. As a team we designed, built and tested a car built to the specific SAE rules. Along with building a new frame we wanted to improve on previous designs of other components. This report will provide information on research, customer features, product objectives, design, and project management for the 2019 University of Cincinnati Baja rear suspension.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

Baja SAE gives students the chance to build an all-terrain vehicle designed to be an ergonomic, reliable, and economic production vehicle. As a team we will design, build, test, and compete with the vehicle built to specific SAE rules. The University of Cincinnati has built cars for years now, and the current Baja car has flaws that will be improved upon. Our 2019 team will be building a brand-new chassis and using some parts from the previous vehicles to complete the final assembly. My focus will be on the rear suspension, creating a design that is capable of traction, maneuverability, crawling, and endurance.

BACKGROUND

Baja SAE dates all the way back to its beginnings in 1976, where the initial goal was to build a single man all-terrain vehicle that would be competitive with commercially manufactured vehicles. Since this time Baja has grown to be a premier SAE competition that includes over 150 universities per event.

RESEARCH

SCOPE OF THE PROBLEM

The goal of SAE International's Collegiate Design Series (CDS) competition for Baja vehicles is to move students beyond just textbook theory. It allows students to design, build, and test the performance of their projects. Students gain exposure with hands on, team engineering experience which requires design, manufacturing, testing, project management, communication, and budgeting [1]. Each year allows students to improve upon previous designs by using data taken from previous years. The competition pushes students from Universities all over the world to improve the design of their vehicles to win the competition. The rear suspension is designed to allow cars to maneuver, and travel over rough terrain with ease. Currently the University of Cincinnati has 3 Baja cars at our disposal allowing the team to research and compare the pros and cons of previous designs.

The suspension of a vehicle has several functions; safety, performance, ride height, and handling. The major function of suspension is dampening, it is used to absorb forces experienced by the vehicle. This dampening is related to the safety of the vehicle, it protects the user as well as the vehicle from potentially harmful forces. The ride height of the vehicle comes from the ground clearance of suspension components. Creating a ride height that has adaquete clearance, as well as maintains a low vehicle roll center is very important in off-road suspensions. Handling comes from different components of a suspension; allowing the car to accelerate, turn, brake, and move over terrain while keeping all four wheels in contact with the ground.

CURRENT STATE OF THE ART

Some state-of-the-art examples for all terrain vehicles are Baja cars, and all-terrain vehicles (ATVs). The most common customer related product is the Polaris RZR. Based on sales the RZR platform is the most common side by side off road vehicle used in the US {2}. The newest addition to the RZR platform is the RS1 single seat ATV. The RS1 rear suspension is a trailing arm suspension with 21 inches of travel, allowing a ground clearance of 13 inches [2]. The RS1 rear suspension can be seen in Figure 1.

Figure 1: Polaris RZR RS1 rear suspension [2]

In the world of offroad vehicles there are several accepted rear suspension methods including trailing arms, swing arms, and double wishbone (dual a arm assemblies).

Trailing arm suspension: A trailing arm suspension uses two arms which are pivoted to the frame on the front, and fixed to the hub on the back. It allows the wheel to move up and down to deal with rough terrain. Arms parallel with the frame increase in angle with the shock/spring assembly and create traction.With the arms mounted paralled with the car it does not allow for camber change. Another version of trailing arms that is becoming more widely used is a semi trailing arm suspension. The arm is pivoted at angles (50-70 degrees) and is split into two vectors, the trailing arm deal with bumps but leads to understeer, where as the traverse component acts as a swing arm suspension and cancels out the understeer caused by the trailing arm [3]. The disadvantage to this system is that throughout the suspension travel the camber angle will change.
The differences in the two types is shown in Figure 2.

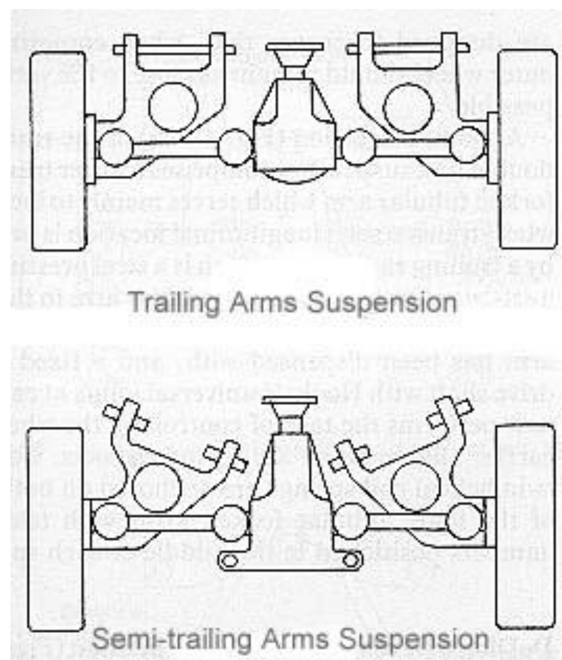


Figure 2: Difference in trailing arm suspensions [3]

Swing arm suspension: A swing arm suspension is one of the earliest designed independent shock absorption suspensions. Its advantages are it is simple in design, sturdy, and cost effective, however due to the design of the system body roll and bouncing can cause unwanted camber gain and understeer [3]. In the ATV/Motorcycle world they use a single swing arm mounted parallel with the front of the frame, this is also a sturdy design but only allows the rear suspension to move as a whole and not indepedently.

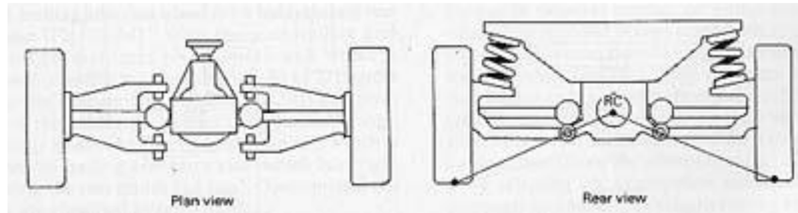


Figure 3: Example of swing arm suspension [3]

Double wishbone suspension: A double wishbone suspension is one of the most common suspensions in both commuting sedans and high performance racecars. The advantage to this design is the suspension always maintains the wheel perpendicular to the road surface throughout the travel of the suspension. This suspension system requires a lot of space in order to be used and can be less cost effective than other suspension systems.

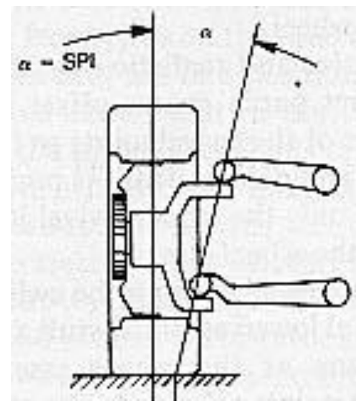


Figure 4: Double wishbone suspension [3]

END USER

The main objective of the Baja SAE is to design a competitive car for competition; however, the secondary objective is to build a car that is designed for the recreational user market. The vehicle will be built to demonstrate reliability, performance, and ergonomics, while keeping in mind it needs to remain economically valuable for a manufacture by a company and use by a recreational user.

The immediate user of the vehicle will be the 2019 University of Cincinnati Baja team. The team will take the car to competition where it will be tested on acceleration, hill climb, maneuverability, and suspension. During these tests the vehicle will prove its ability and worth to a potential recreational consumer.

CONCLUSIONS AND SUMMARY OF RESEARCH

In the Baja SAE competition there are very few restrictions on the rear suspension design. Since the end customer is the University of Cincinnati Baja team, the design will be based around the best suspension design to complete all courses during competition. Each design uses a dampening system, whether it’s a coil over shock or air shock. The best style shock and spring setup will be calculated after the most efficient suspension style is chosen.

CUSTOMER FEATURES

(Weighted Importance)
Accelerates quickly (.1)
Maneuvers easily (.1)
Meets safety specifications (.15)
Drives over large obstacles (.1)
Climbs steep grade (.05)
Requires low maintenance (.05)
Cost efficient (.1)
Brakes quickly (.1)
Ergonomically Designed (.1)
Lightweight (.15)

PRODUCT OBJECTIVES

Driver Safety (30%)

- Cage will meet/surpass SAE 2019 Rules
- Cage will protect drivers from injury
- The vehicle will be equipped with all safety equipment

Driver Comfort (20%)

- Design will be ergonomic for the driver
- Design will fit drivers of different sizes comfortably

Performance (25%)

- The vehicle will meet performance requirements set forth by the customer
- The vehicle will be able to complete all tests during the Baja SAE competition

Cost (25%)

- The build/manufacturing of the Baja car will remain within the University SAE Baja Budget

QUALITY FUNCTION DEPLOYMENT

			Engineering Requirements (units)																	
		Importance wt.	Acceleration 0-20 (mph^2)	Turning Radius (ft)	Factory of Safety (SF)	Ground Clearance (in)	Wheel Travel (in)	45 Degree Incline (Degrees)	Materials Cost ($)	Braking Distance (ft)	Leg Room (in)	Weight (lbs)	Sustains Drop (ft)	Torque (lbf)	Speed (mph)	Stiffness (lbs/in)	Customer Satisfaction Rating (0.00 - 1.00)			
	Customer Requirements		1	2	3	4	5	6	7	8	9	10	11	12	13	14	CP	A	B	C
1	Accelerates Quickly	0.10	9									9		9	3		0.6	0.6	0.5	0.6
2	Maneuvers Easily	0.10		9		1				1		3				3	0.5	0.7	0.9	0.7
3	Meets Safety Specifications	0.15			9				3	1	1		1				0.2	0.8	0.7	1
4	Drives Over Large Obstacles	0.10				9	3						3	3		1	0.6	0.6	0.7	0.7
5	Climbs Steep Grade	0.05	3					9				1		9	1		0.4	0.7	0.8	0.5
6	Low Maintenance	0.05							9								0.7	0.5	0.8	0.6
7	Cost Efficient	0.10							9			3					0.6	0.5	0.6	0.8
8	Brakes Quickly	0.10			1					9		3					0.7	0.8	0.7	0.7
9	Ergonomical	0.10									9						0.6	0.7	0.8	0.6
10	Lightweight	0.15	3		1			3	9	3		9	3	3	3	3	0.7	0.7	0.9	0.9
	Total Importance	1.00																		
	Engineering requirement importance		1.5	0.9	1.6	1	0.3	0.5	3.2	1.2	1.1	3.2	0.9	2.1	0.8	0.9				
Performance	Current Product		2	1	1	2	3	2	3	3	3	4	2	3	3	2				
	competitor A		3	2	4	3	3	3	2	4	4	3	3	3	3	3				
	competitor B		2	2	3	3	2	2	3	4	3	4	3	2	3	3				
	competitor C		1	1	4	2	2	1	3	4	1	4	4	2	2	2				
	New Product Targets		4.5	4	5	3.5	4	4	3.5	4	4.5	4	5	4.5	3.5	4				

Interaction Matrix															
	Engineering Requirements	Acceleration 0-20 (mph^2)	Turning Radius (ft)	Factory of Safety (SF)	Ground Clearance (in)	Wheel Travel (in)	45 Degree Incline (Degrees)	Materials Cost ($)	Braking Distance (ft)	Leg Room (in)	Weight (lbs)	Sustains Drop (ft)	Torque (lbf)	Speed (mph)	Stiffness (lbs/in)
Engineering Requirements		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Acceleration 0-20 (mph^2)	1		-3	-3	-9	-9	3	1	-9	-9	3	-9	9	3	-1
Turning Radius (ft)	2			-3	-3	-3	-9	-1	-9	-9	-9	-9	-1	-1	1
Factory of Safety (SF)	3				-3	-3	1	9	3	1	1	3	-3	1	-3
Ground Clearance (in)	4					9	1	1	-3	-9	3	3	-9	-9	3
Wheel Travel (in)	5						1	3	-3	-9	3	9	-3	-3	9
45 Degree Incline (Degrees)	6							1	-9	-9	3	-3	9	3	1
Materials Cost ($)	7								3	-3	9	3	3	3	3
Braking Distance (ft)	8									-9	9	-9	-3	9	3
Leg Room (in)	9										-9	-9	-9	-9	-9
Weight (lbs)	10											3	3	9	1
Sustains Drop (ft)	11												-9	-9	9
Torque (lbf)	12													3	3
Speed (mph)	13														1
Stiffness (lbs/in)	14														

DESIGN

Design alternatives and selection

Figure 5: A-Arm Suspension

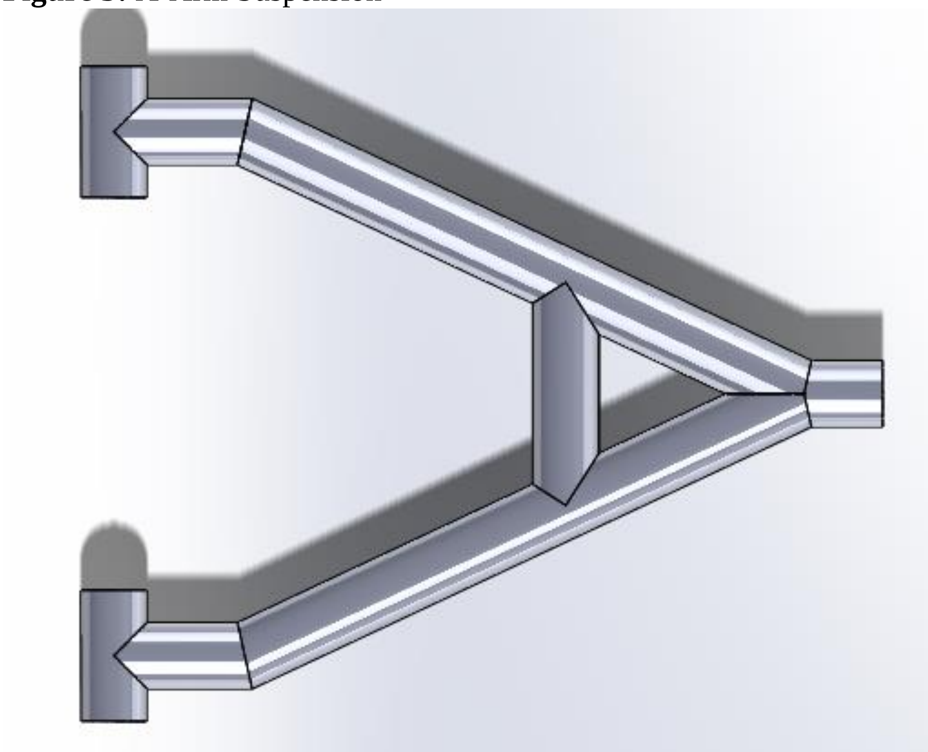


Figure 6: Trailing Arm Suspension

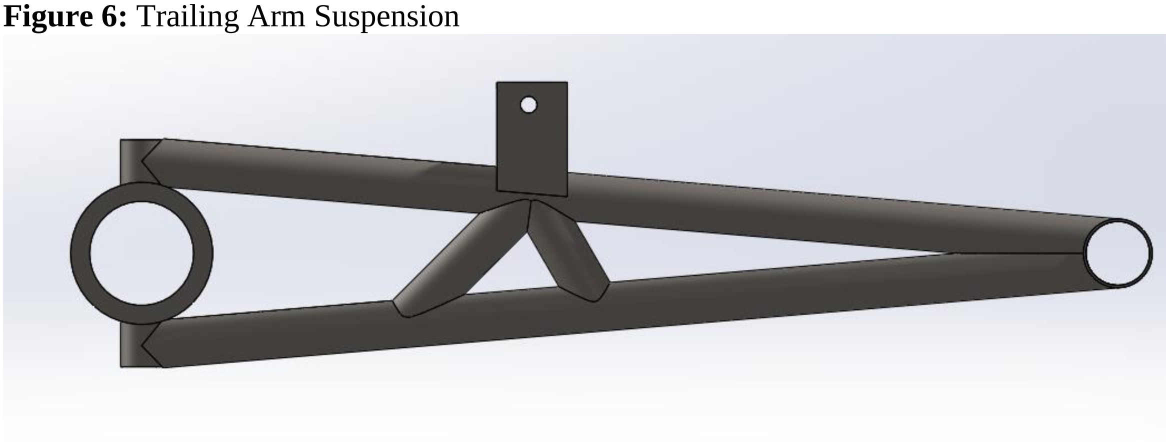
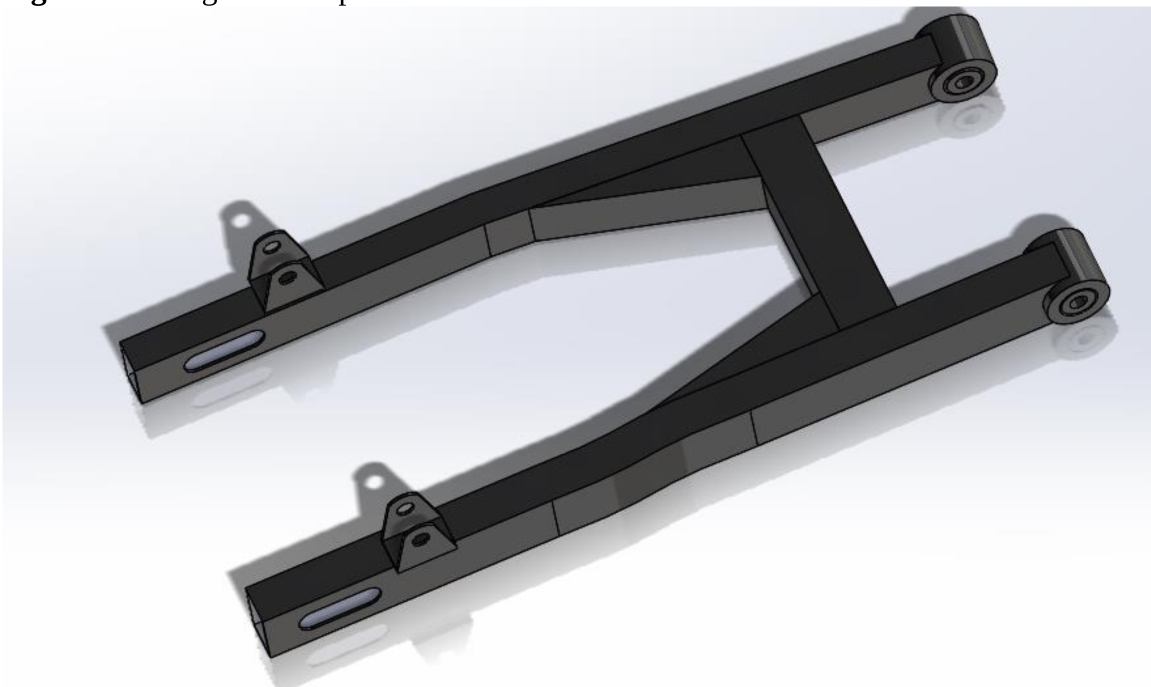
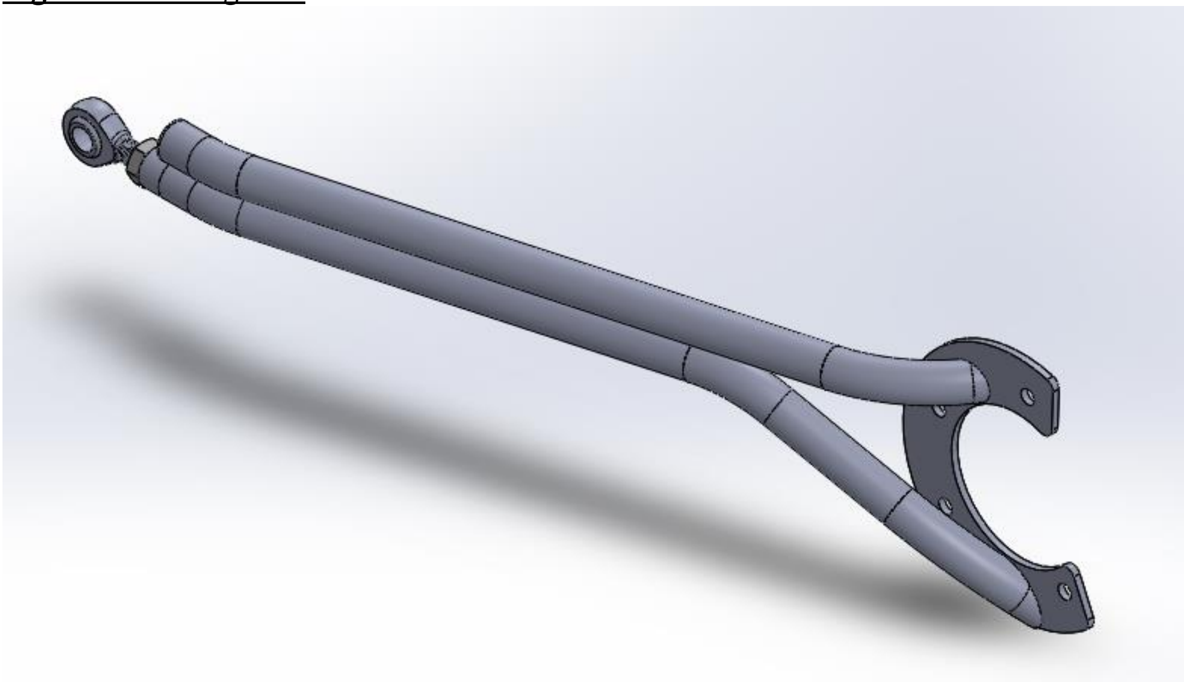


Figure 7: Swing Arm Suspension



Selection

<u>**Figure 8:** Trailing Arm</u>



Drawings

<u>**Figure 9:** Trailing Arm</u>

- Trailing arms were designed to ensure the most ground clearance as possible, by mounting to the frame with the lower trailing arm tube.

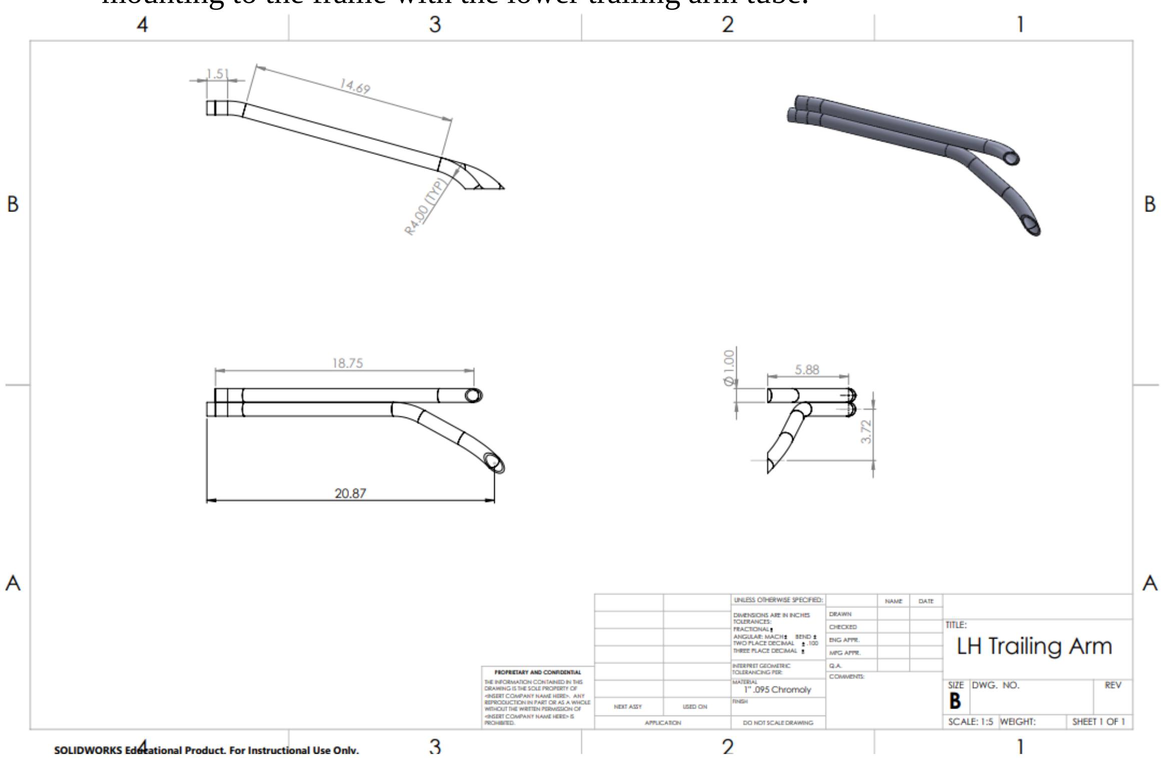


Figure 10: Trailing Arm Plate

- Custom trailing arm plates were waterjet cut to attach the trailing arm to a standard Polaris bearing carrier.

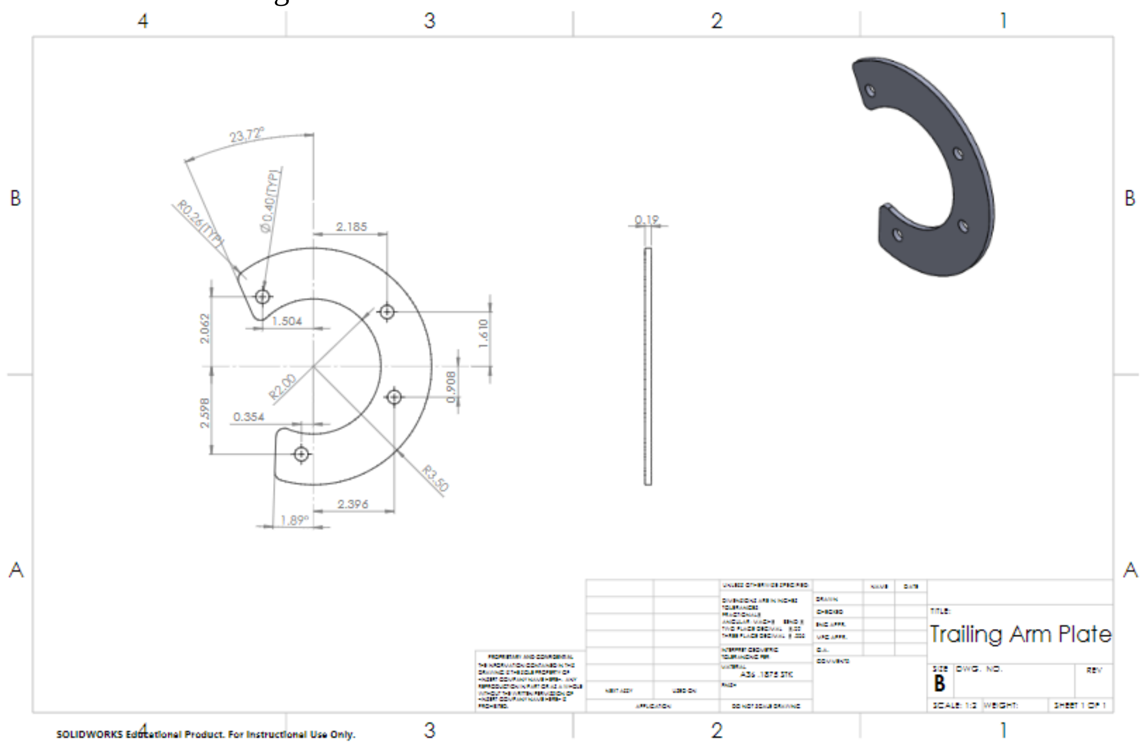


Figure 11: Polaris Bearing Carrier

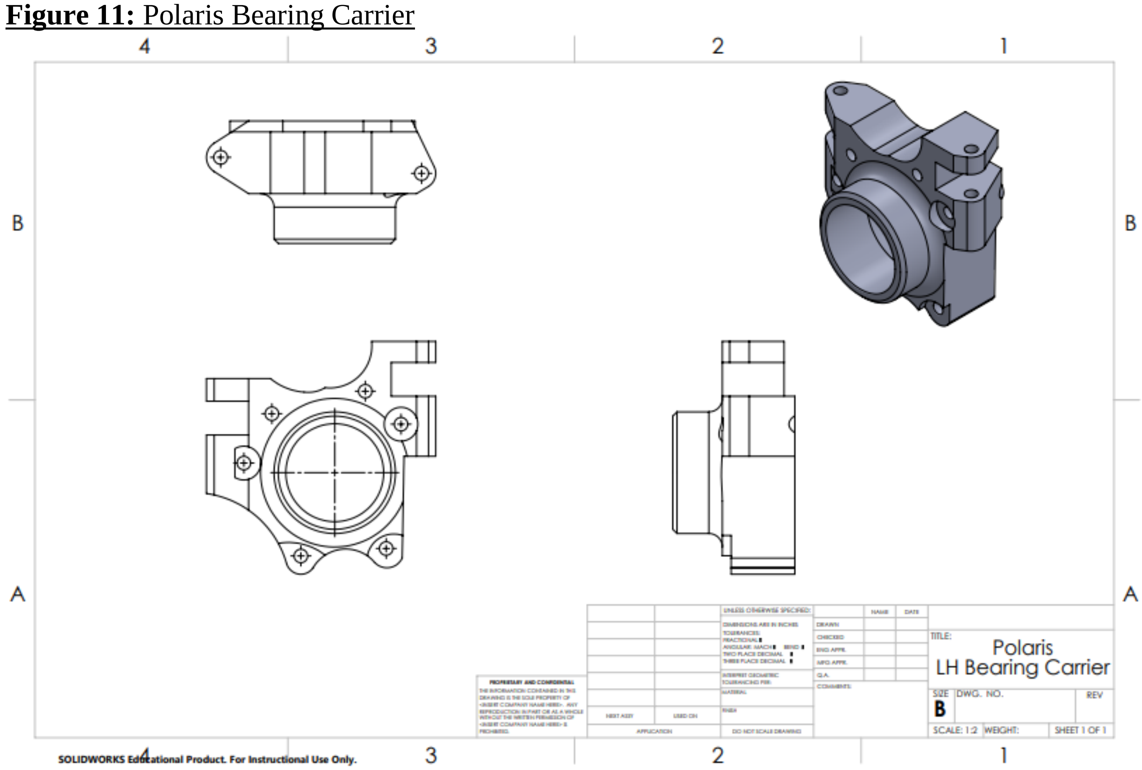


Figure 12: Polaris Rear Hub

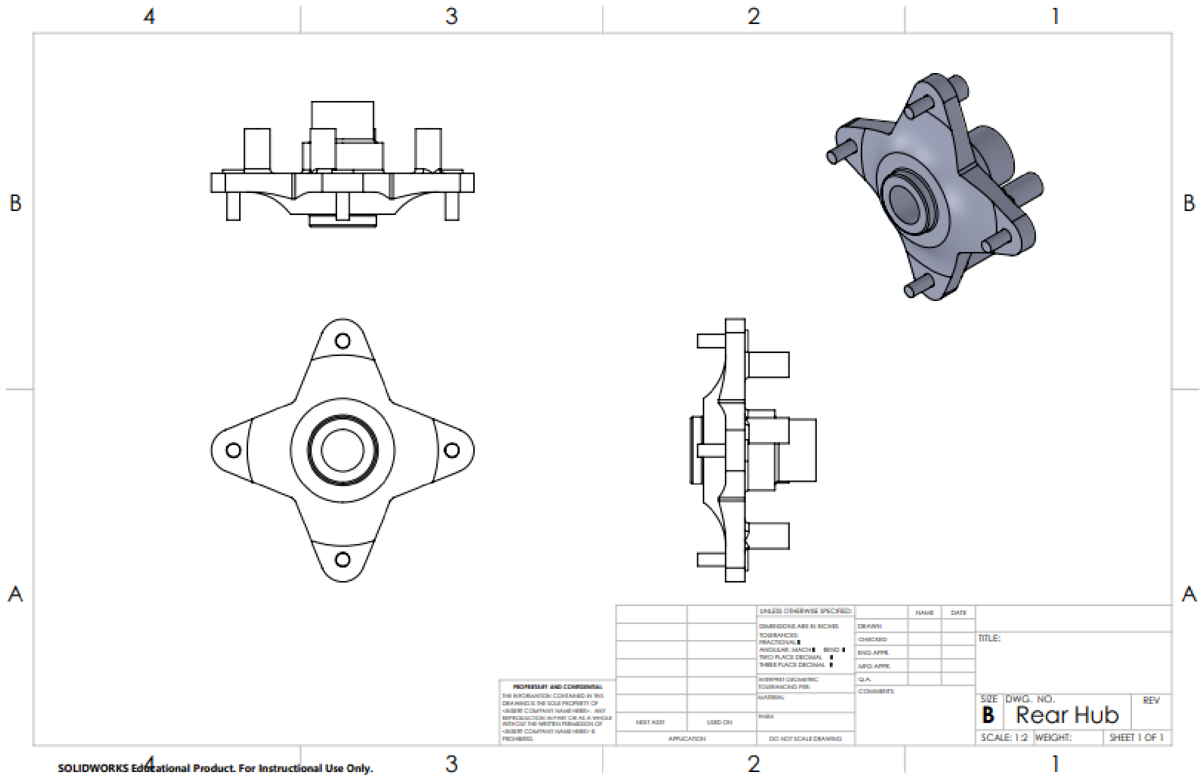


Figure 13: Trailing Arm Assembly

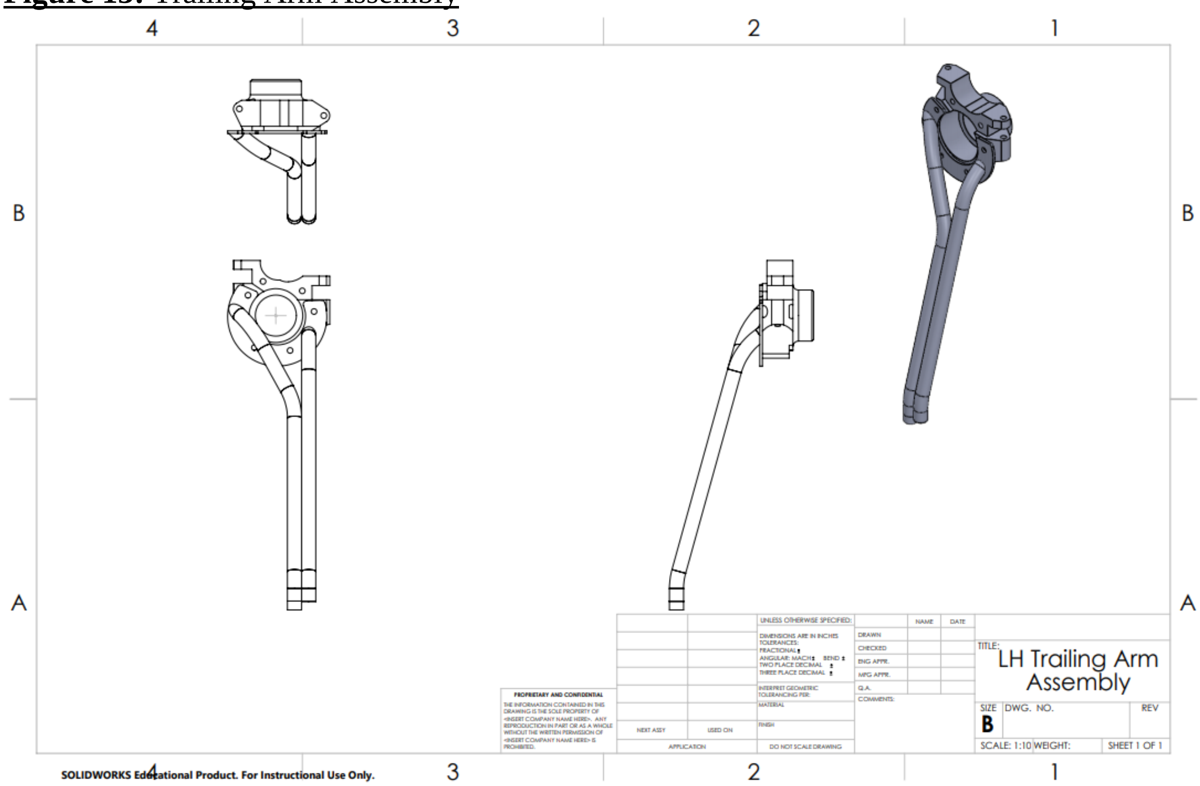


Figure 14: CV Shaft

- Custom CV shafts were built to allow for plunging motion to happen in the shaft since the internal CV joint was replaced with an outer joint for increased angle because of the large amount of ride height and wheel travel.

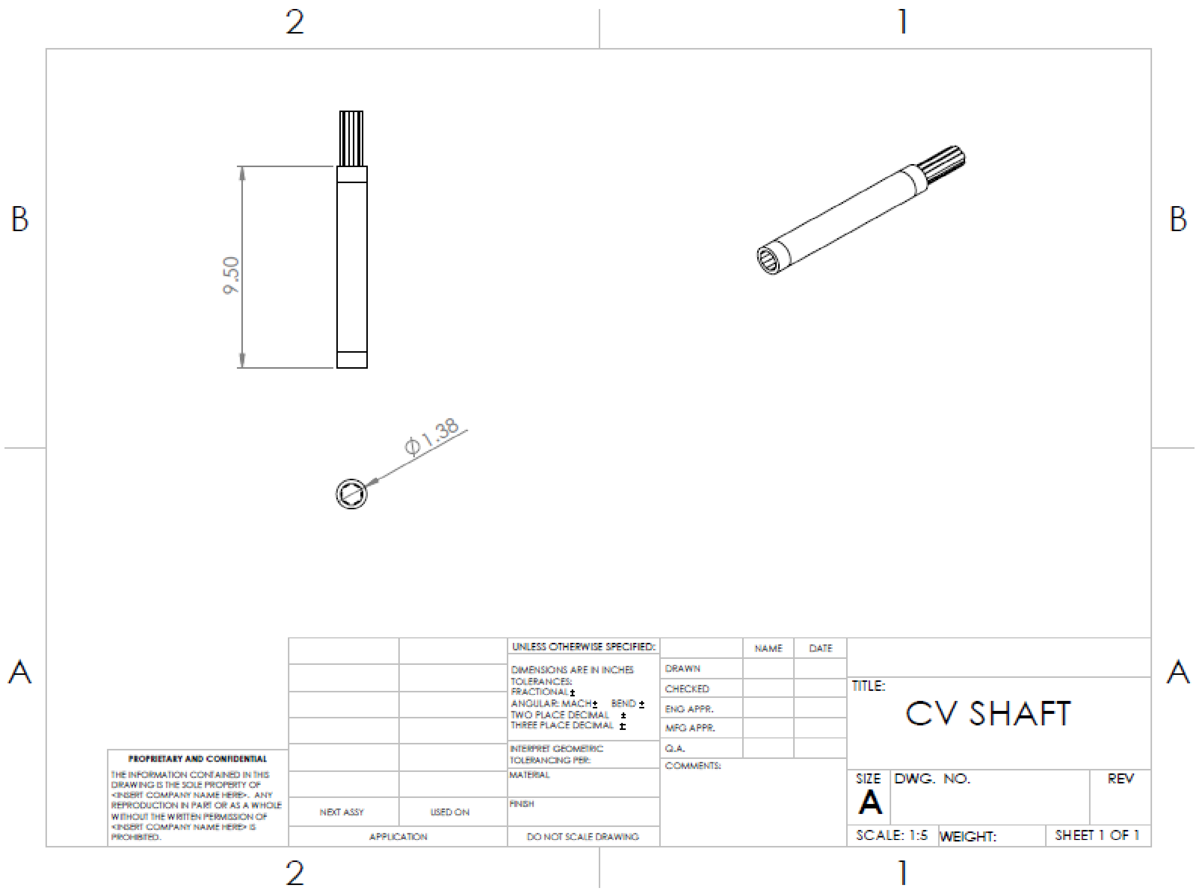


Figure 15: Radius Rods

- Bent lower radius rods were designed to allow for greater clearance when moving over obstacles.

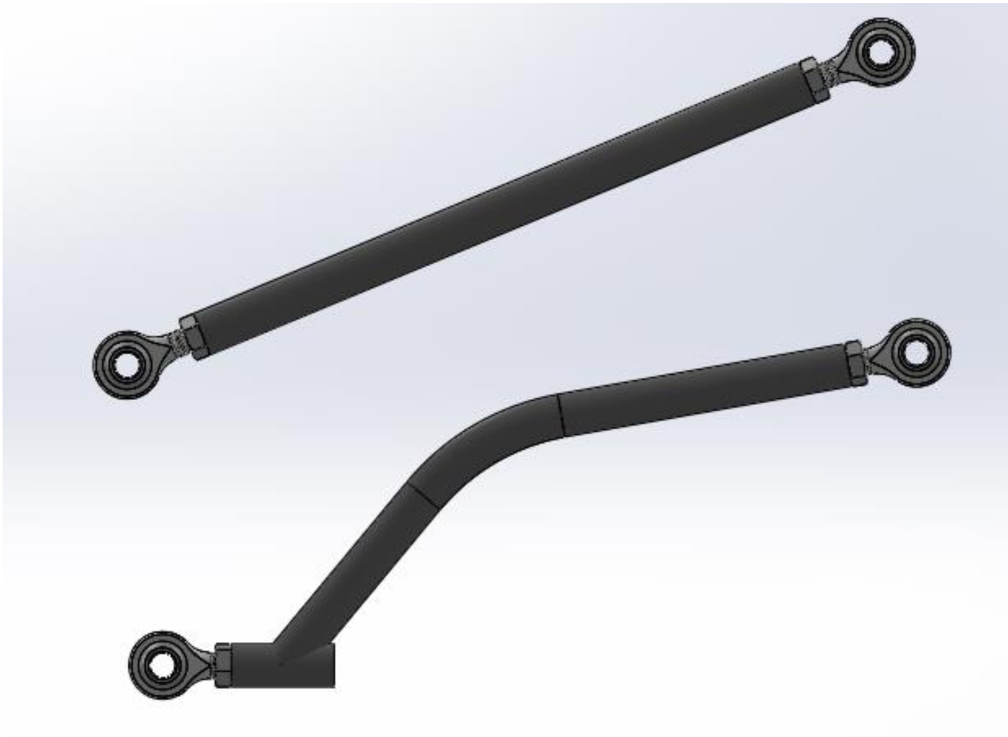
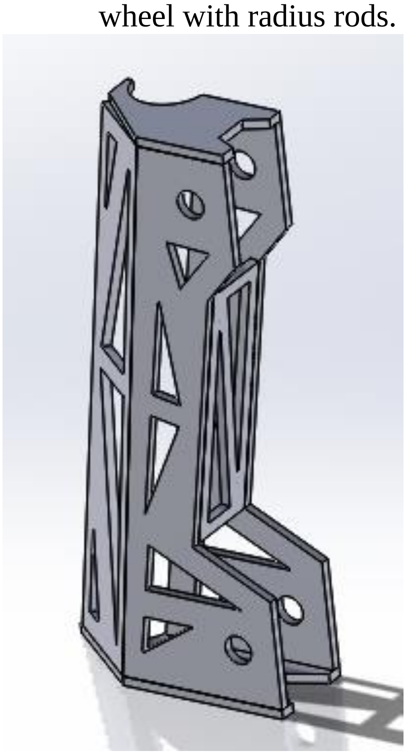


Figure 16: Radius Rod Frame Mount

- Offset radius rod mounts were designed to reduce misalignment from the frame to wheel with radius rods.



Loading Conditions

Initial PE = Final KE

$$mgh = \frac{1}{2}mv^2$$

$$W = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

$$F_{avg} = \frac{\frac{1}{2}mv_f^2}{d}$$

$$\sigma = \frac{F}{A}$$

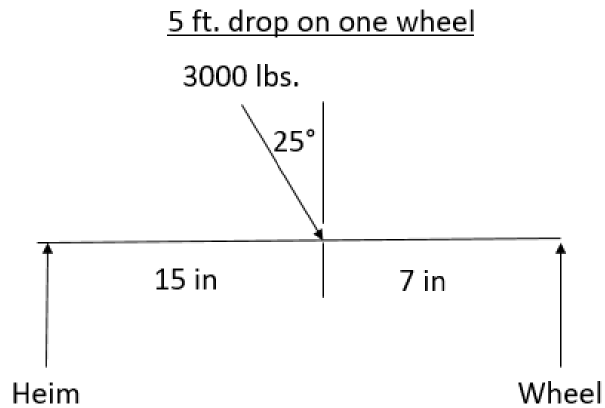
$$A = \frac{\pi}{4}({d_o}^2 - d^2$$

$$Iy = \frac{\pi(d_o^4 - d_i^4)}{64}$$

Table 1: Vertical Drop Test

Vertical Drop Test (5 ft.)	
Weight of car and driver (lbs.)	600
Drop Height (ft.)	5
Gravity (ft./s^2)	32.2
Mass (slugs)	18.63
Potential Energy (ft.-lbs.)	3000
Velocity Initial (ft./s)	0
Velocity Final (ft./s)	17.93
Kinetic Energy (ft.-lbs.)	3000

Figure 17: 5-Foot Drop



Spring Specifications:

- Shock travel: 10 inches
- Static ground clearance: 15 inches
- Motion ratio: .68
- Un-sprung weight: 165 lbs.
- Sprung weight: 130 lbs.
- Shock Angle: 25*
- Angle Correction: .91

$$Motion\ Ratio = \frac{15}{22} = .681$$

$$Spring\ Force = \frac{130}{.68} = 190.9$$

$$Corrected = \frac{190.9}{.91} = 209.8$$

$$Spring\ rate = \frac{209.8}{(17\ x\ .25)} = 55.9$$

$$K_{eff} = \frac{(150\ x\ 75)}{(150+75)} = 50\ lb/in$$

Table 2: Spring Rate VS Force Chart

		Force (lbf)			
		50	100	150	250
		Shock Travel (in)			
Top Spring (k)	75	**0.67**	**1.33**	**2.00**	**3.33**
Bottom Spring (k)	150	**0.33**	**0.67**	**1.00**	**1.67**
Effective Spring (k)	50	**1**	**2**	**3**	**5**

Component Selection

Table 3: Material Properties

Material	Yield Strength (PSI)	Tensile Strength (PSI)
4130	63000	97200
A36	36000	62000

- 1” OD x .095 - 4130 tubing
- .875” OD x .058 - 4130 tubing
- .25” A36 plate
- .125” A36 plate

Bill of Material

Table 4: Bill of Material

BILL OF MATERIAL		
PART NUMBER	**QUANTITY**	**DESCRIPTION**
ALL22046-8	2	1" X .095" ROUND TUBE
TB000140	2	1" X .095" 5/8-18 TUBE END
XML10	2	5/8-18 ROD END
HMS108Z	4	5/8 X 1/2 MISALIGNMENT SPACERS
B8 8125	2	MONOTUBE SHOCK - 10 IN TRAVEL
0350.250.0075	2	75 LB SPRING
1200.250.0150S	2	150 LB SPRING
5137278	2	RZR 900 HUB
5137181	1	RZR 900 RH BEARING CARRIER
5137180	1	RZR 900 LH BEARING CARRIER
R13WH76AG	1	RZR 900 CV/AXLE SET
3514699	2	BALL BEARING
7710440	2	RETAINING RING
7547337	2	M18 X 1.5 CASTLE NUT
7518378	8	3/8-24 X 1.38 WHEEL STUD
0332-00390	2	SPLINE SHAFT -10 INCH
91257A722	4	1/2-13 X 2-1/2 LONG GRADE 8 BOLT
92018A540	4	1/2-13 NYLON LOCKNUT

PROJECT MANAGEMENT

BUDGET, PROPOSED/ACTUAL

Table 5: Proposed Budget

Rear Suspension Budget Proposed		
Item	**Total**	**Type of Funding**
Raw Material	$150	Project Funding
Manufacturing	$50	School Shop
Shocks	$1000	Sponsor
Rod Ends/Spacers	$75	Project Funding
Hardware	$75	Project Funding
Springs (x4)	$220	Project Funding
RZR 900 Bearing Carriers (x2)	$350	Project Funding
RZR 900 Hubs (x2)	$200	Project Funding
RZR 900 Bearings (x2)	$90	Project Funding
RZR 900 CV Joint (x2)	$160	Project Funding
Spline Shaft	$120	Project Funding
Total:	**$2490**	
Adjusted Total:	**$1490**	

Table 6: Actual Budget

ACTUAL BUDGET				
PART NUMBER	QUANTITY	DESCRIPTION	PRICE (EA)	PRICE (EX)
ALL22046-8	2	1" X .095" ROUND TUBE	$ 48.00	$ 96.00
TB000140	2	1" X .095" 5/8-18 TUBE END	$ 3.50	$ 7.00
XML10	2	5/8-18 ROD END	$ 16.00	$ 32.00
HMS108Z	4	5/8 X 1/2 MISALIGNMENT SPACERS	$ 2.20	$ 8.80
B8 8125	2	MONOTUBE SHOCK - 10 IN TRAVEL	$ -	$ -
0350.250.0075	2	75 LB SPRING	$ 61.50	$ 123.00
1200.250.0150S	2	150 LB SPRING	$ 57.00	$ 114.00
5137278	2	RZR 900 HUB	$ 100.00	$ 200.00
5137181	1	RZR 900 RH BEARING CARRIER	$ 175.00	$ 175.00
5137180	1	RZR 900 LH BEARING CARRIER	$ 175.00	$ 175.00
R13WH76AG	1	RZR 900 CV/AXLE SET	$ 139.00	$ 139.00
3514699	2	BALL BEARING	$ 45.00	$ 90.00
7710440	2	RETAINING RING	$ 12.50	$ 25.00
7547337	2	M18 X 1.5 CASTLE NUT	$ 2.25	$ 4.50
7518378	8	3/8-24 X 1.38 WHEEL STUD	$ 0.53	$ 4.24
0332-00390	2	SPLINE SHAFT -10 INCH	$ 61.50	$ 123.00
91257A722	4	1/2-13 X 2-1/2 LONG GRADE 8 BOLT	$ 1.10	$ 4.40
92018A540	4	1/2-13 NYLON LOCKNUT	$ 0.29	$ 1.16
			TOTAL	**$ 1,322.10**

SCHEDULE, PROPOSED /ACTUAL

Figure 18: Proposed Schedule

Proposed Schedule								
	September	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Research								
Concept Selection								
3D Modeling								
Winter Presentation								
Order Materials								
Manufacture								
Testing								
Tech Expo								
Spring Presentation								

Figure 19: Actual Schedule

Actual Schedule								
	September	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Research								
Concept Selection								
3D Modeling								
Winter Presentation								
Order Materials								
Manufacture								
Testing								
Tech Expo								
Spring Presentation								

When starting the project and laying out a schedule, one of the assumptions made was that after designing we would go straight into manufacturing. It was quickly learned that this is not case, there were several major design changes after starting manufacturing once issues were discovered while assembling. Due to these changes the 3D modeling lasted throughout the entire project, whether it was major components, or minor items like tabs that were initially not thought of. Manufacturing and testing were also pushed back due to time constraints. A major setback in my project came from the full car model with all the major components placed into it. The gearbox was not drawn correctly, which then led to changes in the frame. The changes in gearbox location and rear frame design would then change the length of trailing arms and location of upper shock mounts.

CONCLUSIONS

The main goal of this project was to design and manufacture a rear suspension that improves on the flaws of previous years' designs. The primary objectives were increased wheel travel, higher ground clearance, and reduced cost. In 2017 the total wheel travel given by the rear suspension was 9.48" and in 2019 the wheel travel was increased by 4.02 inches with a total of 13.5" of travel. The ground clearance was also improved upon, with a static ground clearance of 15.5 inches, it is 3.5" higher than the 2017 car. Reducing cost was a large factor in the build process of the project this year due to the fact as a whole team we did not have the budget previous years were accustom to having. Comparing again to the cost of the rear suspension in 2017 which was $1996.02, building a whole new rear suspension I was able to reduce the cost to $1322.10 which is a 33.7% savings.

The weight of the 2019 car is the main criteria that could use improvement. When considering the rear suspension lighter tubing could be utilized on the trailing arms, and if possible custom bearing carriers made of aluminum, but similar to the Polaris design to ensure use of standard parts, would significantly reduce the system weight.

PROJECT SUMMARY

In summary the project went well, we were able to complete the car on time for tech expo and testing thereafter. Custom fixtures were machined to hold the trailing arms in place during welding to ensure symmetry between the driver and passenger side. All manufacturing was done in house, with the use of the machine shop at victory parkway, weld shop, and fabrication tools located in the N104 lab room. Even though the university allows for machine shop hours, if it is possible to become a trustee of the machine shop and weld shop it would further expedite the build process when those rooms aren't available.

Figure 20: Custom Jig Table

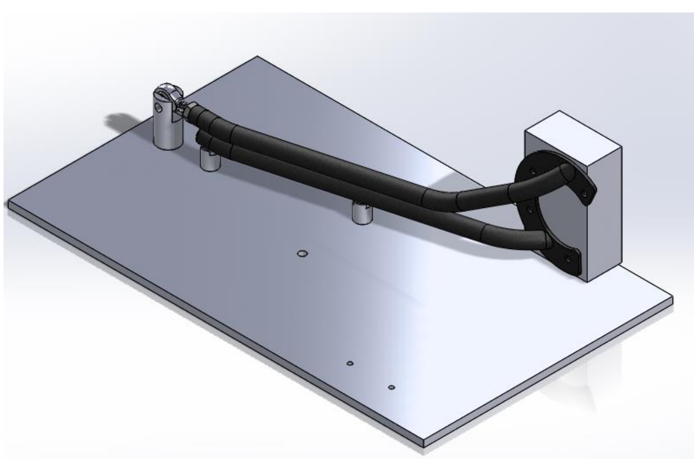


Figure 21: Custom Tube Holders

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APPENDIX A

Completed 2019 Baja Car