2017 Bearcats Baja SAE – 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 2017

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2017 Baja SAE Rear Suspension

Alexander Hurst
Rear Suspension

ABSTRACT

Bearcats Baja SAE is a collegiate team that designs, builds, and races Baja vehicles. This report discusses the design of the rear suspension for the 2017 vehicle.

The design will be working on the University of Cincinnati SAE Bearcats Baja Team's vehicle. The task is to design or reverse engineer a previous year's rear suspension. Types of rear suspension best suited for the vehicle: Trailing arms or A-Arms will be chosen. The report will provide justification on why the certain type of suspension was chosen and provide data to support the design.

PROBLEM DEFINITION

Design a trailing arm rear suspension capable of traversing through muddy and mountain like terrain during an endurance race.

The rear suspension must be compatible with the current frame that was designed and manufactured in 2016. The CAD model of the frame is available on SolidWorks. The suspension must be able to withstand multiple tests that are performed during the endurance race.

The rear suspension is designed depending upon the dynamic events the vehicle will be tested on: Acceleration, Hill Climb or Traction, Land Maneuverability, Suspension, Rock Crawl, and Endurance. Other factors to be included in the design concept will be design evaluations from judges and cost report.

RESEARCH

Previous year's vehicles were reviewed and researched. The reports were compared to one another, and also compared to the results during competition. The 2013 vehicle is the best rear suspension design from the data available. Reverse engineering was focused on the 2013 vehicles rear suspension; however other year's vehicles were analyzed to determine if anything could be improved to the final rear suspension.

2013 vehicle – trailing arm concept was reverse engineered. Out board brakes were utilized.

2017 Rear Suspension SAE Rules:

- Batteries which are not recharged by the alternator may not power any controls or actuation functions on the suspension.
    - Only batteries recharged by the alternator may power controls or actuation functions on the suspension
- Any instrumentation that provides live feedback from the suspension must be added on the cost report.
- All suspension links exposed in the cockpit must be shielded with metal.
- Suspension cannot be capable of pinching any brake line components.
    - Must be able to have full travel without contacting components.

Decisions on the design will be determined whether to use trailing arms or A-arm style suspension. Other components that need designed or purchased include; lateral links, shocks and attachment hardware for the frame, gear box, wheels, tires, shocks, and CV shaft.

CAD Assisted Research

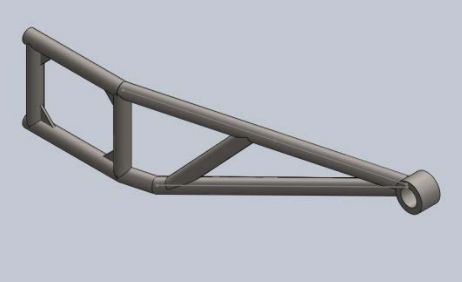


Figure 1 - Initial Trailing Arm Design

Trailing arm design was optimized for weight and strength through SolidWorks Finite Element Analysis (FEA). Initial design displays gussets in each corner of the back portion of the trailing arm. The design was to provide extra support to the tubing where the bearing carrier mounting brackets would be welded. After analysis the gussets were able to be removed from the design while still keeping substantial structural rigidity for the design force. Another change between initial and final design is the diagonal support member was relocated for increased support under the shock.

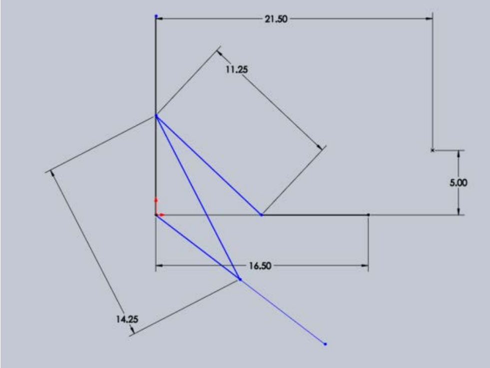


Figure 2 – Rear Suspension Dimensions

The rear suspension was drawn in 2D to determine ideal mounting locations for the trailing arm and air shock on the frame. Geometry was then used to determine the shock force angle as explained below.

Figure 3 - Shock Force Angle

The shock force angle was determined using SolidWorks 3D assembly models. When the shock reaches full compression during a landing the angle between the shock body and a flat landing surface will be 47.44° as shown in Figure 3. The drop force was applied at the full compressed angle.

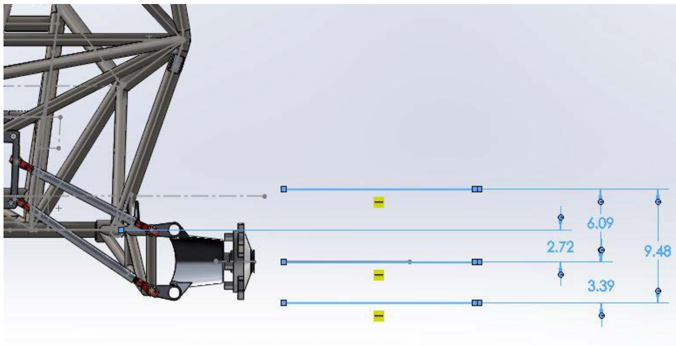


Figure 4 - Wheel Travel

Ground clearance and wheel travel are calculated using SolidWorks 3D assembly models. When the entire load of the driver and gear are in the vehicle the weight was assumed to be 595 lbs. When sitting on a flat surface with this load the center of the wheel will be sitting 2.72” below the frame. This dimension is called ride height. When the vehicle is in the air the shocks will be fully extended which is the droop dimension of 3.39” below the ride height. When shocks are fully compressed the ground clearance loses 6.09” from the ride height. The overall travel of the wheel is 9.48”.

CALCULATIONS

Impact to Stationary Object	
Deceleration (G)	5
Force (lbs)	2975

Figure 5 - Impact Load to Stationary Object

The impact to a stationary object was assumed to be less than a 5G deceleration. This impact would be similar to a vehicle rear ending a stationary vehicle.

Side Load	
Impact Force (G)	4
Force (lbs)	2380.00

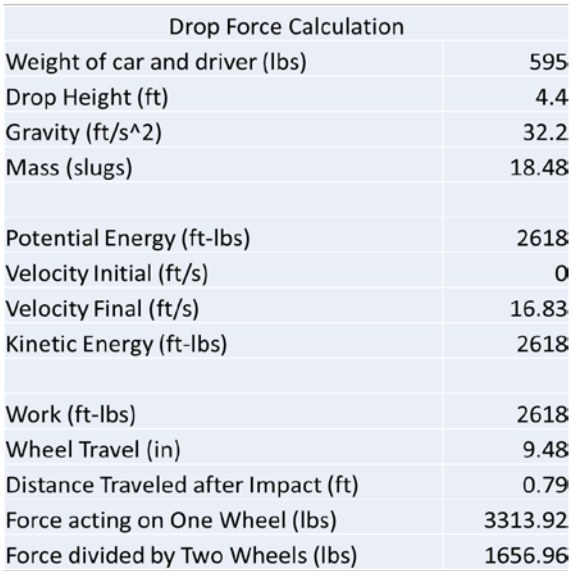
Figure 6 - Side Load

The side load impact force was assumed to be less than 4G of impact. This impact would be similar to sliding into a tree around a corner.

$$mgh = \frac{1}{2}mv^2 \qquad \text{Equation 1}$$

$$W = \frac{1}{2}mv^2{}_f - \frac{1}{2}mv^2{}_i \qquad \text{Equation 1}$$

$$F_{avg} = \frac{\frac{1}{2}mv^2{}_f}{d} \qquad \text{Equation 3}$$



Drop Force Calculation	
Weight of car and driver (lbs)	595
Drop Height (ft)	4.4
Gravity (ft/s^2)	32.2
Mass (slugs)	18.48
Potential Energy (ft-lbs)	2618
Velocity Initial (ft/s)	0
Velocity Final (ft/s)	16.83
Kinetic Energy (ft-lbs)	2618
Work (ft-lbs)	2618
Wheel Travel (in)	9.48
Distance Traveled after Impact (ft)	0.79
Force acting on One Wheel (lbs)	3313.92
Force divided by Two Wheels (lbs)	1656.96

Figure 7 - Apply Drop Force at full shock compression (47.44)

Weight of the gear and driver inside the vehicle is assumed to be 595 lbs. With a drop height of 4.4 ft. the potential energy is transferred to the rear wheels. A landing on both rear wheels will create a force of 1656.96 lbs. acting on the shock mounting locations on the trailing arm and frame positions. When fully compressed the shock will be at the angle of 47.44° which is the angle the drop force was applied.

FEA VERIFICATION

Figure 8 - 4.4ft Drop

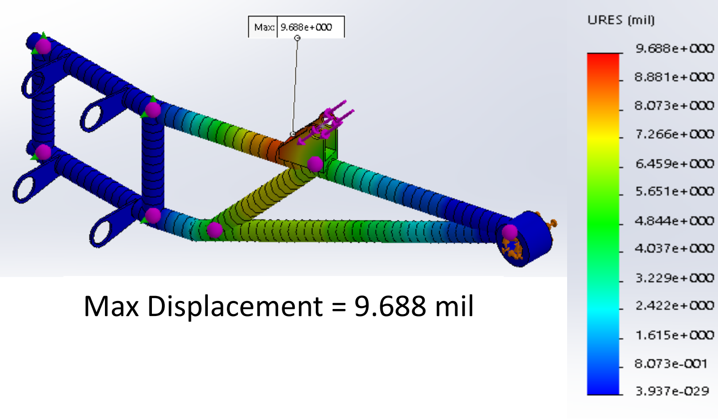


Figure 9 - Deformation

FINAL DESIGN

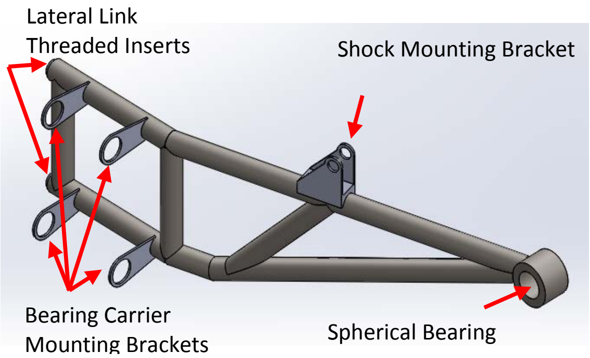


Figure 10 – Trailing Arm

The trailing arm design is the major component of the entire rear suspension design. The tubing was optimized using FEA and the selected material is 4130 Alloy Steel, 0.875" OD, 0.083" wall thickness. The tubing material has a Yield Strength of 70 ksi.

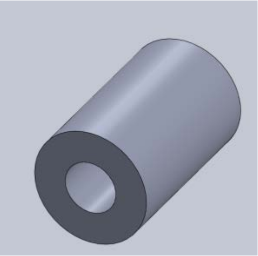


Figure 11 - Lateral Link Threaded Inserts

The lateral link threaded inserts started as a steel alloy rod. The through hole is threaded with 3/8-16 tap for the hardware that connects the trailing arm and heim joint.

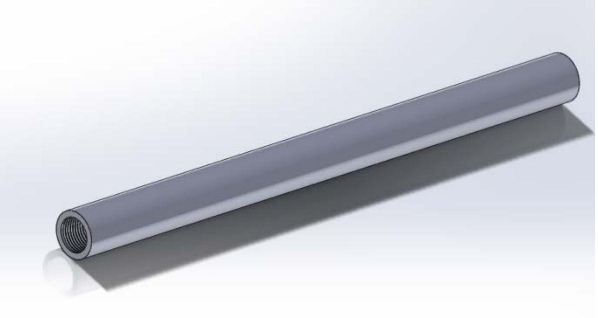


Figure 12 - Lateral Links

Lateral links are made of 6061 Aluminum, ¾" OD. The yield strength of the aluminum rods is 35 ksi. The blind holes are tapped 3/8-24 for the heim joint bolt on each side of the lateral link. The lateral links control the toe and camber setting for the trailing arm.

Mounting Brackets

All mounting brackets were designed and manufactured out of 1/8" steel. Brackets were not analyzed through CAD. Improvements can be made if brackets are optimized with assistance from FEA.

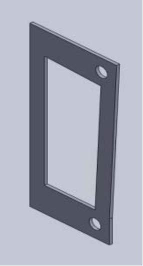


Figure 13 - Lateral Link Mounting Bracket

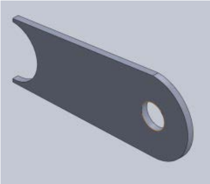


Figure 14 - Hub Mounting Bracket

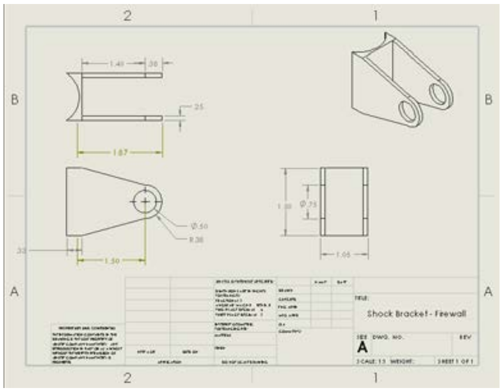


Figure 15 - Firewall Shock Bracket

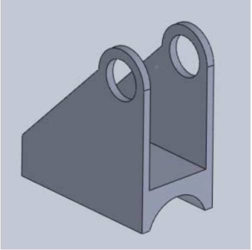


Figure 16 - Shock Bracket on Trailing Arm

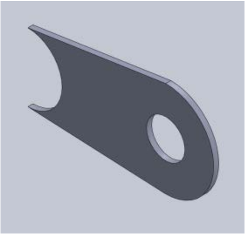


Figure 17 - Trailing Arm Mounting Bracket

The spherical bearing housing is made from a steel alloy rod. The ID is dimensioned for a press fit for the spherical bearing joint assembly.

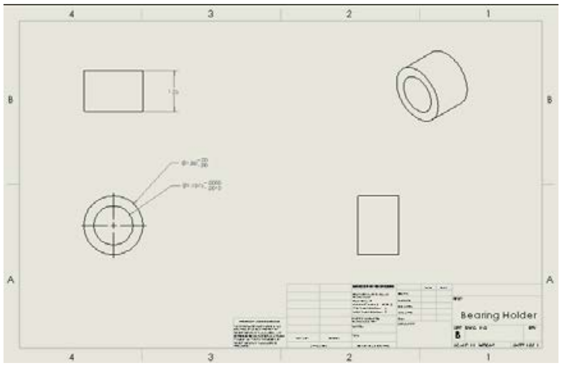


Figure 18 - Bearing Housing

Purchased Components

The spherical bearing is comprised of a steel alloy material with a chrome-plated steel bearing. The spherical bearing's static radial load capacity is 31.9 ksi. The bearing has a PTFE (polytetrafluoroethylene) liner which reduces the friction without requiring lubrication.

Figure 19 - Spherical Bearing

2009 Polaris RZR 800 S parts were used to allow compatibility with brake and drivetrain components. Bearing carriers, wheel bearings, hubs, and hardware components were purchased together for increased ease of assembly.

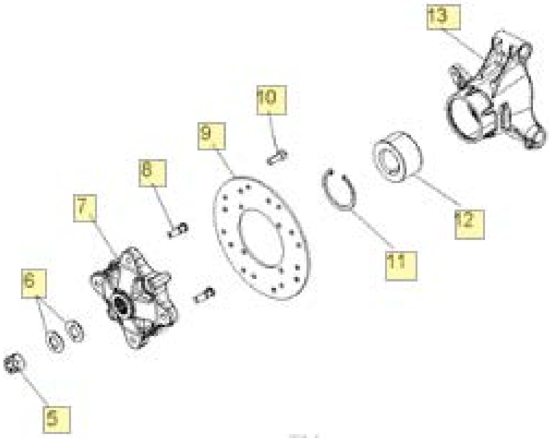
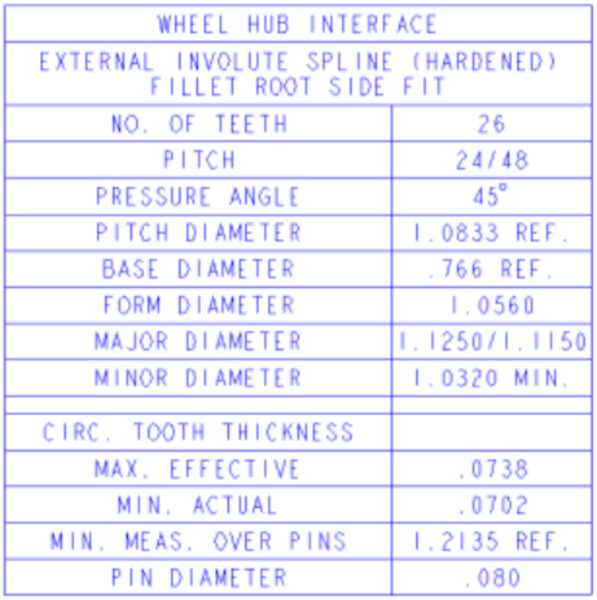


Figure 20 - 2009 Polaris RZR 800 S

The driveshaft spline dimensions which were inserted into the hubs were also part of the 2009 Polaris RZR 800 S assembly. The spline on the gear box side did not match the RZR so manufacturing was completed to combine the two different spline shafts. The spline dimensions are shown in Table 1 below from Polaris.



WHEEL HUB INTERFACE	
EXTERNAL INVOLUTE SPLINE (HARDENED) FILLET ROOT SIDE FIT	
NO. OF TEETH	26
PITCH	24/48
PRESSURE ANGLE	45°
PITCH DIAMETER	1.0833 REF.
BASE DIAMETER	.766 REF.
FORM DIAMETER	1.0560
MAJOR DIAMETER	1.1250/1.1150
MINOR DIAMETER	1.0320 MIN.
CIRC. TOOTH THICKNESS	
MAX. EFFECTIVE	.0738
MIN. ACTUAL	.0702
MIN. MEAS. OVER PINS	1.2135 REF.
PIN DIAMETER	.080

Table 1 - Outer CV Spline

Tires were chosen based off best traction quality and size dimensions to assist wheel travel, ground clearance, and brake force required. The tires selected are 24x8-12 Kenda K299 Bear Claw Tire.

Figure 21 - Kenda K299 Bear Claw Tire

A new wheel was selected which is lighter and stronger than previous years. The Douglas .190 aluminum wheels were chosen with a 4/156 bolt pattern to be compatible with the RZR hubs. The wheels are 12x7 to match the Bear Claw tires. The 4.0+3.0 offset allows for easy access to the calipers which has been an issue in previous years. The access becomes an issue when attempting to bleed the brakes; typically the entire wheel must be removed. 2017 design allows bleeding of the brakes without any disassembly required. This would allow for a quicker pit stop if brake adjustments were required.

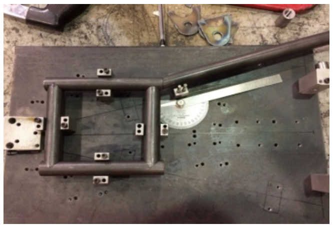
Figure 22 - Douglas .190 Wheels

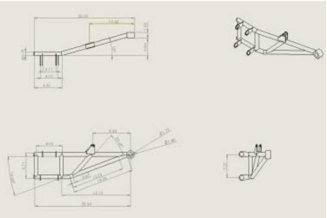
Fox Float Shocks were 13.0” x 2.8” extension. The 16.2” x 4.5” extension was the initial design, but drive shaft travel problems arose with the increase in travel which prohibited the use of longer shocks. The shorter 2.8” extensions shock were the final design which allowed a 9.48” total wheel travel, surpassing the goal wheel travel.

Figure 23 - Fox Float Shocks

Manufacturing

Trailing Arm





Tubing was notched, cut, and ground to create a flush surface before TIG welding. Welding fixtures were created to allow the manufacturing of symmetrical trailing arms in a time efficient manner.

Lateral Link Threaded Inserts

Steel rod was turned down on lathe to correct OD, ID, and length. Insert was then tapped using 3/8-16 tap on the lathe to ensure straight cutting. Initial weld assembly included 3 tack welds along edge of insert and tubing. A failure at Haspin Acres during testing caused a redesign on the weld. Rev2 design: Corner joint weld placed around entire threaded insert diameter without distorting threads.

Figure 24 - Turning material on lathe

Mounting Brackets

Figure 25 - Plasma Cutting

Mounting brackets were initially designed out of 1/16” steel which was chosen because of the similar thickness from past year’s vehicles. Testing proved to have too thin of brackets to withstand maximum forces required. Force was too great acting in the horizontal direction when a braking torque was applied. Brackets were redesigned with Rev2 design: Brackets are 1/8” steel along with additional horizontal reinforcement.

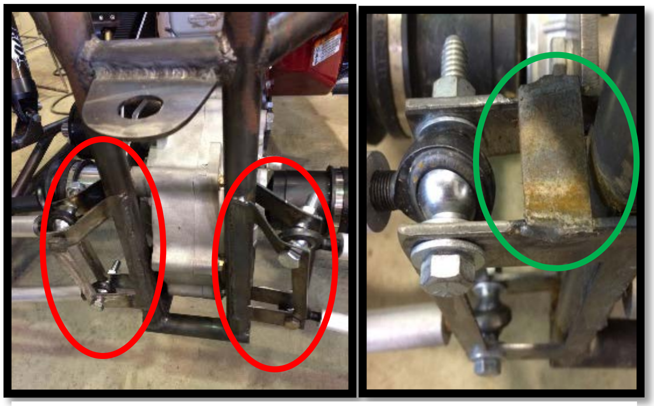


Figure 26 Mounting Bracket Rev1 - Rev2 Change

Lateral link aluminum rod was turned down to ¾” OD and 12” in length for the upper and lower link on each side of the vehicle. The aluminum has a blind-hole drilled 1.5” with a 3/8-24 tap for the heim joints.

Figure 27 - Lateral Links

Spherical bearing housing was welded to the 4130 trailing arm tubing material. Before heat dissipated the spherical bearing was pressed into the housing using Loctite 648 retaining compound as a press fit adhesive. The machined ID of the housing was 15 thousandths of an inch smaller than the spherical bearing OD. When heated from welding the housing allowed for an easier press because of heat expansion while also allowing the adhesive to be applied on the rough surface finish of the housing ID.

Figure 28 - Spherical Bearing Joint Assembly

The driveshaft used a sleeve design to allow two different drive shafts to be combined. A steel alloy rod was turned down to correct dimensions and welded to each of the drive shafts for the gear box and the hub.

Figure 29 - Driveshaft Sleeve

Results

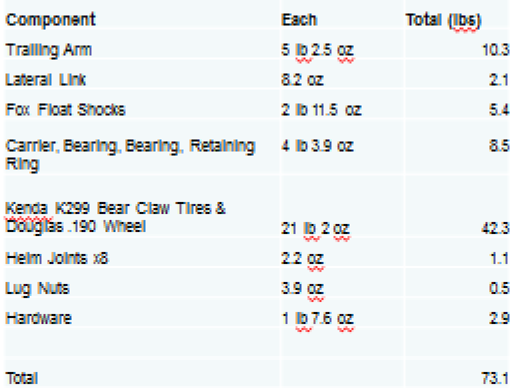
Rear Suspension Results

Weight:	73.1 lbs.
Cost:	$1996.02
Track Width:	57”
Wheel Base:	60.5”
Ground Clearance:	12”
Wheel Travel:	9.48”

Haspin Acres and stair climbs at Victory Parkway Campus were successful. The vehicle tested a 3 ft. drop height which gives the design drop (4.4 ft.) a 1.47 safety factor. Traction from the bear claw tires was essential to obtain the 28 mph speed at the muddy endurance test.

Figure 30 - 3ft Drop Test

The mud tires were 14 lbs. heavier than the 2016 vehicles wheels. This extra weight put the entire rear suspension system 13.1 pounds over the goal weight of < 60 lbs. for a final weight of 73.1 lbs. (21.8% increase).



Component	Each	Total (lbs)
Trailing Arm	5 lb 2.5 oz	10.3
Lateral Link	8.2 oz	2.1
Fox Float Shocks	2 lb 11.5 oz	5.4
Carrier, Bearing, Bearing, Retaining Ring	4 lb 3.9 oz	8.5
Kenda K299 Bear Claw Tires & Douglas .190 Wheel	21 lb 2 oz	42.3
Helm Joints x8	2.2 oz	1.1
Lug Nuts	3.9 oz	0.5
Hardware	1 lb 7.6 oz	2.9
Total		73.1

Table 2 - Weight Summary

Wheel travel was limited due to the driveshaft preventing greater extension. The goal travel was 9” with an actual travel of 9.48” (5.33% improvement).

Rear Suspension - Cost Analysis			
Item	Quantity	Price ea.	Price Total
NUT-M18X1.5,CASTLE	2	1.58	$ 3.16
WASHER, CONE	4	4.39	$ 17.56
Hub, Wheel, Rear	2	63.13	$ 126.26
STUD-3/8-24X1.38,PRESS FIT-Z	8	1.14	$ 9.12
Ring, Retaining	2	8.81	$ 17.62
Bearing, Wheel	2	31.19	$ 62.38
Carrier, Bearing, LH	1	88.54	$ 88.54
Carrier, Bearing, RH	1	88.54	$ 88.54
Asm., Halfshaft, LT, Rear	2	236.99	$ 473.98
Kenda K299 Bear Claw Tire, 24x8-12	2	66.97	$ 133.94
Douglas .190 Wheels 4/156 12x7 4.0+3.0	2	138.95	$ 277.90
4130 Alloy Steel Round Tube, .875" OD, .083" Wall	3	51.55	$ 154.65
6061 Aluminum, 3/4" Diameter	1	21.12	$ 21.12
Fox Float Shocks 13.0" x 2.8"	1 (set)	521.25	$ 521.25
Suspension Total		$ 1,324.15	$ 1,996.02

Table 3 - Cost Analysis

The goal budget of less than $2,000 was met with a final amount of $1996.02 used on the rear suspension (0.2% reduction). 50.1% of this expense is from the driveshaft and Fox Float shocks.

Conclusion

The Kenda Bear Claw mud tires were essential in reaching the 28 mph top speed during the Haspin Acres testing. The traction gained by the mud tires was helpful at the muddy event; however the tires and wheels are 14 lbs. heavier than the 2016 vehicle. The 2016 vehicle used two front tires on the rear which would not have provided enough traction for the event. For events that don’t require as much traction a lighter tire could be a better option to reduce weight. The aluminum wheels attempted to compensate for the extra tire weight.

The ideal shock would be the 4.5” extension instead of the 2.8” actual shock used for the design of the 2017 vehicle. The limiting factor was the shortened travel of the driveshaft and gear box. Just beyond the 2.8” full extension the driveshaft bottoms out in the gear box. The bottoming out would dramatically shorten the lifespan of the spline and bearing in the gearbox. A possible solution to increase travel would be to lower the gearbox, or to come up with a new alternative for the driveshaft.

Mounting brackets were referenced from previous vehicles. Brackets have not been optimized through FEA. A recommendation is to perform analysis on each mounting bracket which could improve the durability and performance of the entire rear suspension.

The budget and weight could both be improved by researching new alternatives for parts which were purchased for the 2017 vehicle. Parts were purchased through Polaris to ensure compatibility due to schedule limitations. These stock parts have been improved by aftermarket retailers, and can be manufactured for an even more financial and performance improvement.

ACKNOWLEDGEMENTS

Thanks to the University of Cincinnati and all of the sponsors for the generous support given to fund Baja SAE. Also a special thanks to Nicholas Platniotis for his dedication to teaching and expertise in the manufacturing field.

CONTACT

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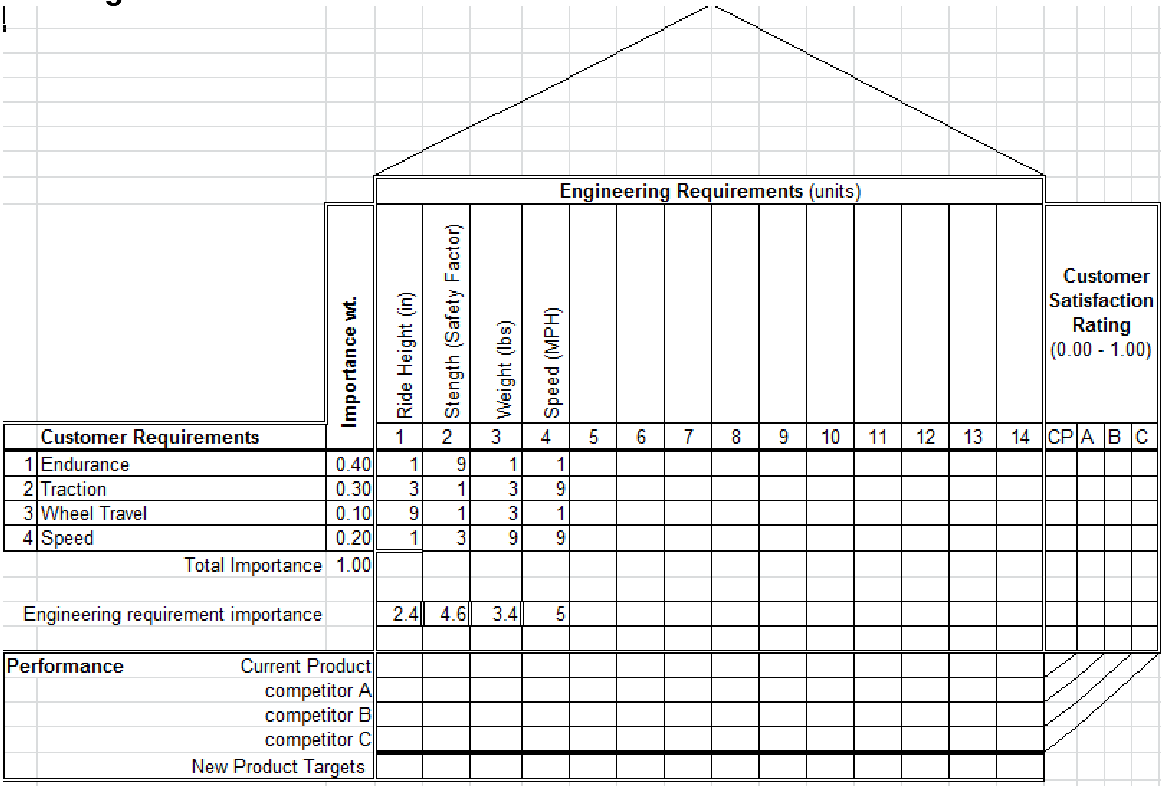
ADDITIONAL SOURCES

"SAE Collegiate Design Series." *Rules*. Web. 25 Sept. 2016

"Explore 34 Snow Forks." *FOX*.. Web. 19 Apr. 2017

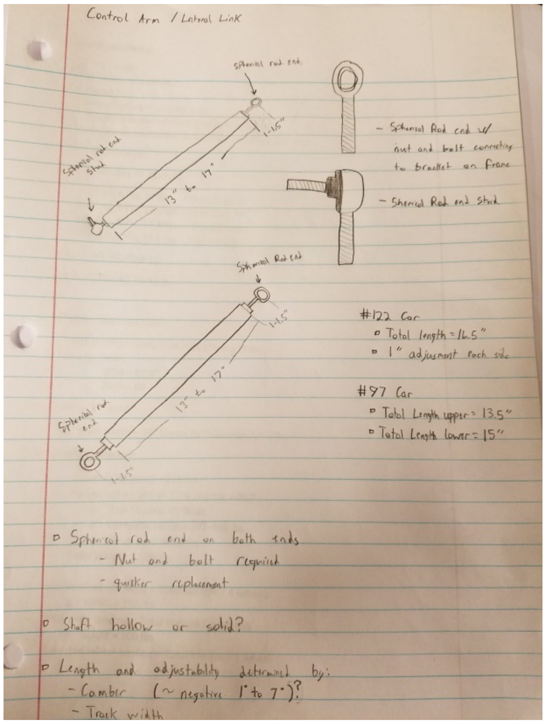
"Wheel Alignment Explained - What Is Camber, Caster and Toe?" *Yospeed*., 26 Mar. 2015. Web. 19 Apr. 2017.

Additional Background



			Engineering Requirements (units)														Customer Satisfaction Rating (0.00 - 1.00)			
		Importance wt.	Ride Height (in)	Stength (Safety Factor)	Weight (lbs)	Speed (MPH)														
	Customer Requirements		1	2	3	4	5	6	7	8	9	10	11	12	13	14	CP	A	B	C
1	Endurance	0.40	1	9	1	1														
2	Traction	0.30	3	1	3	9														
3	Wheel Travel	0.10	9	1	3	1														
4	Speed	0.20	1	3	9	9														
	Total Importance	1.00																		
	Engineering requirement importance		2.4	4.6	3.4	5														
Performance	Current Product																			
	competitor A																			
	competitor B																			
	competitor C																			
	New Product Targets																			

Table 4 - House of Quality



Control Arm / Lateral Link

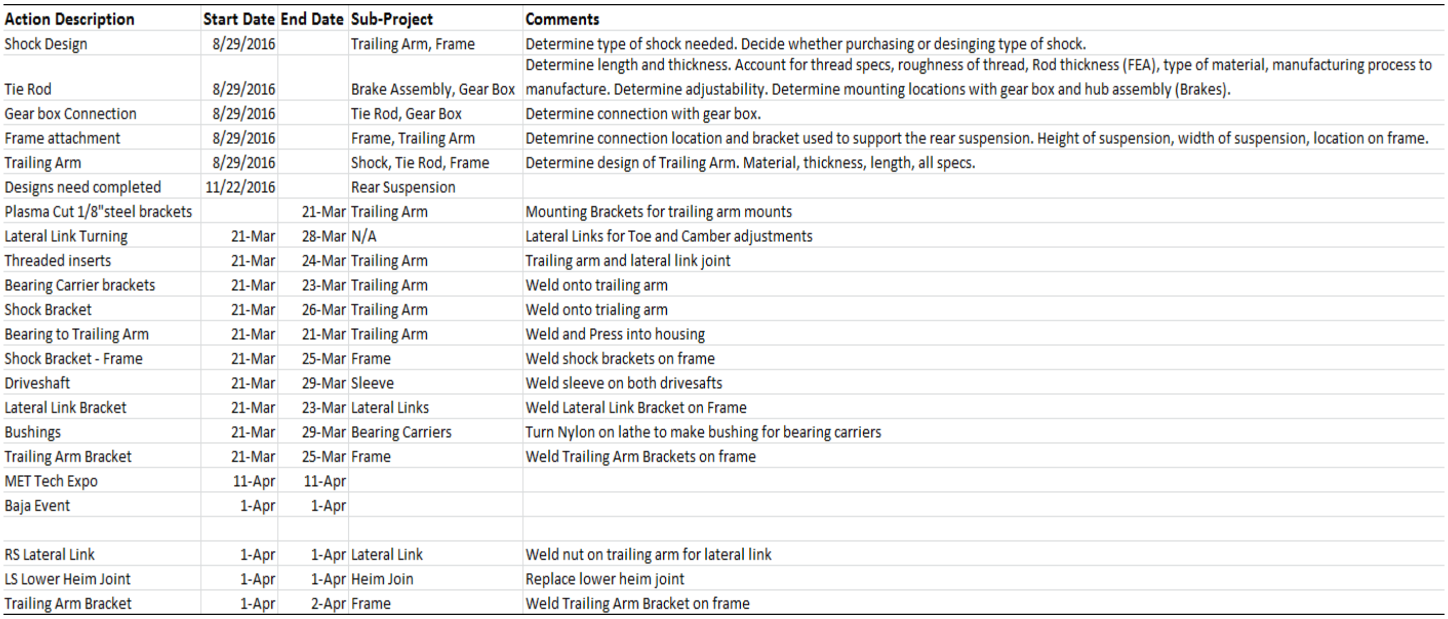
- Spherical Rod end w/ nut and bolt connecting to bracket on frame
- Sherical Rod end Stud

#122 Car
- Total length = 16.5"
- 1" adjusment each side

#97 Car
- Total Length upper = 13.5"
- Total Length lower = 15"

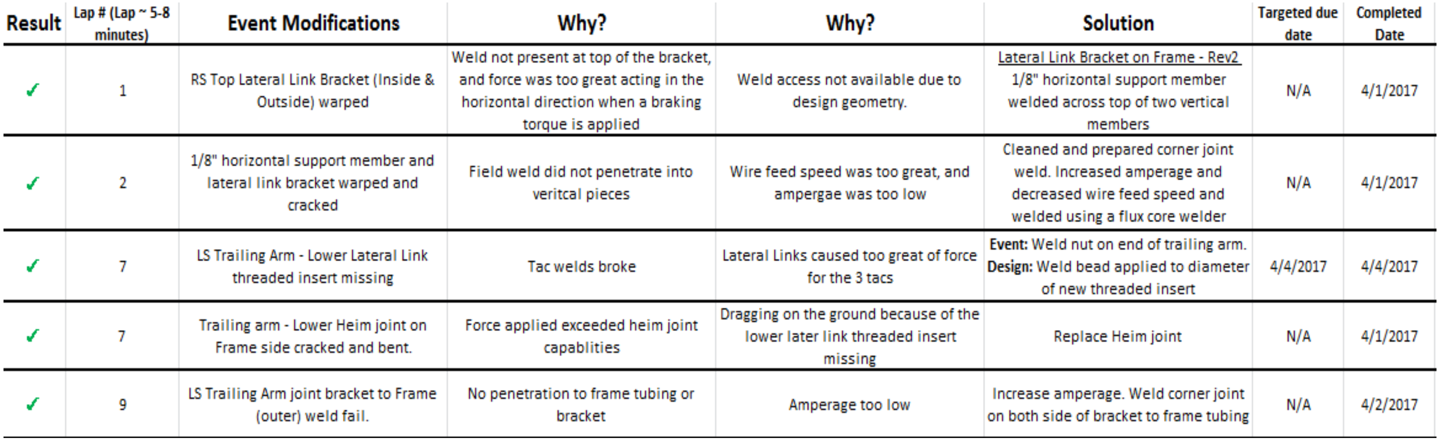
- Spherical rod end on both ends
  - Nut and bolt required
  - quicker replacement
- Shaft hollow or solid?
- Length and adjustability determined by:
  - Camber (~ negative 1° to 7°)?
  - Track width

Figure 31- Initial Lateral Link Design



Action Description	Start Date	End Date	Sub-Project	Comments
Shock Design	8/29/2016		Trailing Arm, Frame	Determine type of shock needed. Decide whether purchasing or desinging type of shock.
Tie Rod	8/29/2016		Brake Assembly, Gear Box	Determine length and thickness. Account for thread specs, roughness of thread, Rod thickness (FEA), type of material, manufacturing process to manufacture. Determine adjustability. Determine mounting locations with gear box and hub assembly (Brakes).
Gear box Connection	8/29/2016		Tie Rod, Gear Box	Determine connection with gear box.
Frame attachment	8/29/2016		Frame, Trailing Arm	Detemrine connection location and bracket used to support the rear suspension. Height of suspension, width of suspension, location on frame.
Trailing Arm	8/29/2016		Shock, Tie Rod, Frame	Determine design of Trailing Arm. Material, thickness, length, all specs.
Designs need completed	11/22/2016		Rear Suspension	
Plasma Cut 1/8"steel brackets		21-Mar	Trailing Arm	Mounting Brackets for trailing arm mounts
Lateral Link Turning	21-Mar	28-Mar	N/A	Lateral Links for Toe and Camber adjustments
Threaded inserts	21-Mar	24-Mar	Trailing Arm	Trailing arm and lateral link joint
Bearing Carrier brackets	21-Mar	23-Mar	Trailing Arm	Weld onto trailing arm
Shock Bracket	21-Mar	26-Mar	Trailing Arm	Weld onto trialing arm
Bearing to Trailing Arm	21-Mar	21-Mar	Trailing Arm	Weld and Press into housing
Shock Bracket - Frame	21-Mar	25-Mar	Frame	Weld shock brackets on frame
Driveshaft	21-Mar	29-Mar	Sleeve	Weld sleeve on both drivesafts
Lateral Link Bracket	21-Mar	23-Mar	Lateral Links	Weld Lateral Link Bracket on Frame
Bushings	21-Mar	29-Mar	Bearing Carriers	Turn Nylon on lathe to make bushing for bearing carriers
Trailing Arm Bracket	21-Mar	25-Mar	Frame	Weld Trailing Arm Brackets on frame
MET Tech Expo	11-Apr	11-Apr		
Baja Event	1-Apr	1-Apr		
RS Lateral Link	1-Apr	1-Apr	Lateral Link	Weld nut on trailing arm for lateral link
LS Lower Heim Joint	1-Apr	1-Apr	Heim Join	Replace lower heim joint
Trailing Arm Bracket	1-Apr	2-Apr	Frame	Weld Trailing Arm Bracket on frame

Table 5 - Project Schedule



Result	Lap # (Lap ~ 5-8 minutes)	Event Modifications	Why?	Why?	Solution	Targeted due date	Completed Date
✓	1	RS Top Lateral Link Bracket (Inside & Outside) warped	Weld not present at top of the bracket, and force was too great acting in the horizontal direction when a braking torque is applied	Weld access not available due to design geometry.	Lateral Link Bracket on Frame - Rev2 1/8" horizontal support member welded across top of two vertical members	N/A	4/1/2017
✓	2	1/8" horizontal support member and lateral link bracket warped and cracked	Field weld did not penetrate into veritcal pieces	Wire feed speed was too great, and ampergae was too low	Cleaned and prepared corner joint weld. Increased amperage and decreased wire feed speed and welded using a flux core welder	N/A	4/1/2017
✓	7	LS Trailing Arm - Lower Lateral Link threaded insert missing	Tac welds broke	Lateral Links caused too great of force for the 3 tacs	**Event:** Weld nut on end of trailing arm. **Design:** Weld bead applied to diameter of new threaded insert	4/4/2017	4/4/2017
✓	7	Trailing arm - Lower Heim joint on Frame side cracked and bent.	Force applied exceeded heim joint capablities	Dragging on the ground because of the lower later link threaded insert missing	Replace Heim joint	N/A	4/1/2017
✓	9	LS Trailing Arm joint bracket to Frame (outer) weld fail.	No penetration to frame tubing or bracket	Amperage too low	Increase amperage. Weld corner joint on both side of bracket to frame tubing	N/A	4/2/2017

Table 6 - Failure Analysis

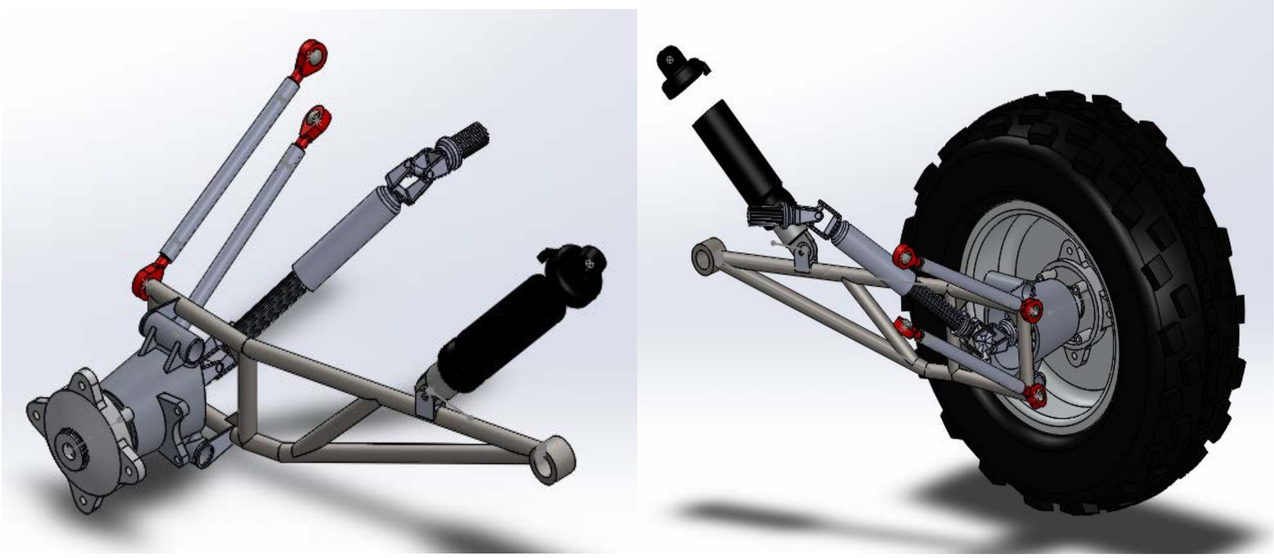


Figure 32 - Rear Suspension CAD Assembly

Figure 33 - Stair Climb

Figure 34 - Final Design