2017 Bearcats Baja SAE – Steering System

A Baccalaureate thesis submitted to the
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Bachelor of Science

in Mechanical Engineering Technology

by

Eric Wessels

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Thesis Advisor:
Professor Allen Arthur

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ABSTRACT

This document discusses the process of designing and manufacturing of a steering system for the Bearcats Baja team. This project was done as the senior design capstone as a requirement to receive a Mechanical Engineering Technology degree at the University of Cincinnati. The paper goes into further detail regarding research, design, manufacturing, and testing to produce an effective SAE mini baja steering system.

INTRODUCTION

BACKGROUND

Engineering students from all over the world will compete in these SAE Baja competitions. The most efficient and effectively designed cars will come out on top during these rigorous events. The purpose for putting on these competitions is for SAE to give students a real-world experience to apply their engineering knowledge and skills picked up in the classroom.

The steering system for the car will allow the driver to effectively maneuver the baja car over rough terrain through tight obstacles designed to test the limits of the overall car design. The car must maintain traction and control over various surface types including large rocks, logs, ruts, and mud. This was the main challenge in designing a steering system that worked on all surfaces while maintaining durability. All these factors will be tested during a maneuverability event at a SAE competition.

Unfortunately, this year's team was unable to register for the SAE competition in Illinois due to extreme demand to compete here. The only competition we could register for was in California. This competition is held over the University of Cincinnati's commencement weekend. The cost to travel out West with the car, tools, and gear was too expensive for the team's budget. Considering these factors the team was unable to attend an SAE sponsored competition this year.

PROBLEM STATEMENT

I will design a steering system to provide effective and precise maneuverability for the 2017 baja car. This design will meet SAE criteria to pass technical inspections for competition events.

RESEARCH

The steering for the car will be constrained by overall vehicle dimensions set by the Baja SAE rules. Below is a section out of the rule book for overall vehicle sizing.

B1.1.2 Maximum Vehicle Dimensions
Width: 162 cm (64 in) at the widest point with the wheels pointing forward at static ride height.
Length: Unrestricted, see note below.
NOTE: Teams should keep in mind that Baja SAE® courses are designed for vehicles with the maximum dimensions of 162 cm (64 in) width by 274 cm (108 in) length. (1)

These length and width requirements will affect the wheel base as well as the distance between the front tires (track width). These aspects affect the turning radius, which is an important factor to consider when designing the steering system. These dimensions affect the overall handling of the vehicle too, especially in tight turns.

A rack and pinion design steering system was chosen by evaluating the steering systems from the 2013 and 2014 cars. Both were rack and pinion designs, and both cars performed well in the maneuverability events. This is a simplistic design which allows for the reduction of weight.

CUSTOMER FEATURES

There are no specific requirements for the steering system for the baja car. Although there are several variables that do affect the design of the steering system.

- Turning radius
- Torque required to turn steering wheel

PRODUCT OBJECTIVES

The information that determines how the turning radius and the torque required to turn the steering wheel is mentioned below.

- Turning radius
  - Dependent upon gear box design
    - Forward-Neutral-Reverse: Design for larger turning radius
    - Forward-Neutral: Will need to design for smaller turning radius

- Torque required to turn steering wheel
  - Dependent upon:
    - Steering wheel size
    - Pinion pitch diameter
    - Weight of car
    - Steering rack ratio

DESIGN

DRIVER ERGONOMICS

Due to SAE regulations, the driver must be able to evacuate the vehicle in under five seconds. This has been difficult to accomplish in past years' vehicles. Some changes to the frame design were carried out to help decrease this time. The design of the steering column and steering wheel location were considered to make egress of the baja car easier this year. The angle of the steering column will be at a slightly steeper angle with a higher steering wheel location than previous designs. The new design can be seen below.

Figure 1: The new design is shown in darker grey and black. The lighter grey model shows the 2014 steering column shape.

TURNING RADIUS

The turning radius of a vehicle is defined as the radius of the smallest possible circular turn that the car can make. Below is a simplified vehicle model showing a diagram of how turning radius (R) is measured.

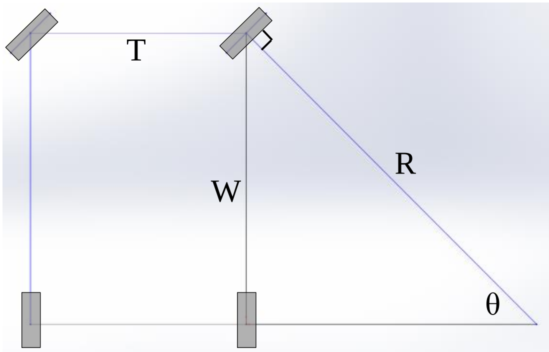

Figure 2: Shows the turning radius of the vehicle in relation to the track width and wheel base.

The factors that determine the turning radius are the degrees the front wheel rotates and the wheel base (W) of the car.

$$R = \frac{W}{sin\theta}$$

The team is designing the car with a track width (T) of 52 inches and wheel base of 70 inches. Designing for front wheel rotation of 45° determines θ to be 45° as well. Using this information to solve for R, the turning radius goal is 8.25 feet.

ACKERMAN

Having Ackerman steering is defined by having the inner front tire turn at an increased angle compared to the outer front tire. This is necessary because the outer tire follows a larger radius than the inner tire during a turn. The difference between the steering rotation angle of the tires increase as the car turns sharper. Maintaining this geometry allows for zero-slip conditions while turning the car. A car with 100% Ackerman will decrease tire wear and minimize rolling resistance in turns.

BUMP STEER

Bump steer occurs when the front wheels steer themselves due to change in suspension travel. The path that the wheel takes when the tire impacts a bump is due to the geometry of the A-arm suspension design. The each of the upper and lower A-arms follow an arc. The radius of the arc is determined by the length of the A-arm. This length of the tie rod will need to be equal to the length of the arc radius.

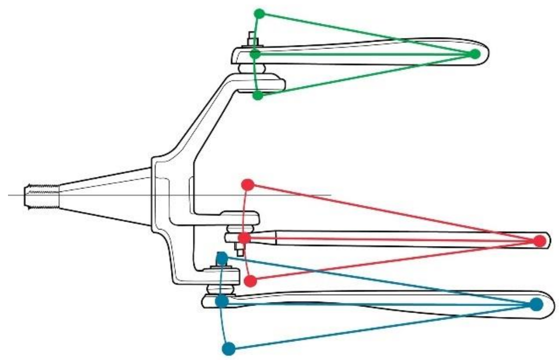

Figure 3: This figure shows how the suspension arms rotate (green and blue) in relation to the tie rod (red).

STEERING SYSTEM DESIGN

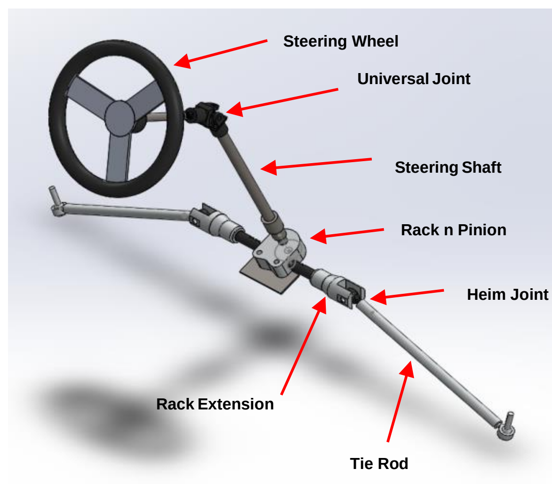

Figure 4: Shows the seven main components of the steering system for the 2016 design, modeled in Solidworks.

Steering Column

One common failure in previous car designs are the universal joints, or U joints. The purpose of this part is to link two different angled shafts to rotate at the same angular velocity. In the past two U joints, have been used in the steering shaft. This creates more "play" or lateral movement in the steering assembly. To provide increased control, the steering column was designed with one U joint. This design also increases the life of the steering column. Due to 32° limit of the U joint the steering wheel could not be angled further to be parallel with the driver's torso.

Figure 6: New steering column with one U joint, rather than two.

Steering Rack Selection

The selected steering rack was the Stiletto Fast Rack N Pinion. This model has a 6.4:1 ratio resulting in a total of 4.5 inches of rack travel from 315° of pinion rotation. The lower ratio steering rack is necessary to get more steering rotation out of the front tires because the car will not have reverse.

Figure 7: The chosen steering rack is a Stiletto Fast Rack N Pinion C42-334.

With this steering rack, it was verified that the driver was going to be able to turn the steering wheel under the static load of the car. The static friction coefficient of rubber on pavement is 0.9. This resulted in a 225-lb. force due to friction at the wheel.

$$F_f = \mu F_N$$

This creates a torque at point B equal to 85.3 ft. lb. The force applied to the steering rack by the driver needs to overcome this torque about point B so the wheels will turn.

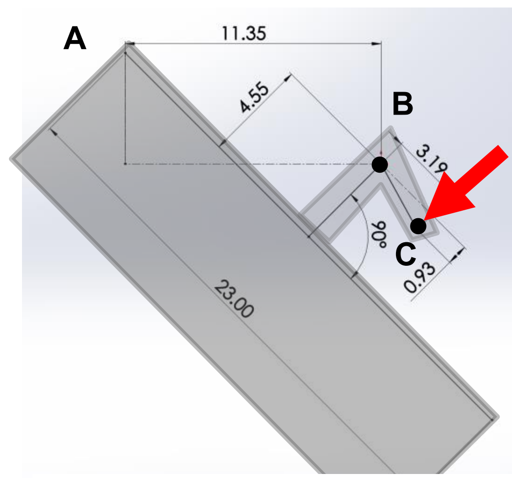

Figure 5: Wheel and spindle geometry used to calculate forces and torques at kingpin axis (point B).

The torque in the steering column input by the driver is 20 ft. lb. This translates to 400 lb. force in the steering rack. This force creates a 106.3 ft. lb. torque about point B. This is greater than the torque due to the friction of the tires; therefore, the driver will be able to steer the car under its static load. Since this is a worst-case scenario, the driver will have more control while the car is moving over surfaces like mud and grass.

Rack Extension Model

The purpose of the rack extension is to provide the correct location for the tie rod to mount to the rack. This allows for the prevention of bump steer. The tie rod will mount to the rack extension via a heim joint. This allows the car to steer while the wheel moves with the suspension.

The two inner surfaces indicated below determine how much room the heim joint can move/rotate. In the previously designed cars this width was only a ½ inch wide. This was not allowing enough room for the heim joint to rotate causing the threaded shaft to bend and eventually break. The new design increases the width by ¼ inch allowing for 33° more movement of the joint.

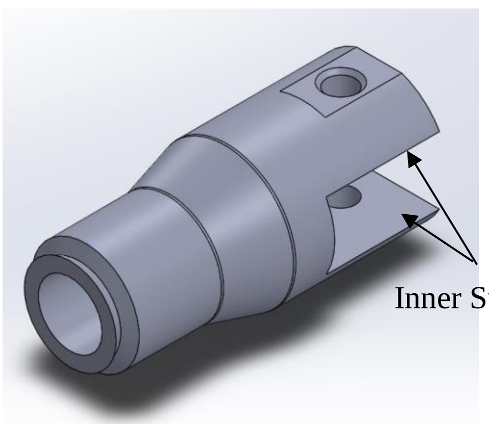

Figure 9: Shows the increased distance between the two inner surfaces.

Figure 10: The increased distance shown in figure 8 is necessary to provide room for rotational movement in the new heim joints.

Rack Extension Loading Condition

The force on the rack extension is calculated using a frontal impact to the tire while it is at a 45° angle. The force at point A was calculated using the equation for conservation of momentum.

$$m_1 v_1 = m_2 v_2 + Ft$$

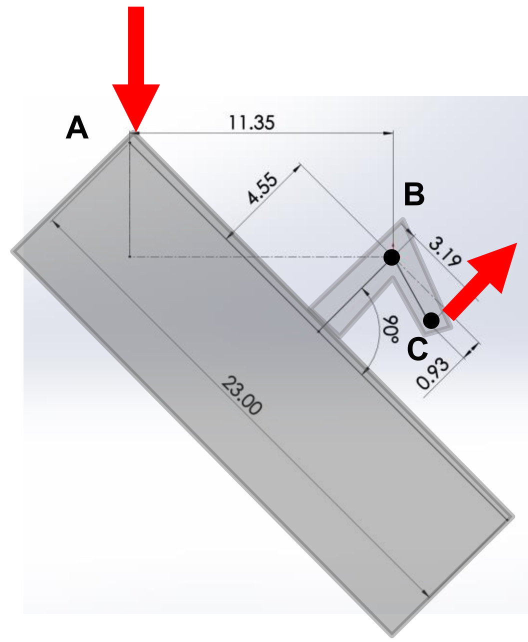

Figure 8: This picture shows the geometry of the wheel and spindle. These measurements were used to calculate the force applied to the rack extension.

The mass of the car remains constant while the velocity changes from 35mph to 30mph. The impact occurs over a period of 0.25 seconds. This results in a 499.2 lb. force into the wheel. As seen in the figure below, this creates a torque about point B. This torque results in a 1955 lb. force at point C, which goes through the tie rod into the rack extension. The force is represented by the red arrow at a 22.3° angle from the horizontal.

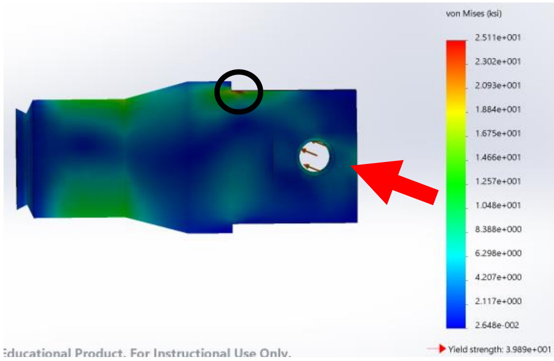

Figure 11: The red arrow shows the 1955 lb. force applied to the rack extension. The black circle shows where the maximum stress occurred in the model.

The extension is made from 6061-T6 aluminum with a yield strength of 39.89 ksi. The maximum stress on the extension in 25.11 ksi. This results in a safety factor of 1.6.

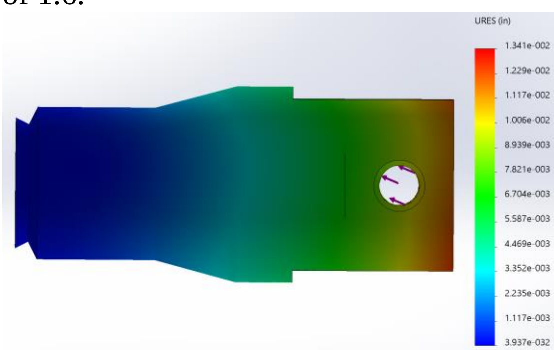

Figure 12: This figure shows where the maximum deformation occurred in the Solidworks model when the force was applied. The largest amount of deformation is shown in red.

The above picture shows the deformation the part undergoes during impact. Logically the maximum deformation occurred farthest from the fixed surfaces at 0.013 inches. This amount is minimal enough that steering control will not be compromised.

MANUFACTURING & ASSEMBLY

RACK EXTENSION

The custom designed rack extension required lathe and mill operations to get the desired product. A triangular carbide cutter was used to get the outer cylindrical shape as well as the groove for the rubber boot. Next a hole was drilled through the center of the part for the rack mounting bolt. The last lathe operation was boring a hole for the extension to slide over the rack.

Figure 13: This picture shows the hole being bored into the end of the rack extension. The tool used for this operation was a boring bar.

Figure 14: This figure shows the fixturing for the end milling operations.

The rest of the operations were carried out using a mill. To fixture the part properly a chuck from the lathe was used to hold the extension. Then the chuck was then clamped to the table. This setup can be seen below. The middle section of material and flat faces for the bolt and nut were removed using a square end mill.

The part was then clamped horizontally using a v-block to carry out the final operations. The hole was intentionally drilled last to verify the desired extension distance was achieved (shown below as a blue line). This distance is crucial to remove bump steer.

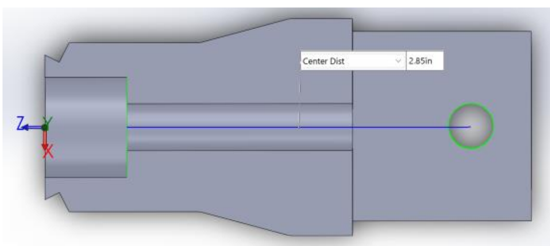

Figure 13: A section view of the rack extension is shown above. The critical measurement is shown by the blue line.

Figure 14: This is a picture of the two rack extensions after the machining operations have been completed.

Tie Rod

The tie rods were made from 6061-T6 aluminum ¾" round bar. The rods were cut to length using a lathe. Next holes were drilled in the ends of the tie rods using the chuck on the lathe to hold the drill bit. Then 3/8"-24 spiral taps were used to start threading the holes using the lathe. This sped up the tapping process and verified the hole was tapped straight. The tap is pictured below; it has spiral flutes to evacuate the chips during the tapping process, different from a traditional tap.

Figure 15: Above is a picture of the spiral tap used to machine threads into the ends of the tie rods.

One end of the tie rod was right hand threaded and the other was left hand threaded. This allows the tie rod to be rotated after installation for easy adjustment of toe angle.

TESTING & ANALYSIS

The car was taken to Haspin Acres to test its performance. The 2014 bearcats baja car was also taken to provide a benchmark for comparison. The 2014 car placed 13th out of 100 cars in the maneuverability event at the Baja SAE Tennessee Tech competition.
The newly designed steering system proved its capabilities at Haspin. No parts broke over the tough muddy rocky terrain. The car handled well with minimal to no bump steer. After measurement, there is about 1° of toe change throughout the nine-inch suspension travel. The turning radius of the car was eight feet. This is a 1½ ft. reduction from the 2014 car and 3 inches less than the design estimate. The

last specification tested was driver egress time. With the improved steering column design, the largest member of the team could exit the car in under five seconds.

Figure 16: This is a picture of the completed baja car after testing at Haspin Acres on April 1, 2017.

Figure 17: The tie rod is shown in red. This gives an idea of the tie rod alignment and location in relation to the suspension arms to prevent bump steer.

Weight Analysis

The goal for the steering system weight was 12 pounds or less. As seen in the table the final weight of the steering system was 10.425 pounds. This was a 3.5-pound reduction from the 2014 car.

Table 1: The table below shows the estimated weight of each steering system component as well as the total estimate. The final weight of the steering system is shown too.

Weight Analysis	
Part	**Weight (lb)**
Steering Wheel	2.25
Short Spline Shaft	0.675
Universal Joint	0.8
Long Spline Shaft	0.8
Stilleto Fast Rack n Pinion	2.74
Rack Extensions (x2)	1.2
Heim Joint (x2)	0.4
Tie Rod (x2)	1.2
Ball Joint (x2)	0.5
Hardware	1
Total Estimate	**11.565**
Actual	**10.425**

Cost Analysis

The goal for the steering system cost was to stay under $500. Where there is no cost, parts were used from inventory or previous years failed designs. A lot of the cost included spare part purchases, like steering rack which makes up most of the money spent. All tooling used in the manufacturing process was either property of Bearcats Baja or the University of Cincinnati. In the end the project came in under budget by $50.

Table 2: The money spent on components for the steering system is shown below.

Cost Analysis	
Part	**Cost**
Steering Wheel	$0.00
Short Spline Shaft	$0.00
Universal Joint	$0.00
Long Spline Shaft	$0.00
Stilleto Fast Rack n Pinion	$339.08
Rack Extensions (raw material)	$25.34
Rod End (heim joint)	$49.60
Tie Rod (raw material)	$21.12
Ball Joint	$0.00
Hardware	$15.00
Total	**$450.14**

CONCLUSION

Overall the design and manufacturing process for the 2016 baja car went smoothly. It was difficult to maintain proper mating when combining Solidworks assemblies for the full car model. This was a minor hiccup in the overall production process. All deadlines were still met without any delays. The schedule can be seen in Appendix B. The car including the steering system was put to test at Haspin Acres on April 1st, 2016 and performed successfully. Hopefully next year's team will have the opportunity to test the car at a SAE Mini Baja competition. The car was designed to SAE specifications to excel at competition events. All design specifications were either met or exceeded, therefore the project is considered successful.

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CONTACT

Eric Wessels
Steering System Design Engineer
wesselep@mail.uc.edu
513-706-5459

APPENDIX A

Definitions, Acronyms, Abbreviations

<u>Bump Steer</u>: Output steering motion without driver input resulting from vertical movement of the suspension and wheel.

<u>SAE</u>: Society of Automotive Engineers

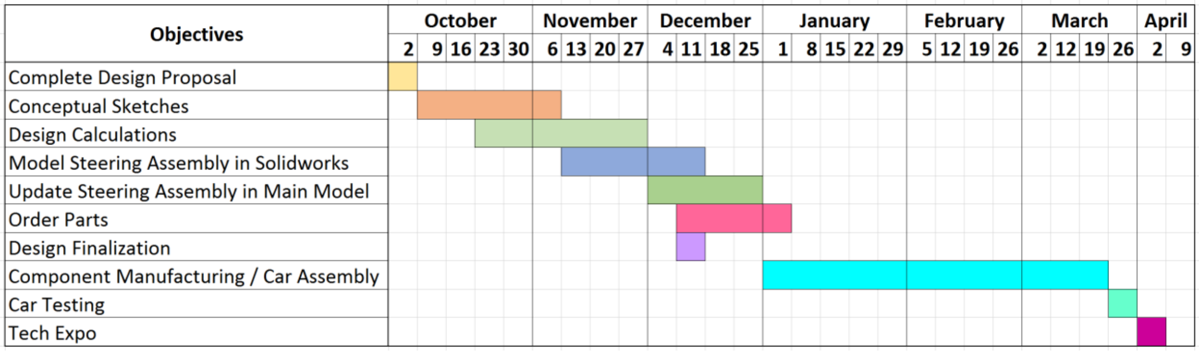
<u>Track Width</u>: The distance between the middle of the front tires when looking at a frontal view of a car.

<u>Toe Angle</u>: The positive or negative angle of the tire from pointing straight ahead. Outward toe angle is considered positive resulting in less stability.

<u>Wheelbase</u>: The distance between the middle of the front and rear tires when looking at a side view of a car.

APPENDIX B

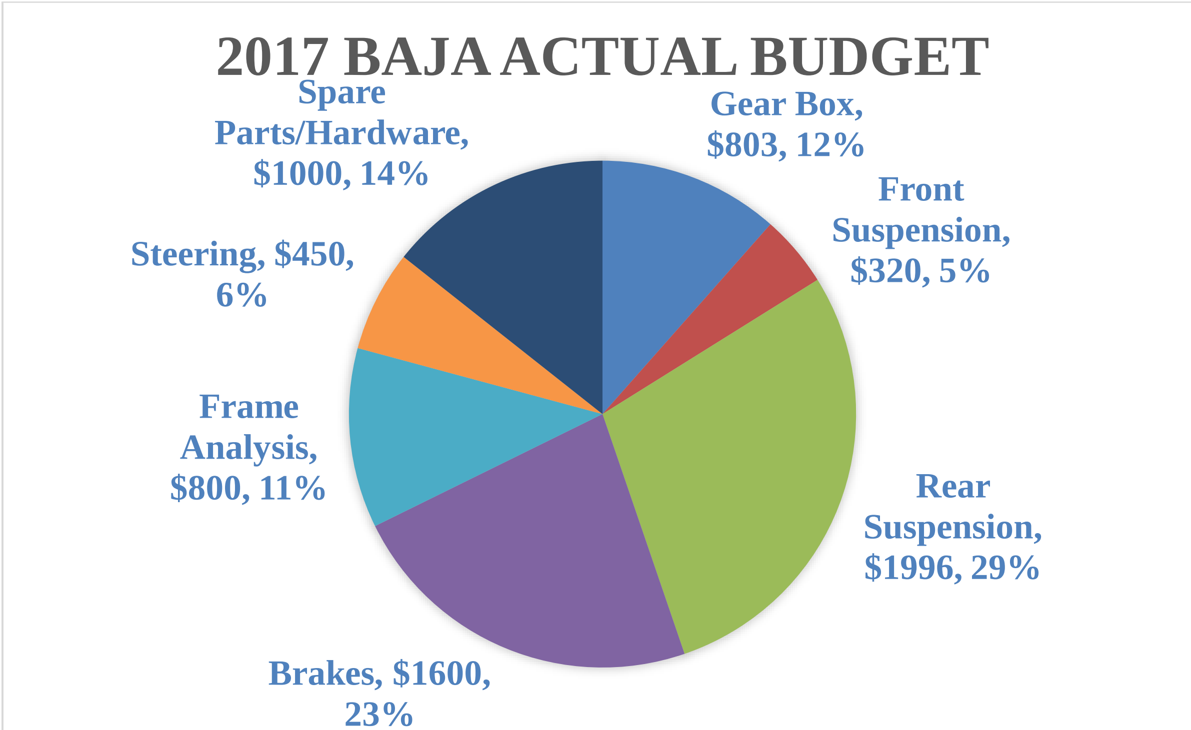
Steering System Production Schedule



Steering House of Quality

			Engineering Requirements (units)														Customer Satisfaction Rating (0.00 - 1.00)			
		Importance wt.	turning radius (°)	Applied torque to turn steering wheel (ft lb)																
	Customer Requirements		1	2	3	4	5	6	7	8	9	10	11	12	13	14	CP	A	B	C
1	Small turning radius	0.70	9	1													0.5			
2	Low torque to turn steering wheel	0.30	1	9													0.4			
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
	Total Importance	1.00																		
	Engineering requirement importance		6.6	3.4																
Performance	2014 Baja Car		11	12																
	competitor A																			
	competitor B																			
	competitor C																			
	New Product Targets		9.5	10																

2017 Total Vehicle Costs



Rack Extension Drawing for Manufacturing