



Optimized Rack and Pinion steering system with Steering Stops incorporation over Rack-Casing Assembly for a BAJA SAE All terrain Vehicle

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Abstract: This study focuses on the design and optimization of Rack and Pinion steering system of a BAJA SAE All-terrain vehicle. The major challenge in the design of a steering system is the weight reduction within the limits of structural integrity of the design confining to the guidelines of BAJA SAE, which should easily run through the harshest of conditions. Various parameters of the design of the steering system were analytically calculated and decided upon. The basic design of the Rack and Pinion was made in SolidWorks. A number of iterations were then carried out and analyzed in HyperWorks to finalize the design dimensions viz. Rack's diameter, teeth's face width. Al 7075 was finalized as the material based on its superior hardness and strength and being 1/3rd the density of Steel*. The weight reduction was then carried out based on the least stress concentration which could further achieve a 15% weight reduction in the design. This study would also display a new design for incorporation of steering stop in the rack and casing assembly itself.

Keywords: Baja SAE; Optimization; Rack and Pinion; Steering Stop; Weight Reduction.

I. Introduction

The prime objective of a steering system is to provide maximum directional control and easy manoeuvrability of the vehicle in all types of terrains with optimum safety and minimum effort. In case of an ATV (All terrain vehicles), the steering system must be designed according to the worst possible terrain conditions while carefully considering parameters like weight, space, and structural rigidity. The use of Rack and pinion type steering geometry in vehicles is very common because of its simplicity in design [6], good suitability with the front wheel drive system, adaptability to vehicles without frames [5][7] and easy manufacturing.

In order to provide pure rolling to the road wheels and to reduce wear and tear of the tires, a steering linkage must handle the vehicle so that it follows Ackermann principle (see Fig. 1). It states that during low speed cornering when free from lateral inertia forces, the lines drawn from the centres of the wheels (axes) should intersect at the centre of the bend (or the instantaneous centre) [4], i.e., point O of Fig. 1. For a two-wheel steering vehicle, this point must lie on the common axis of the rear wheels. Referring to Fig. 1, the relation between the inner wheel angle δ_i , and the outer wheel angle δ_o , according to Ackermann principle, is given by,

$$\delta_o = \arctan \frac{1}{\cot \delta_i + \frac{w}{l}}$$

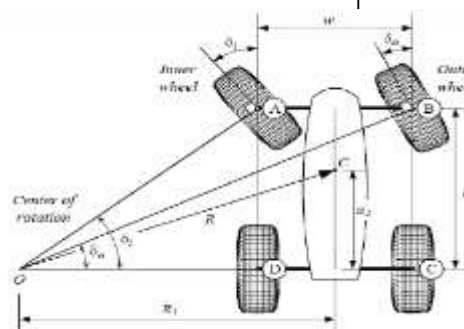


Figure1. Ackermann Geometry

II. Methodology

The designing process of the rack and pinion was taken in a systematic order so that various objectives of the vehicular design must be attained with the utmost perfection. This was accomplished with the initial scrutiny of previous designs and the various parameters it lacked and the limitations associated with them. The vehicle needs to be designed within the guidelines of BAJA SAE rule book and the parameters be within defined [8].



Our Objective for the vehicle's steering system was to incorporate a steering Stop on the rack casing itself and design the system according to the desired steering ratio with oversteer characteristics with optimum driver comfort. This was to be achieved with a geometry that needed to be easy to assemble, having a low lock to lock rotation and highly reduced weight.

Design Parameters and Calculations

The steering system calculations were done taking into consideration the desired dynamical characteristics of the vehicle. A set of conditions best suitable for the design were first analyzed and then taken as the initial parameters of the steering system of the vehicle.

Table 1. Design Parameters

Mass of the vehicle	140kg
Mass with driver	200kg
Wheel base	55inches
Track width	52inches
Turning Radius	1.75 m
Lock to lock Angle	180 degrees
Radius of Steering Wheel	5 inches
Displacement of Rack	90mm

The Inner wheel angle and outer wheel angle were first calculated using a number of iterations of the fixed parameters, for 100% Ackerman Geometry using,

$$\delta_i = \arctan \frac{1}{R1 + w/2} \quad (1)$$

Similarly,

$$\delta_o = \arctan \frac{1}{R1 - w/2} \quad (2)$$

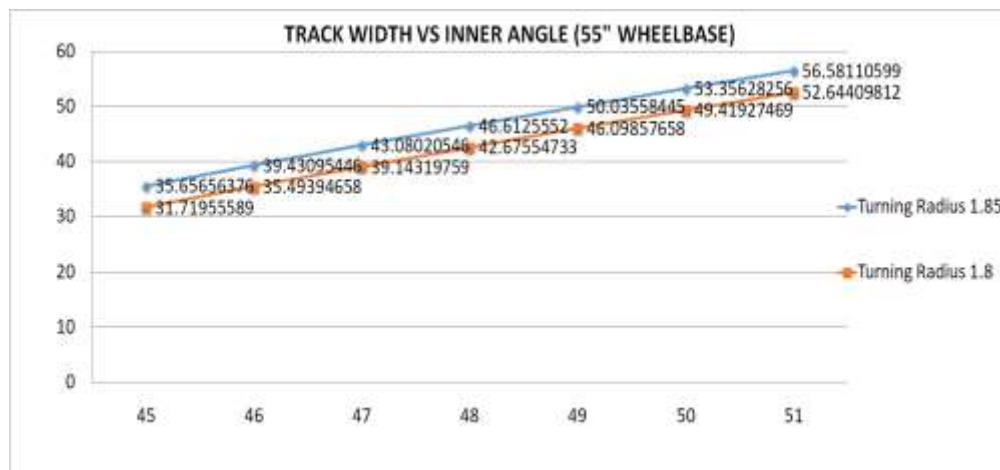


Figure 2. Track width VS Inner angle

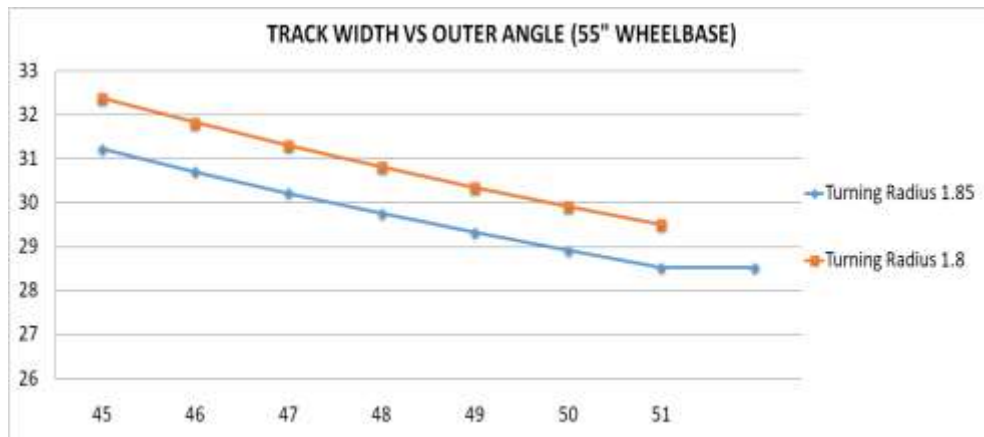


Figure 3. Track width VS Outer angle

The angles along with the parameters were then tested and validated on the steering geometry based on the optimum strength and alignment of the various Suspension points using LOTUS Shark. A 68% Ackerman geometry was used which could work efficiently based upon the overall dynamics of the vehicle.

Rack and pinion design calculation

Initially, the Steering Ratio was analyzed based upon the optimum driver comfort and steering effort. The Pinion radius was then designed using the best suitable steering ratio for a BAJA ATV. Consequently, the module was calculated for the pinion and the Torque acting over the pinion was analyzed.

$$\text{Displacement of Rack} = \text{Radius of Pinion} * \varnothing$$

$$\text{Displacement of rack (l)} = \pi Z \varnothing m / 360^\circ \quad (3)$$

Where, Z = no. of teeth on the pinion
 $\varnothing$ = angle of rotation of pinion
 m = module

Steering ratio

The Steering Ratio is defined as the ratio of steering wheel rotation angle to steer angle at the road wheels.

$$\begin{aligned} \text{Steering ratio} &= \text{degrees of steering wheel turned} / \text{degrees of driving wheels turned} \\ &= 90 / 52 \\ &= 1.73 : 1 \end{aligned}$$

Steering Characteristics (oversteer, understeer)

$$\begin{aligned} \text{Under Steer Gradient, } K &= W_f/C_f - W_r/C_r \\ &= (90/56346 - 110/56346) \\ &= -0.02033 \text{ deg/g} \\ &\text{i.e. Oversteer Condition} \end{aligned} \quad (4)$$

In this case, the lateral acceleration at the Centre of Gravity causes the slip angle on the rear wheel to increase than the front wheels. The outward drift at the rear of the vehicle turns the front wheel inward, thus diminishing the radius of turn.

Steering effort

Steering effort is the effort to be made by the driver in turning the steering wheel. This can be calculated in either static condition i.e. when the vehicle is stationary and in dynamic conditions. Steering effort is maximum when the vehicle is stationary.

Vehicle weight was designed so as to distribute the weight in the ratio of 55:45 rear to front.

Weight on the front tires, $W_f = 0.45 * 200 = 90 \text{ kg}$

Weight on the rear tires, $W_r = 0.55 * 200 = 110 \text{ kg}$

Corner mass front = 45kg

Corner mass rear = 55kg

Steering Force Calculations

$$\begin{aligned} \text{Force of friction (on one wheel)} &= \mu \times g \times \text{corner mass} \\ &= 0.8 \times 9.81 \times 45 \\ &= 353.16 \text{ N} \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Input torque from ground (on one wheel)} &= \text{force of friction} \times \text{lateral distance between contact patch and kingpin centre} \\ &= 353.16 \times .12831 \\ &= 45.31 \text{ Nm} \end{aligned}$$

This torque will be equal to the lateral push from the tie rod.

$$\begin{aligned} \text{Torque due to lateral push from tie rod} &= \text{force on tie rod} \times \text{longitudinal distance between outer tie rod end and front axle} \\ &= \text{force on tie rod } (f_i) \times 0.0945 \text{ m} \end{aligned}$$

$$f_i = 479.47 \text{ N}$$

$$\text{Total force on rack} = 479.47 \times 2 = 958 \sim 1000 \text{ N}$$

$$\text{Radius of pinion} = 28.1 \text{ mm} = .0281 \text{ m}$$

$$\text{Torque on pinion} = 1000 \times .0281 = 28.1 \text{ Nm}$$

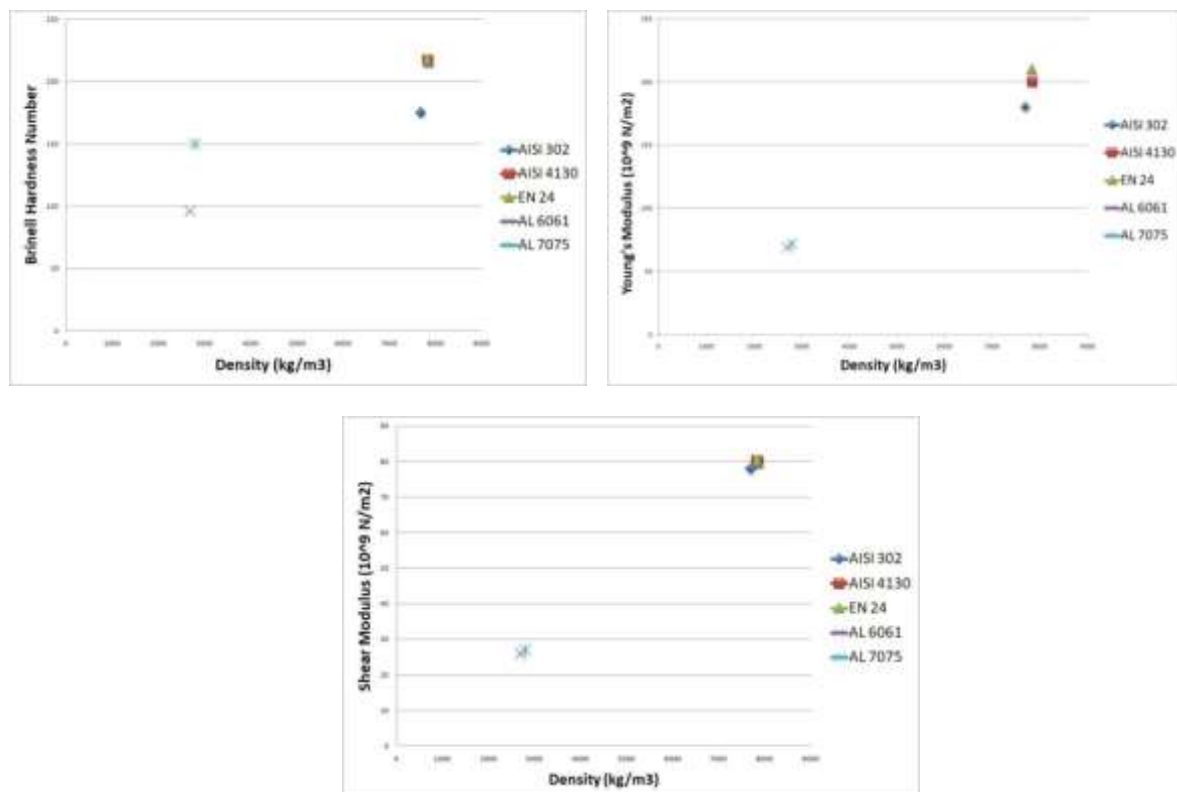
$$\text{Torque on steering wheel} = \text{Torque on pinion} = 28.1 \text{ Nm}$$

$$\text{Radius of steering wheel} = 5 \text{ inch} = 0.127 \text{ m}$$

$$\begin{aligned} \text{Force applied by the driver to steer the wheels} &= \text{torque on steering wheel} / \text{radius of steering wheel} \\ &= 28.1 / .127 \\ &= 221.26 \text{ N} \end{aligned}$$

Material selection

To design a lightweight steering system without compromising its strength and integrity various material properties were studied and components were designed according to their optimum use. Material selection was carried out by Ashby Method.



For the Rack and Pinion Al 7075 was finalized due to its low weight, suitable tensile and shear strength and hardness. It was also concluded that EN 24 can be utilized for Tie Rods due to their superior bending strength, and stiffness.

Table 2 Properties of Al 7075

S.No	Properties	Values
1.	Density	2700 kg/m ³
2.	Young's Modulus	72 GPa
3.	Ultimate Tensile Strength	590 MPa

Table 3 Properties of EN 24

S.No	Properties	Values
1.	Density	7850 kg/m ³
2.	Young's Modulus	205 GPa
3.	Ultimate Tensile Strength	1110 MPa

Design, Analysis and Optimization

Taking into account the Numerical Results and the parameters, the CAD model of the steering geometry was designed on SolidWorks and its Finite Element Analysis was carried out on HyperWorks. The Suspension and Steering geometry was analyzed over LOTUS Shark.



Figure 4. Steering Geometry Design

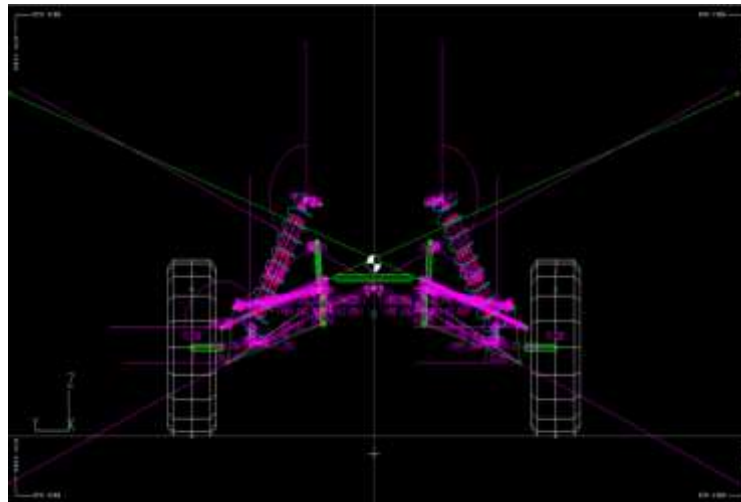


Figure 5. Suspension analysis on LOTUS Shark

Stress concentrations over the rack and pinion were analyzed for different compressive and shear loads. The overall deformation was also analyzed over the rack due to the various loads acting over the vehicle.

A number of iterations were carried out and a highly optimized Rack and Pinion were designed by eliminating material from around the neutral axis and regions of low stress concentrations. A circular cutout was made along the length of the circular Rack without compromising the required strength of the member.

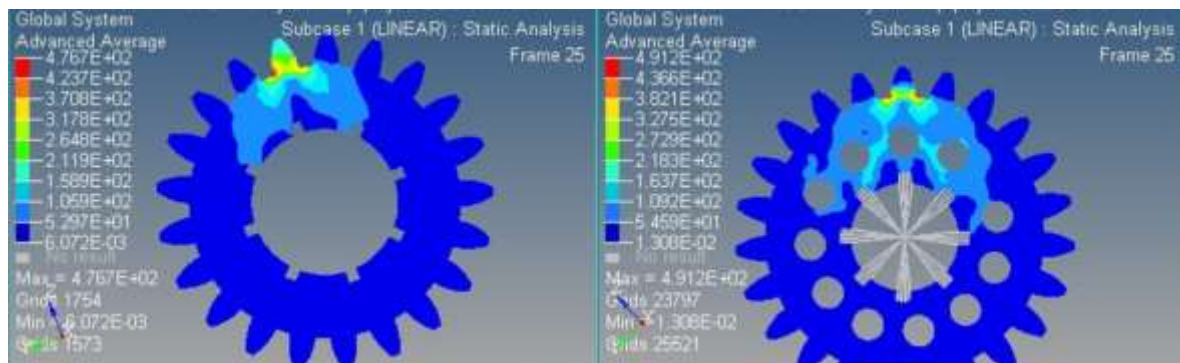


Figure 6. Stress analysis over pinion

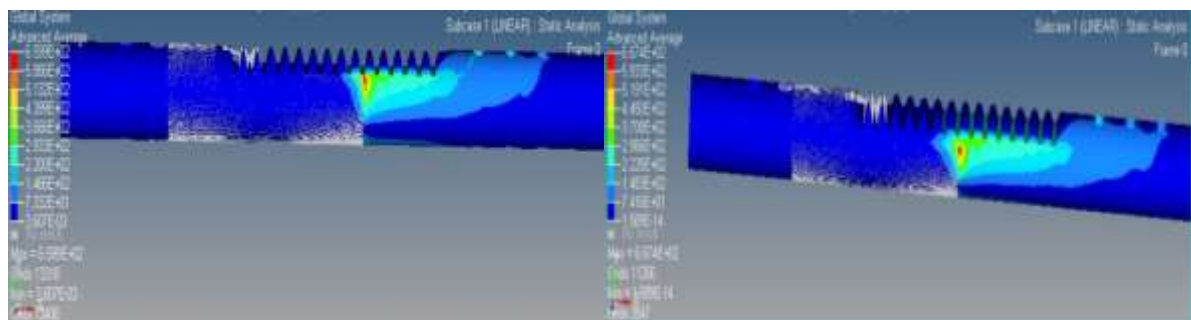


Figure 7. Stress analysis over rack

Steering Stop

Steering stops are used in vehicles so as to limit the turning of wheels after a certain limit. They are designed to prevent the steering system to turn to a point where they resist turning back to thus straining the geometry. In commercial power steering systems, the vehicle uses software stops, limit switches and valves to maintain the steering angle.

A locking mechanism to limit the steering angles from lock to lock was designed for the vehicle. This was designed taking into consideration to be lightweight and employable over the BAJA SAE vehicle providing safe and better driving conditions for the driver.

Due to the extreme stresses generated over the tie rods and steering linkages at sharp turns, and to avoid major failure of the vehicle, steering stop was incorporated over the rack casing assembly in the vehicle. The steering stop would also allow the vehicle to avoid excessive Oversteer and in turn avoid rollover of the vehicle.

The design was then further scrutinized and tested through computational analysis and then validated through experimental testing of the vehicle.

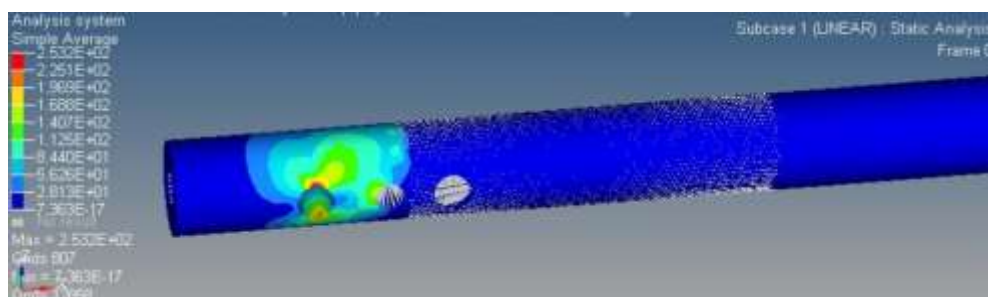


Fig 5. Stress analysis over the rack casing assembly

III. Conclusions

The main objective of the study was to design an efficient steering mechanism with the incorporation of steering stop having minimum weight. Rack and pinion steering systems promise the most efficient system for a BAJA SAE vehicle. It was concluded that

- Lightweight vehicle reduces inertia losses and ensures a faster response of the steering system.
- Aluminum being one of the lightest metals provides the necessary strength and hardness and thus

offers a great potential to be used as the material for manufacturing rack and pinion.

- A steering stop incorporated over the rack casing provides the necessary stopping mechanism without compromising the safety and effectiveness.
- The steering stop design ensures safe loads over the steering linkages.

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