DESIGN AND FABRICATION OF THE SUSPENSION SYSTEM FOR A FORMULA STUDENT CAR

A Final Year Project Report

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ABSTRACT

The objective of this project is to design and manufacture the Suspension System of a Formula Student Car adhering to the principles of Mechanical Engineering focusing especially on Statics, Dynamics, Mechanics of Machines, Solid Mechanics, Mechanical Vibrations and Finite Element Analysis. The design of the suspension system includes creating a suspension and steering geometry, designing and selecting components accordingly, performing structural analysis on the designed parts, manufacturing and procurement of the components, and integration of suspension system with the formula student car. The design has been finalized after subsequent iterations made on the basis of the objectives that are to be achieved. Different tools like SolidWorks, ANSYS and Lotus Shark are used in the design process. The design, wherever, inspired by existing designs has been credited to the rightful individuals.

ACKNOWLEDGMENTS

We would like to thank Almighty Allah for giving us the ability to take on such an ambitious project and then the faculty of SMME for allowing us to register this endeavor of ours as our Final Year Project.

ORIGINALITY REPORT

It is to certify that the work shared in this report is original and is an effort of the authors of this report solely. The design, wherever, inspired has been credited to the original owners.

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ABBREVIATIONS

FSUK	Formula Student United Kingdom
FSAE	Formula Society of Automotive Engineers
IMechE	Institution of Mechanical Engineers
NASA	National Aeronautics and Space Administration
UAS	Unmanned Aerial Systems

CHAPTER 1: INTRODUCTION

Problem Statement

To design and manufacture a suspension system for a Formula Student Electric Car following good Engineering practices and the limitations set out by the Formula Student UK (FSUK) 2023 rulebook.

Motivation

Engineering students worldwide compete in ambitious projects like Formula Student, NASA Rover Design Challenge, IMechE UAS Design Challenge etc. to apply and test their knowledge gained in engineering programs. Our driving force is to not only make a functional Formula Car but also represent our country on an international platform. With this project, we laid out a new team for the undergrad students of National University of Sciences and Technology (NUST). This new team is named Team Alif – Formula Student Electric. Team Alif is the first Electric Formula Student car building team from NUST H-12. This is a platform where students from different degrees work together to achieve the common goal of building a Formula Student Electric car. The essence of our project and of our team lies in the cross-functional collaboration between the different departments and the motivation of the individuals that are part of it. With a proper framework of a society, our online presence and our recruitment drives, we have started something that is going to be a driving force for many Engineering students to take part in such competitions and learn Engineering by doing.

While Team Alif is comprised of many sub-teams like Powertrain, Suspension, Chassis and Electrical System. Our Final Year Project is the designing, manufacturing and integration of the suspension system in the Formula Student Car being developed by Team Alif.

Objectives

The objectives directly linked with our Final Year Project are:

1) Kinematic analysis of suspension geometry and steering

2) Ride and force analysis of suspension geometry

3) CAD modelling and FEA of suspension geometry, steering and brakes

4) Manufacturing and integration of suspension into the formula student vehicle

Requirements

Our Formula Electric Car is being designed and manufactured according to the requirements set out in the FSUK Rulebook 2023, and requirements imposed by the hub motors used in the car. Some requirements for the suspension system, steering system and the wheels are listed below:

1. The vehicle must be equipped with fully operational front and rear suspension systems including shock absorbers and a usable wheel travel of at least 50mm and a minimum jounce of 25 mm with driver seated.
2. The minimum static ground clearance of any portion of the vehicle, other than the tyres, including a driver, must be 30mm.
3. Tyres on the same axle must have the same manufacturer, size and compound.
4. The steering wheel must directly mechanically actuate the front wheels.
5. Allowable steering system free play is limited to a total of 7° measured at the steering wheel.
6. The vehicle must have a wheelbase of at least 1525 mm.
7. The smaller track of the vehicle (front or rear) must be no less than 75 % of the larger track.
8. The track and centre of gravity of the vehicle must combine to provide adequate rollover stability.

   The design of rear suspension is influenced by the in-wheel hub motors (QS 260 3kW 48V v4). Two motors are used at rear, one in each wheel. Each motor weighs 24 kg. The motors give the car a maximum speed of 85 km/h.

Considerations

During the design process, the safety of driver was on the top priority. The suspension was designed such that the vehicle has a good stability and performance both in straight line and high-speed cornering. Following factors were taken into consideration:

1. Vehicle should be lightweight overall.
2. The vehicle should have low center of gravity.

3. Vehicle must have roll stability as to not roll during operation.
4. Increased Traction during acceleration, braking and cornering.

CHAPTER 2: LITERATURE REVIEW

Several Research papers and books have been referred to for the design of our suspension system, brake system and the steering system. Some online forums like FSAE Reddit has also been referred to take design decisions and study the already existing designs.

Basic Concepts

Following are some basic concepts for suspension system:

1. Wheel base:

   It is the distance between the front and rear wheel centers. Formula Student Cars have wheelbase greater than 1525 mm. Usually it is in the range of 1550 to 1750 mm [1], [2] & [9].

2. Track width

   It is the distance between wheel centers of left and right wheels when viewed from front. Front track width is greater than rear track width in formula-style cars, because the front wheels turn quicker than rear wheels, and the rear wheels might hit the boundary wall during a turn when driving on the edge of the track if front and rear track widths are the same.

   Formula Student cars have track widths of 1250 to 1300 mm (front), and 1150 to 1250 mm (rear) [1], [2] & [9].

3. Sprung Mass

   The mass of the vehicle supported by springs is called sprung mass. It includes the mass of chassis, seat, bodywork etc.

4. Unsprung Mass

   The mass of vehicle which is not supported by the springs is called unsprung mass. It includes the mass of tires, rims, pushrods, dampers etc.

5. Roll Center

The roll center of a car refers to an imaginary point around which the vehicle's body would rotate in roll (side-to-side) motion during cornering. It is a critical concept in vehicle dynamics and suspension design.

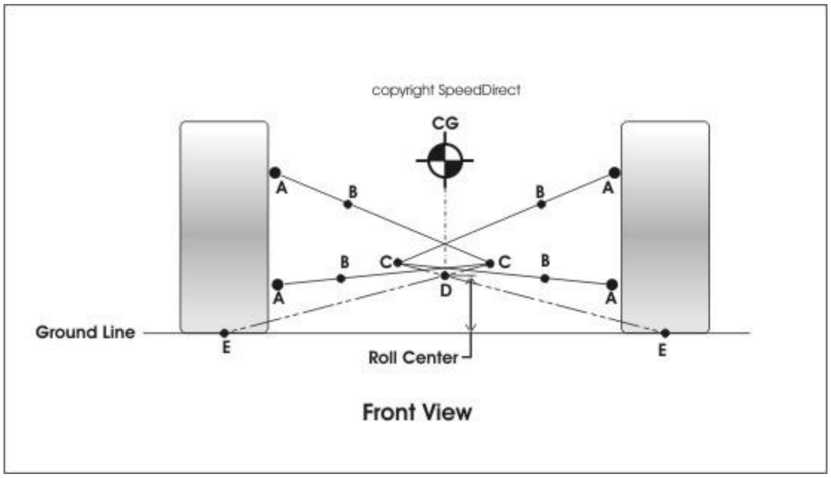


Figure 1: Roll Center

6. Slip Angle

When a vehicle is cornering, the tires generate lateral forces that allow the vehicle to change direction. As the vehicle turns, the tires experience a slip angle due to the difference between their orientation and the direction of motion. The slip angle is measured in degrees and can be positive or negative.

7. Ride Frequency

It is the frequency at which the vehicle oscillates in response to vertical disturbances, like bumps and road irregularities. Ride frequencies are generally between 2 to 3 Hz [3] & [9].

8. Roll Gradient

It is the resistance of body to roll when acted upon a centrifugal force during cornering. Its value is usually around 1.2 – 1.8 deg/g [9].

9. Camber Angle

   The angle between vertical axis of the wheel and the vertical axis of the vehicle when viewed from front. Formula Student Cars are generally given a static camber of 1^0 to 2^0 [1], [2], & [9]

10. Caster Angle

    The angle between vertical axis of the wheel and the vertical axis of the vehicle when viewed from side. Formula Student Cars are generally given a caster of 5^0 to 14^0 [1], [2], & [9].

11. Toe Angle

    Toe angle, also known as toe-in or toe-out, refers to the angle between the centerline of a pair of wheels and the vehicle's longitudinal axis (an imaginary line running from the front to the rear of the vehicle). It is the measurement of how much the front or rear of the wheels are turned inward or outward when viewed from above.

Figure 2: Camber, Castor and Toe Angle

Suspension Configuration

Several types of suspension systems are popular and used in cars. For high performance cars, double wishbone suspension system and Macpherson Strut are usually considered.

Double Wishbone Suspension System

A double wishbone suspension system employs two control arms (wishbones) for each wheel to control its motion. The arms are in the shape of wishbone, hence the name double wishbone. The control arms attach wheels to the chassis, and the arms work in conjunction to control the vertical motion of the wheel.

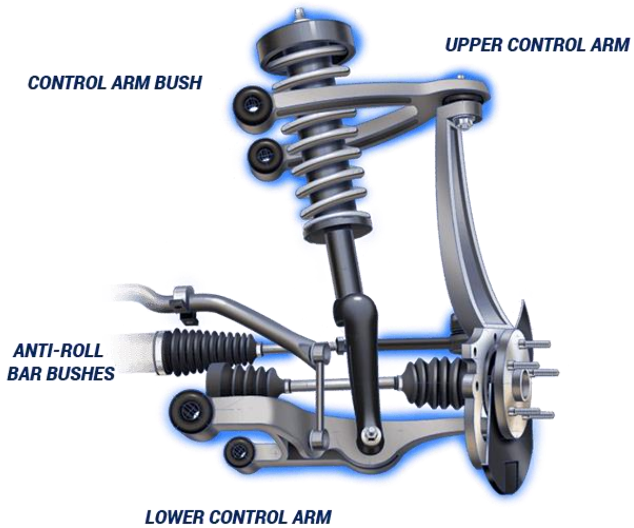


Figure 3: A Double Wishbone System with vertical orientation of the shock absorber.

The double wishbone system provide high degree of control over wheel's motion, and is usually a first choice for race cars. It is used in three configurations, direct mounted spring and damper, pushrod and pullrod actuated damper system.

In the direct mounted spring and shock system, the damper and spring system is attached directly with the lower wishbone, and the chassis. Pushrod system employs a pushrod which transfer the upward and downward movement of a wheel to the spring and damper system through a rocker/bell crank. The rocker pivots at a point on chassis, and is connected to the pushrod, and the spring and damper. The pushrod is attached to lower wishbone, and the rocker. As the wheel is raised relative to the chassis, the rod pushes the rocker and rotates it. The pullrod suspension system employs a pullrod, instead of a pushrod. The rocker in case of the pull rod suspension system is attached at the bottom of the chassis and the rod pulls the rocker as the wheel is raised instead of the pushing the rocker. The rocker converts the linear motion exhibited by the push rod into the rotational motion. The reaction forces induced in both type of systems are shown in Figure 2.

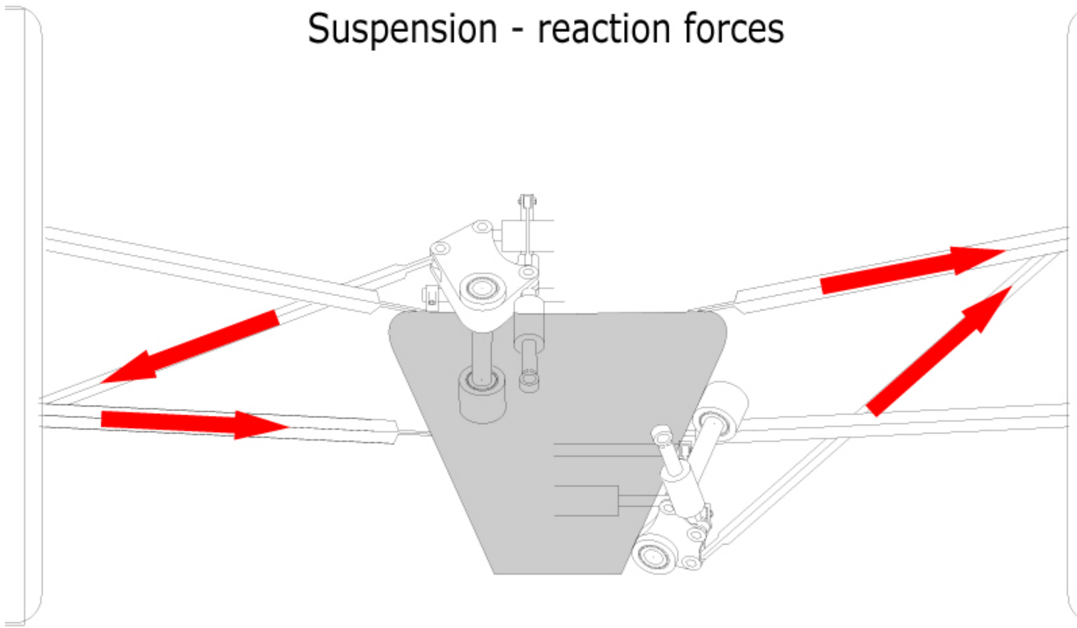


Figure 4: Comparison of transmission of forces in Push Rod and Pull Rod Suspensions

<u>Macpherson Strut Suspension System</u>

The Macpherson Strut combines the functions of a shock absorber and a suspension control arm into a single unit. It consists of a vertically mounted strut that connects the wheel hub to the chassis, and a coil spring which carries vehicle's weight.

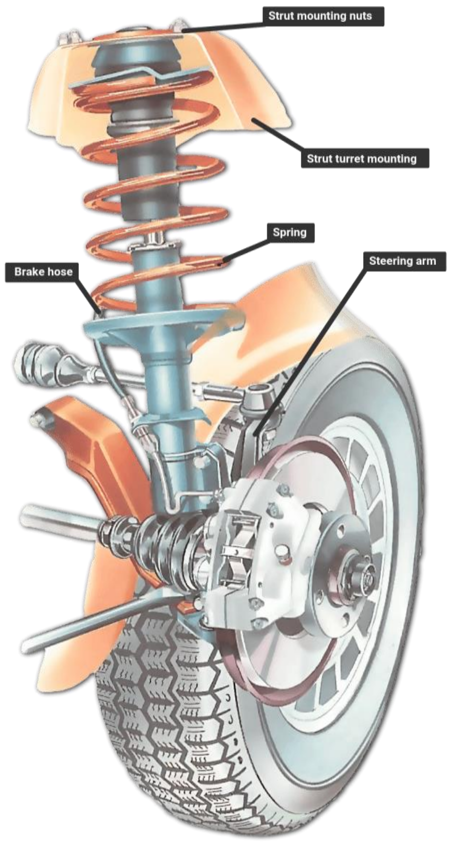


Figure 5: Macpherson Strut Suspension

Macpherson Strut allows having a good control over the wheel, and occupies less space. Its less space requirements makes it a good choice for race cars with packaging constraints.

Double Wishbone System and Macpherson Strut

Double Wishbone System has been selected compared to Macpherson Strut for the following reasons:

1. Improved Handling: In a Double wishbone suspension, there is better control over wheel movement. Better control over wheel movement is important for which can improve handling. High performance cars should have better handling capabilities and double wishbone system allows that.
2. Weight: To achieve the optimal performance from the race cars, it is important that the weight of the race car is light. Macpherson strut is heavier compared to Double Wishbone system so Double Wishbone system is again better than the Macpherson strut.

3. Better Force Transfer: In a Double Wishbone system, better force transfer from the wheels to the chassis and vice versa is observed compared to Macpherson strut. These are the forces that are generated during vehicle motion at the contact patch of the tyres.
4. Adjustability: Fine tuning and adjustability of Double Wishbone system can be done easily compared to Macpherson strut. It means that camber and caster angles can be manipulated more easily in the Double Wishbone system. Optimised performance from the suspension system can be achieved because of this adjustability.
5. Durability: In racing, suspension system undergoes high stresses and forces, thus a suspension system that can withstand higher forces should be selected. Macpherson strut in this sense is less capable than the Double Wishbone system.
6. Steering precision: Double Wishbone systems also gives steering precision which is important for handling and control of the car.

Pushrod and Pullrod Systems

Pushrod system has been selected over direct mounted and pullrod configurations. It is simpler to design than the pullrod system. It allows for ride height adjustability, easier integration of the Anti-roll bar and better tuning of the vehicle than direct mounted system.

Steering System

Steering Mechanism

Several types of steering mechanisms are available. Power Steering is not allowed as per the FSUK 2023 rule book, so it was not considered. Following mechanisms were taken into consideration for steering system.

1. Recirculating Ball Steering
2. Rack and Pinion Steering

Recirculating Ball Steering

This system has a recirculating channel with gears and ball bearings which are connected with the steering wheel. The turning of the steering wheel moves these gears and ball bearings and the movement is transferred to the wheels. This type of steering system is used in heavy vehicles, large SUVs and trucks. This is not used in Formula Cars because it has less accurate steering response and is heavier compared to the rack and pinion steering.

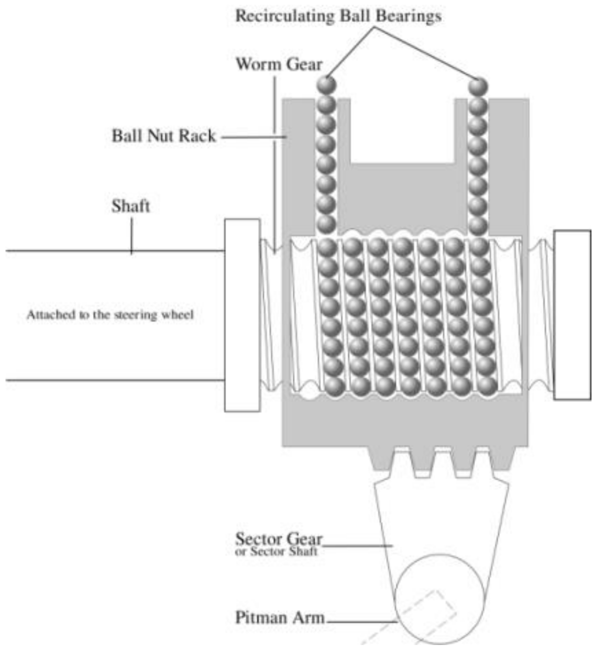


Figure 6: Recirculating Ball Steering System

Rack and Pinion Steering

In this system, the steering wheel is connected to a pinion gear that meshes with a rack, this rack is attached to the wheels. The pinion gear rotates when the driver moves the steering wheel, moving the rack and, ultimately, the wheels.

Rack and Pinion steering system is preferred over recirculating ball steering as rack and pinion system is:

1. Lightweight
2. Compact
3. Lower friction thus lower steering effort
4. Better control and feedback from steering
5. Cheaper, and easily available in the market

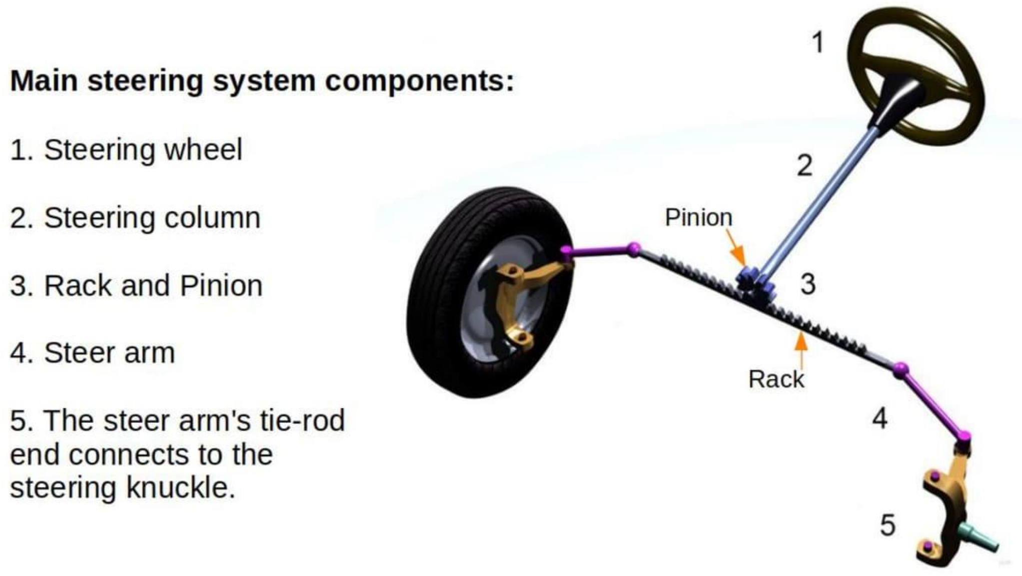


Figure 7: Steering System and its parts.

Rack and Pinion mechanism was selected for steering system due to above mentioned reasons.

Steering Geometry

When a vehicle takes a turn, the inner wheel follows an arc with smaller radius, and the outer wheel moves over an arc with greater radius. This means the inner wheel should turn more than the outer wheel in order to avoid tire slipping/scrubbing. A steering geometry is employed to turn the inner and outer wheel by correct amount. Different steering geometries are used in different cars, but the most widely used are:

1. Ackermann Geometry
2. Anti-Ackermann geometry

Ackermann Geometry

In this geometry, the imaginary lines drawn perpendicular at the wheel center of front wheels when car is turned intersect the imaginary line drawn by extending the rear axle as shown in Figure 6. The inner wheel turns more than the outer wheel. This geometry provides a perfect balance between inner and outer wheel turn if slip angles of wheels are zero.

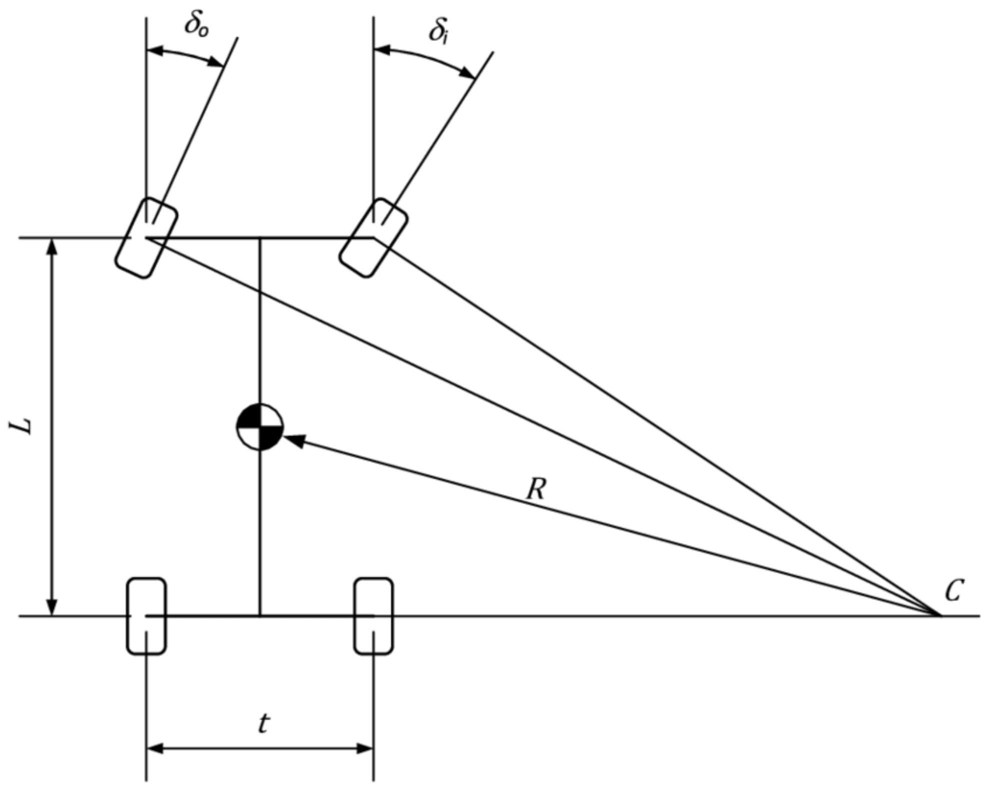


Figure 8: Ackermann Steering Geometry.

Anti-Ackermann Geometry

In anti-ackermann geometry, the outer wheels are turned more than the inner wheels. The anti-ackermann geometry is usually used in race cars, where relatively soft tires are used. When a race car goes into a turn at high speed, the weight on outer tire becomes significantly more than the inner tire, due to which the slip angle at outer tire is large. To account for the effect of slip angle, the outer wheel should turn more than the inner wheel. That is why Anti-Ackerman is popular in race cars.

Selection of Steering Geometry

Ackermann steering geometry is used for the car. Passenger car tires are used in the car, which have high stiffness. The weight and speed of the car are low in magnitude, owing to which slip angles will be negligible. Ackermann geometry better satisfies the requirements.

Brake System

Hydraulic brakes are used as it is the requirement of the rule book. Following brakes were considered:

1. Drum Brakes
2. Disk Brakes

Drum Brakes

Drum brakes operate by pressing the brake shoe against the brake drum when the brake pedal is pressed to generate the friction for stopping the wheel. When the brake pedal is pressed, hydraulic pressure is transmitted to the wheel cylinder, which contains pistons. The pistons are pushed outward by the hydraulic pressure, forcing the brake shoes against the inner surface of the brake drum.

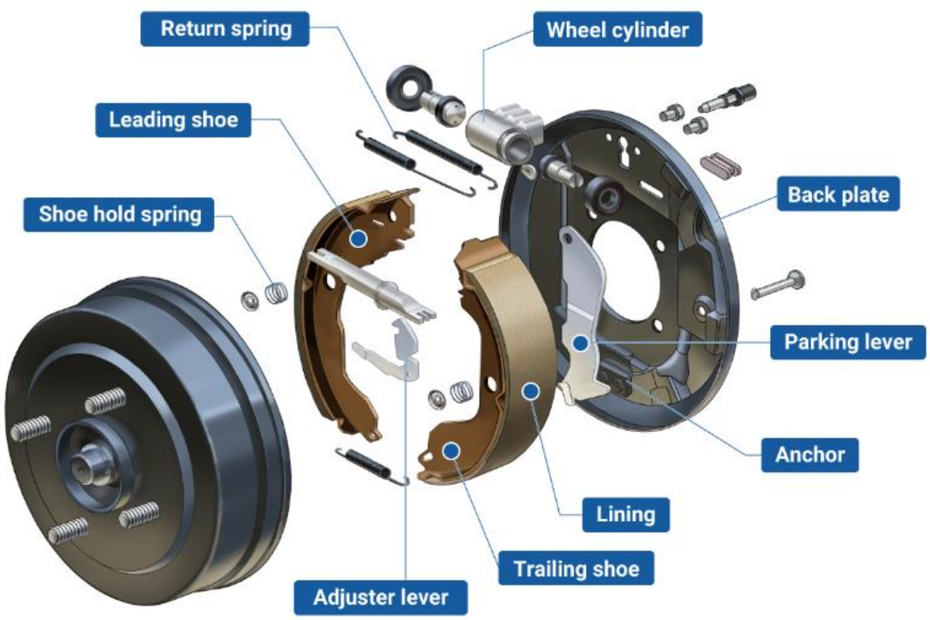


Figure 9: Drum Brakes

Disc Brakes

Disc brakes consist of a brake rotor (brake disc), a caliper with brake pads and brake actuation mechanism. Caliper is mounted on the upright, and the rotor is mounted on the wheel hub. When brake is pressed, the caliper presses the brake pads against the rotor, which stops the car.

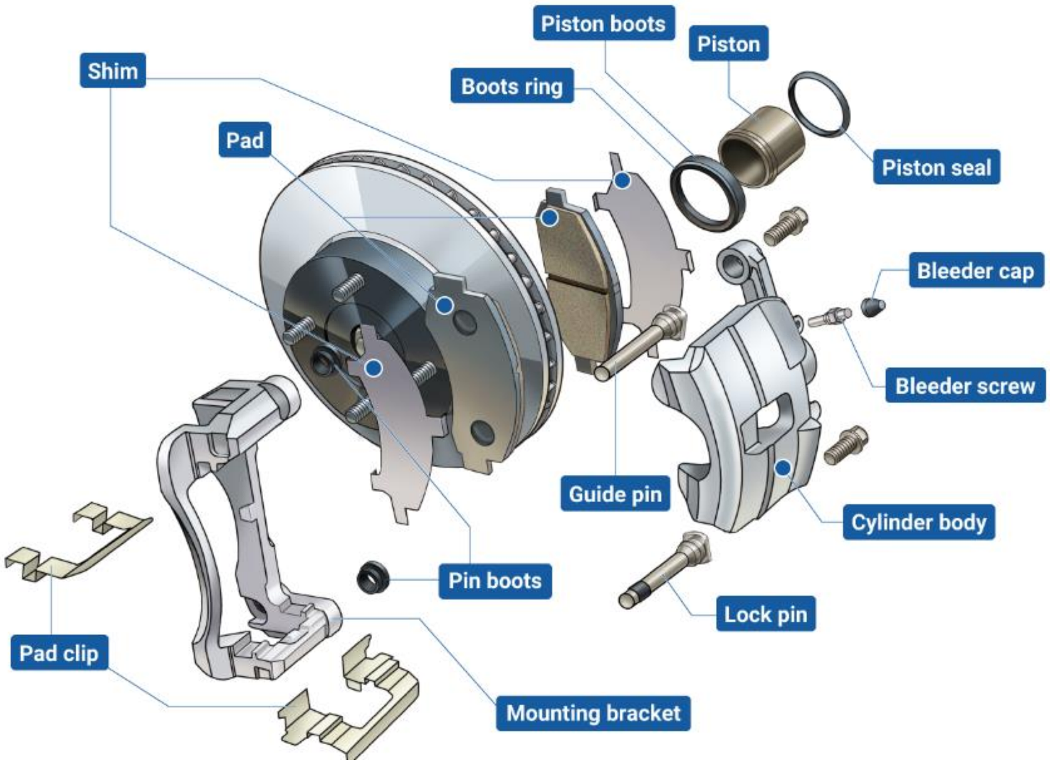


Figure 10: Disc Brake

<u>Brake Selection</u>

Disc brakes are selected compared to Drum brakes for the following reasons:

1. Heat Dissipation:

   Formula student cars undergo high speeds and intense braking giving rise to high temperatures. Disc brakes rae better at dissipating heat than drum brakes and do not undergo brake fade.

2. Weight:

   The drum brakes are heavier and do not align with the reduced weight concept of Formula Cars.

3. Better Stopping Power:

   Disc brakes have better stopping power. They also are more suitable fore precise braking during high-speed cornering in Formula Cars.

4. Maintenance:

   Disc brakes are easier to maintain and replace.

5. Brake Fade: Drum brakes can undergo brake fading whereby drum brakes cannot dissipated the generated heat, the brakes overheat and their braking efficiency reduces considerably.

CHAPTER 3: METHODOLOGY

Based on the literature review, following parameters and design targets were defined to start the design process:

Table 1: Vehicle parameters for initiating design process

Wheel base	1700 mm
Front Track	1300 mm
Rear Track	1250 mm
Weight Distribution	40:60 (F:R)
Total mass (including driver)	300 kg
Camber Angle	-1.5^0 (F), -1^0 (R)
Castor Angle	12^0 (F), 6^0 (R)

Suspension System

The design of suspension system includes

1. Ride Analysis
2. Kinematic Analysis
3. Design of suspension components based on above analysis

Ride Analysis

Ride analysis was performed for spring selection. The goal is to select springs such that rear stiffness is slightly less than front stiffness, the roll gradient lies in the range of 1.2 – 1.8 deg/g, and the car does not bottom out while cornering.

Rear stiffness is kept slightly lower than the front stiffness to avoid oversteer. The rear wheels provide the driving force, so they cannot provide as much lateral force as front wheel during a corner. Higher stiffness at front means higher lateral load transfer at front, which leads to less front grip during corner.

Ride analysis is an iterative process. Ride frequencies are chosen first, and spring rates, roll gradient, weight transfer and spring compression are calculated.

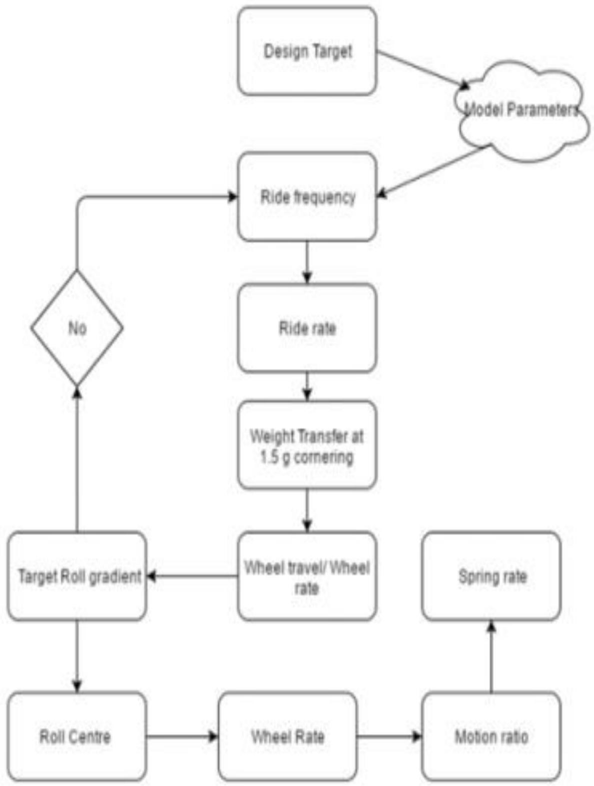


Figure 11: Methodology for calculating spring rates

Few assumptions are made in the process:

1. Ride height of car is constant
2. Tire stiffness remains constant
3. Lateral load is transferred only due to cornering

Since the suspension is independent, therefore the ride frequency is given by:

$$\omega = \frac{1}{2\pi}\sqrt{\frac{K_R * 2}{W_1}}$$

Wheel center rate can be found out by:

$$K_W = \frac{K_R K_T}{K_T - K_R}$$

Next step is to find roll rate:

$$K_{\phi} = \frac{t_F^2 * K_R}{2}$$

Then roll gradient is determined:

$$\frac{\phi}{A_Y} = \frac{W * H}{K_{\phi F} + K_{\phi R}}$$

By using the above method and equations, and after performing many iterations, we found the spring rates to be 2.1 kN/m and 2.4 kN/m respectively.

Kinematic Analysis

Kinematic analysis is performed to figure out an optimal suspension geometry. Changes in some parameters in response to roll angle are taken in consideration. It is an iterative process.

A software program "Lotus Shark" was used for performing Kinematic analysis. Based on the car's wheelbase, front and rear track, and packaging requirements in the chassis, suspension hard points are chosen, tires and suspension type are defined in the software, and the software performs the analysis. Graphs are obtained which show the variation of various parameters with respect to roll angle. The analysis is performed again and again until an acceptable trend is obtained.

The car is given a roll angle from -2.5^0 to $+2.5^0$. These values depend upon the roll gradient of the car.

Following figures show the graphs of the final analysis.

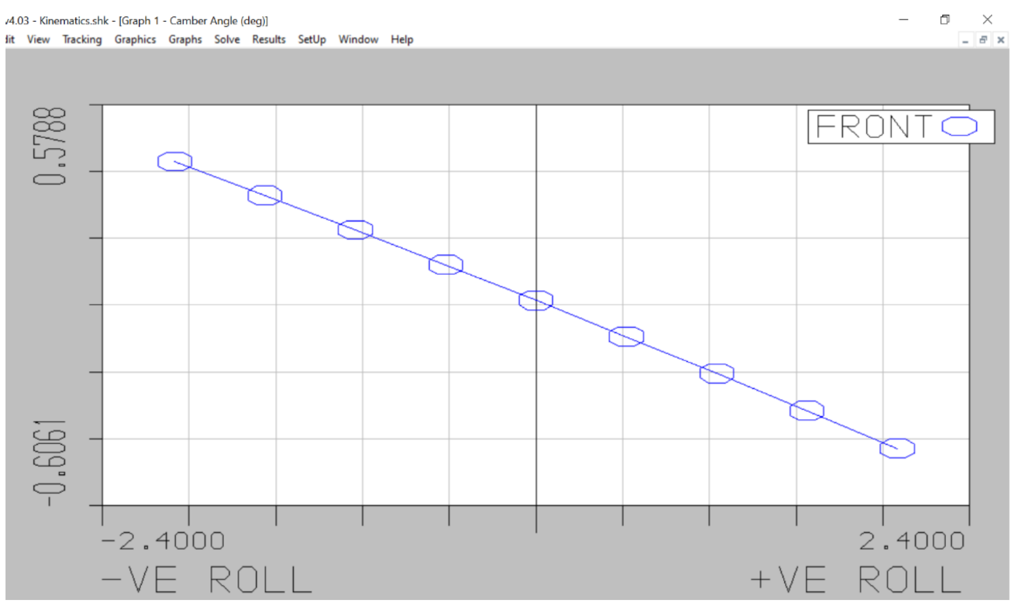


Figure 12: Camber vs Roll

As seen in above graphs, there is a camber gain (about 0.6^0) at outer wheel when the car rolls.

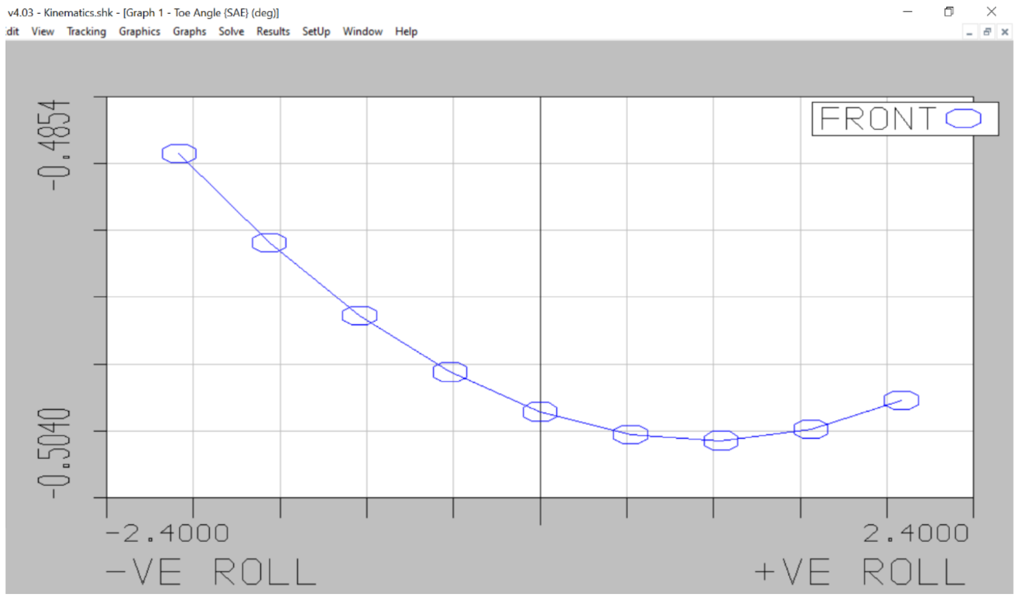


Figure 13: Toe vs Roll

The changes in car tow angle should be minimized when the car rolls. The above graph shows that there is a small variation in the toe angle of car.

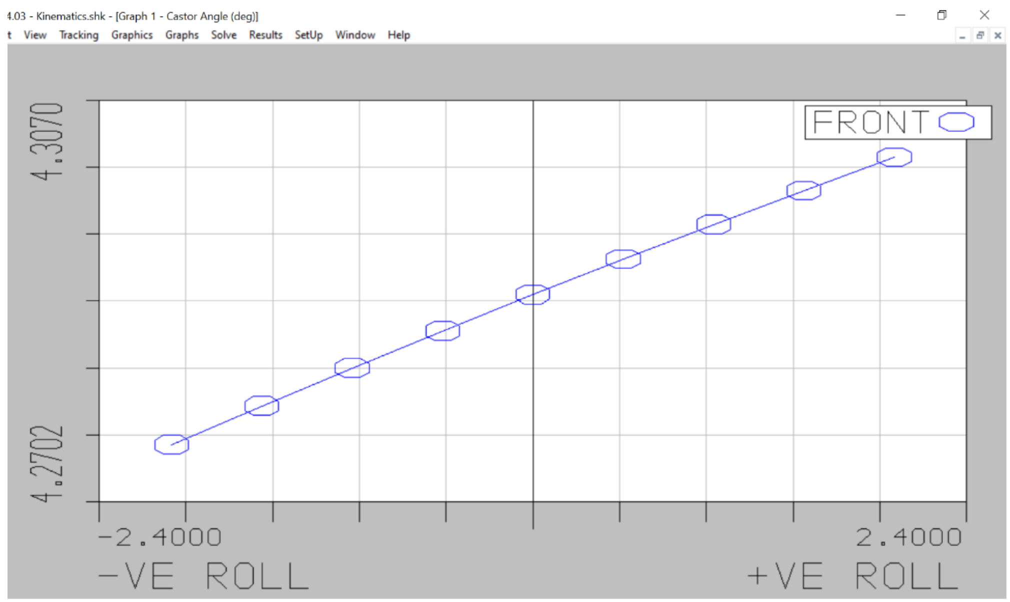


Figure 14: Castor vs Roll

The castor angle at outer wheel should increase slightly when the car rolls during a turn, this increases self aligning torque. This trend is depicted in above graph.

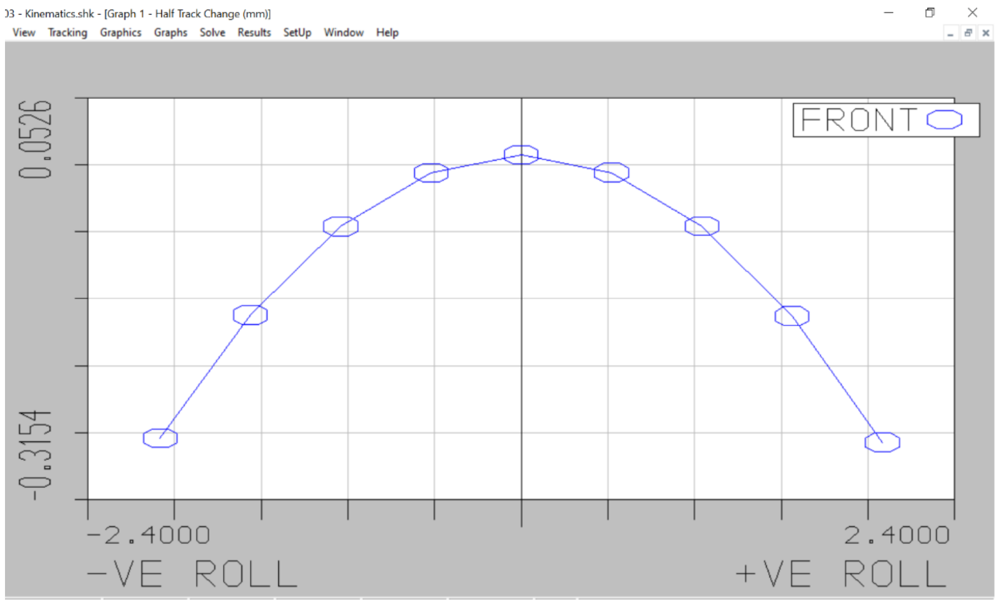


Figure 15: Half Track vs Roll

Designing/Procurement of Suspension Components

The following table shows the components of the suspension system being fabricated and those which are bought off the shelf.

Table 2: List of components of the Suspension System being fabricated and bought off the shelf.

S. No.	Components	Fabricated/Off the Shelf
1.	Wishbones	Fabricated
2.	Shock Absorbers	Off the shelf
3.	Ball joints	Off the shelf
4.	Wheel Hubs	Fabricated
5.	Uprights	Fabricated
6.	Trailing Arms	Fabricated
7.	Knuckle	Fabricated
8.	Bushings	Fabricated
9.	Springs	Off the shelf

Upright Design

The Upright is the structure that holds the upright assembly together, it connects the wheel, wheel hub, brake disc and other materials to the wishbones and consequently to the chassis of the vehicle. As such, the design process of the part starts with a basic box-like structure that simply connects all the parts together, with the same base model being used to develop both the front and the rear uprights, as shown below.

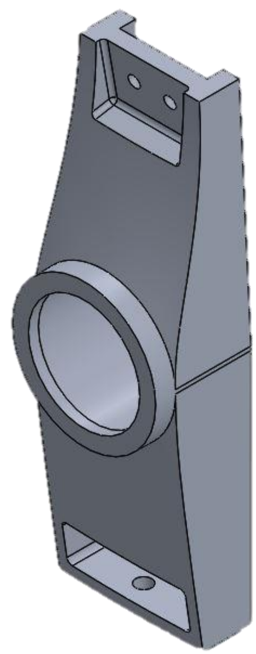


Figure 16: Upright – First Iteration

Material is removed from the part, reducing its weight with minimal loss to the load-bearing capacity of the part. This is achieved with the topology optimization tool in ANSYS. The finalized part is then validated in ANSYS static structural.

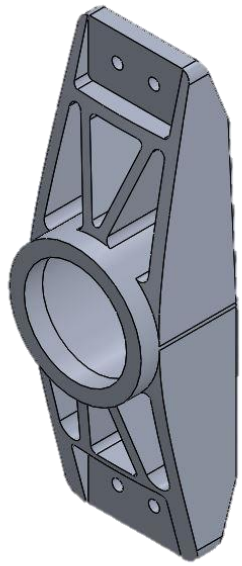


Figure 17: Front Wheel Upright – Second Iteration

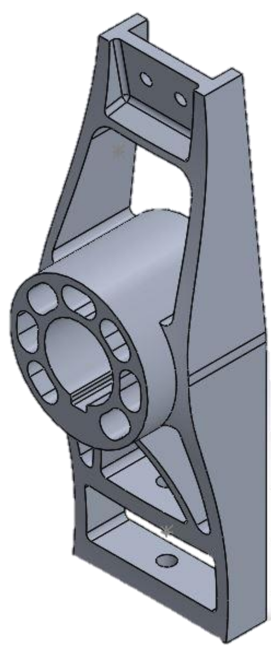


Figure 18: Rear Wheel Upright – Second Iteration

The upright FEA consists of a static structural analysis carried out with a 2mm size cartesian mesh which was able to achieve a quality of about 0.91. Higher qualities can be achieved with more refined meshes. The load values calculated using the load paths were applied the top and bottom attachment points of the upright and the central hole was constrained using a cylindrical support, the simulation results demonstrated a factor of safety of about 2 compared to the yield stress of the material.

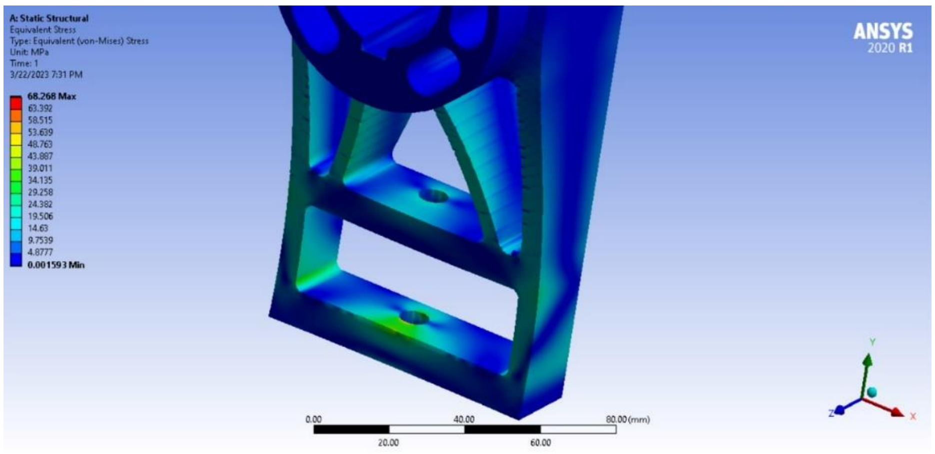


Figure 19: FEA of Rear Upright

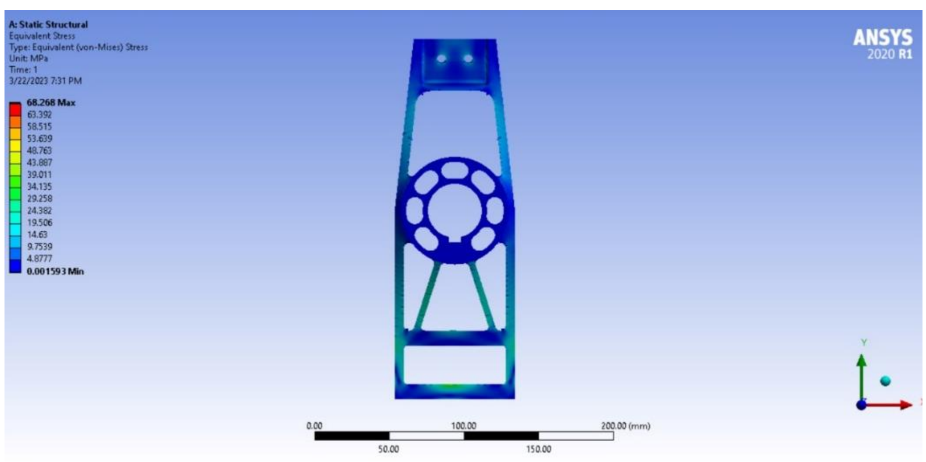


Figure 20: FEA of rear upright (xy – plane)

Wheel Hub Designing

The wheel hub connects the upright assembly to the rim and the brake disc, this part undergoes all three types of loading namely bending, axial, and torsional loading. The design process involves a basic revolute shape in which the mounting points of the rim, brake disc, and bearings are defined.

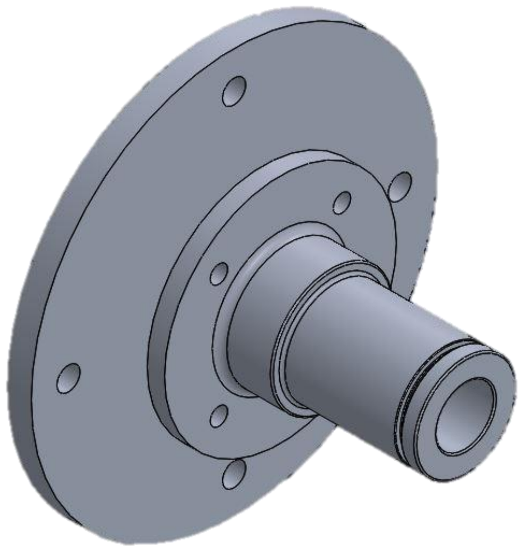


Figure 21: Wheel Hub – First Iteration

This base shape is then made altered in the ANSYS mechanical topology optimization to reduce weight while maintaining strength. The finalized part is then validated in ANSYS static structural.

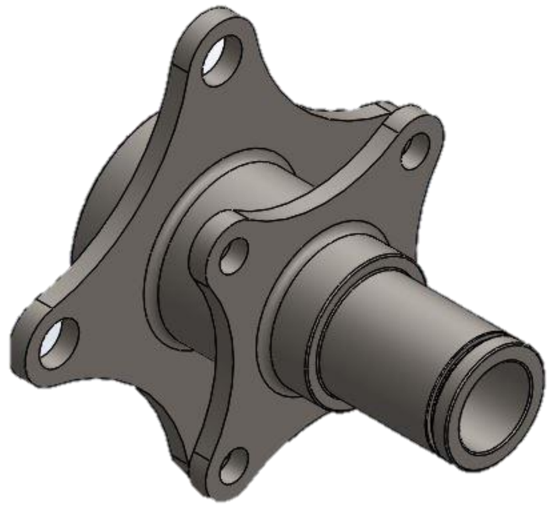


Figure 22: Wheel Hub – Second Iteration

The wheel hub FEA was carried out in static structural module using a mesh size of 1mm for a cartesian mesh. Due to the finer mesh used as compared to the upright, a higher quality of 0.94 was achieved in this case. The wheel hub was analyzed separately for braking and vertical wheel load and then for a combined load simulating braking and cornering which is the largest design load for the part. In order to account for the lack of modal analysis, the part was designed for a much larger factor of safety of about 3. This factor of safety requirement was validated by the simulation which showed a factor of safety of about 3.25.

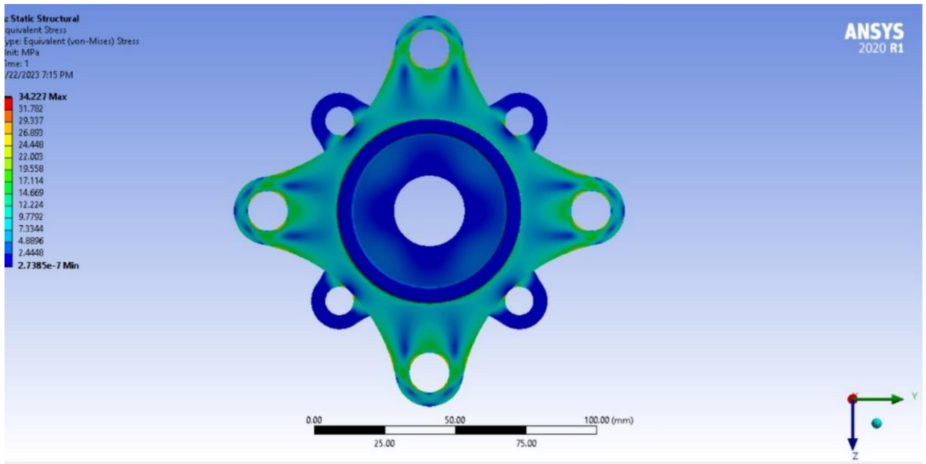


Figure 23: Static Structural Analysis of Wheel Hub (x-z plane)

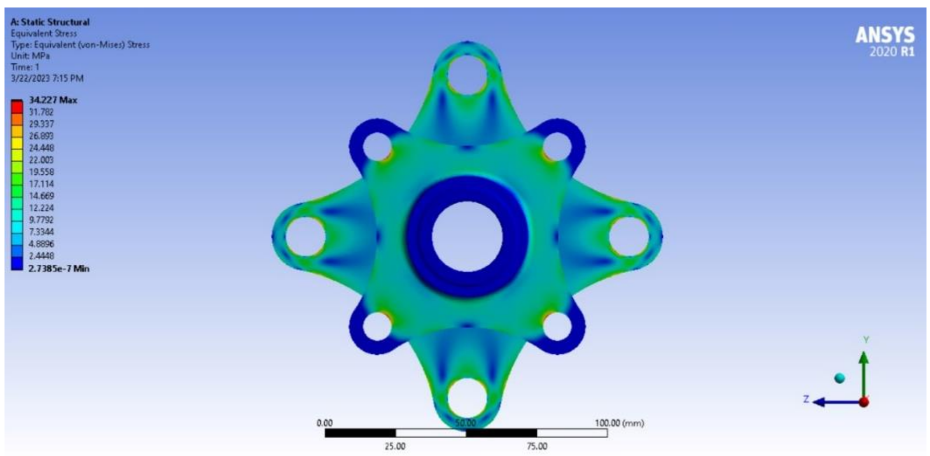


Figure 24: Static Structural Analysis of Wheel Hub (y-z plane)

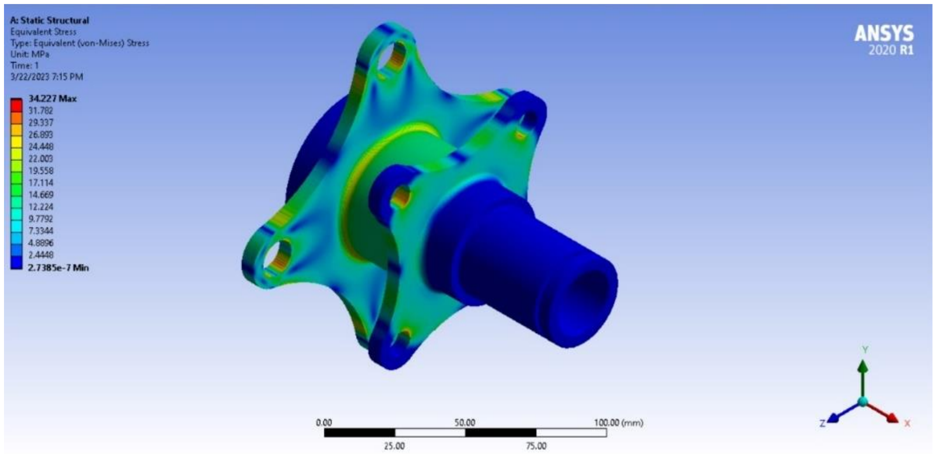


Figure 25: Static Structural Analysis of Wheel Hub (isometric view)

<u>Wishbone Design</u>

The Wishbone connects the Upright Assembly to the chassis. They are made with round metal tubes due to their light weight and high rigidity. Originally, the wishbones were mounted onto the chassis and uprights with radial spherical bearings. However, this layout was relatively difficult and time consuming to manufacture. Due to this, rodends have been attached at the chassis end of the wishbone using tube adapters, increasing manufacturiability of the final assembly.

Figure 26: Wishbone – First Iteration

Figure 27: Wishbone – Second Iteration

Rocker Designing

The rocker arm allows for the vertical load of the suspension to be transmitted into a lateraly placed shock-absorber. The initial design comprised of a rocker arm as a single part. This part required manufacturing using either CNC machining or welding of multiple parts together. In order to simplify the manufacturing process, each rocker arm has been designed as two parallel plates, each of which has been optimized and validated on ANSYS. This new design is simple enough to be laser cut and bolted onto the chassis quickly using bushings.

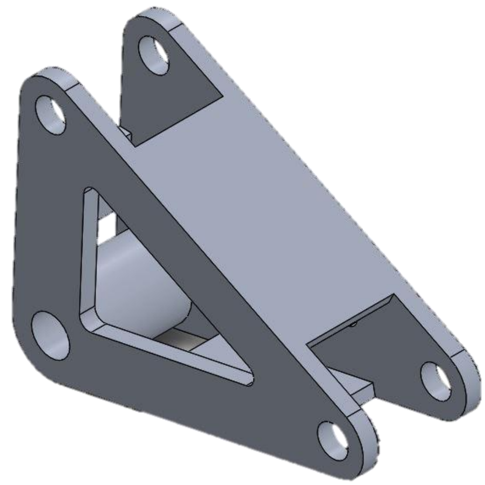


Figure 28: Rocker – First Iteration

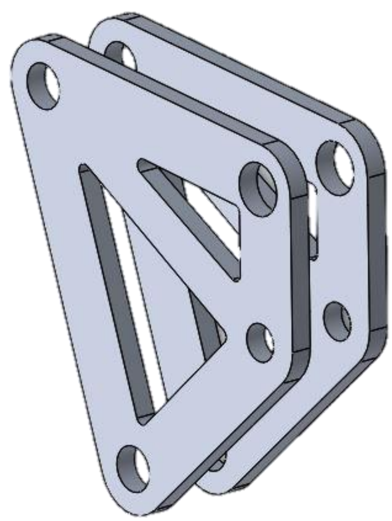


Figure 29: Rocker – Second Iteration

Brake System

The main objective of the braking system is to convert the kinetic energy of the vehicle into thermal energy, thus allowing the vehicle to decelerate. The braking system was designed as a hydraulic system with two master cylinders, one for the braking of the front two tires and one for braking of the rear two tires. Attached to each master cylinder are two floating calipers, one located at each of the tires for a total of four calipers for the system, as well as four rotors or brake disks.

Weight transfer during braking will be:

$$F_T = \frac{\mu_B W H}{L}$$

Where μ_B is the friction coefficient between road and tyre, W is the weight of car, H is the height of center of gravity and L is the wheel base.

Normal forces on front and rear tires will be:

$$F_{NF} = \frac{W L_R}{L} + F_T$$

$$F_{NR} = \frac{W L_F}{L} - F_T$$

Clamping forces will be:

$$F_{FCP} = \mu_{CP} F_{NFCP}$$

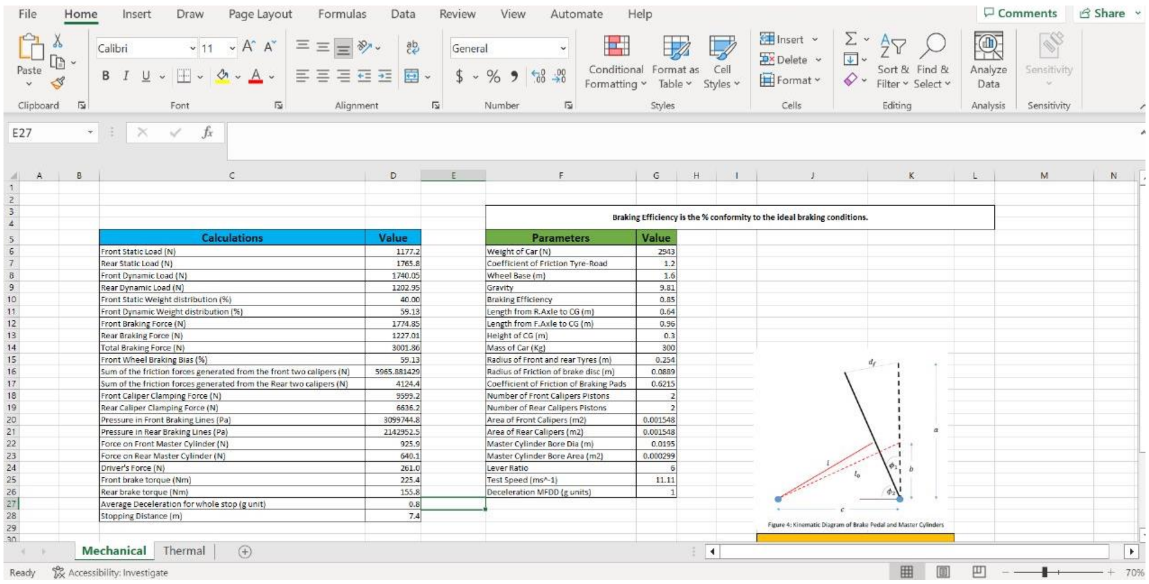
$$F_{RCP} = \mu_{CP} F_{NRCP}$$

Clamping forces will be:

$$P_F = \frac{F_{NFCP}}{\#\ of\ front\ caliper\ pistons\ * A_{FCP}}$$

$$P_R = \frac{F_{NRCP}}{\#\ of\ rear\ caliper\ pistons\ * A_{RCP}}$$

Using the above methodology and equations, following calculations were performed on excel.



Braking Efficiency is the % conformity to the ideal braking conditions.

Calculations	Value
Front Static Load (N)	1177.2
Rear Static Load (N)	1765.8
Front Dynamic Load (N)	1740.05
Rear Dynamic Load (N)	1202.95
Front Static Weight distribution (%)	40.00
Front Dynamic Weight distribution (%)	59.13
Front Braking Force (N)	1774.85
Rear Braking Force (N)	1227.01
Total Braking Force (N)	3001.86
Front Wheel Braking Bias (%)	59.13
Sum of the friction forces generated from the front two calipers (N)	5965.881429
Sum of the friction forces generated from the Rear two calipers (N)	4124.4
Front Caliper Clamping Force (N)	9599.2
Rear Caliper Clamping Force (N)	6636.2
Pressure in Front Braking Lines (Pa)	3099744.8
Pressure in Rear Braking Lines (Pa)	2142952.5
Force on Front Master Cylinder (N)	925.9
Force on Rear Master Cylinder (N)	640.1
Driver's Force (N)	261.0
Front brake torque (Nm)	225.4
Rear brake torque (Nm)	155.8
Average Deceleration for whole stop (g unit)	0.8
Stopping Distance (m)	7.4

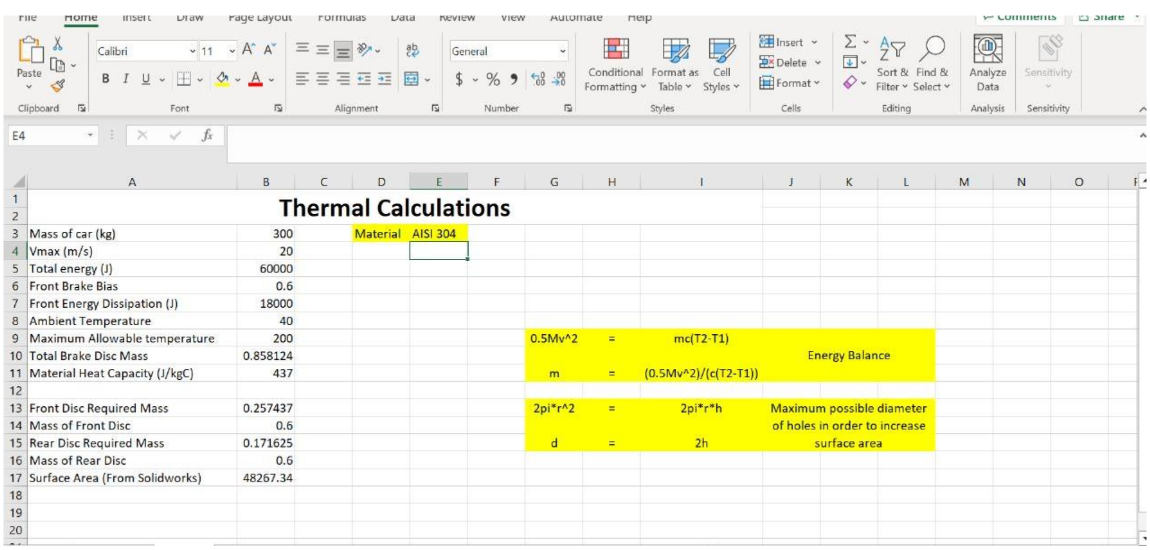
Parameters	Value
Weight of Car (N)	2943
Coefficient of Friction Tyre-Road	1.2
Wheel Base (m)	1.6
Gravity	9.81
Braking Efficiency	0.85
Length from R.Axle to CG (m)	0.64
Length from F.Axle to CG (m)	0.96
Height of CG (m)	0.3
Mass of Car (Kg)	300
Radius of Front and rear Tyres (m)	0.254
Radius of Friction of brake disc (m)	0.0889
Coefficient of Friction of Braking Pads	0.6215
Number of Front Calipers Pistons	2
Number of Rear Calipers Pistons	2
Area of Front Calipers (m2)	0.001548
Area of Rear Calipers (m2)	0.001548
Master Cylinder Bore Dia (m)	0.0195
Master Cylinder Bore Area (m2)	0.000299
Lever Ratio	6
Test Speed (ms^-1)	11.11
Deceleration MFDD (g units)	1

Figure 30: Brake Calculations

When brake is applied, the kinetic energy of the car is converted into thermal energy at brake disk. Using the energy conservation concept, i.e.:

Kinetic Energy of the Car = Thermal Energy of brake disk

Using this concept, following calculations were performed:



Thermal Calculations

Mass of car (kg)	300
Vmax (m/s)	20
Total energy (J)	60000
Front Brake Bias	0.6
Front Energy Dissipation (J)	18000
Ambient Temperature	40
Maximum Allowable temperature	200
Total Brake Disc Mass	0.858124
Material Heat Capacity (J/kgC)	437
Front Disc Required Mass	0.257437
Mass of Front Disc	0.6
Rear Disc Required Mass	0.171625
Mass of Rear Disc	0.6
Surface Area (From Solidworks)	48267.34

Figure 31: Brake Thermal Calculations

The following table shows the components of the Brake system being fabricated and those which are bought off the shelf.

Table 3: List of components of the Brake System being fabricated and bought off the shelf.

S. No.	Components	Fabricated/Off the Shelf
1.	Brake Calipers	Off the shelf
2.	Brake Pads	Off the shelf
3.	Brake Discs	Fabricated
4.	Brake Lines	Off the shelf
5.	Brake Master Cylinder	Off the shelf
6.	Brake Fluid	Off the shelf
7.	Brake Bias Adjuster	Fabricated
8.	Brake Calipers	Off the shelf
9.	Brake Pads	Off the shelf

Brake Disc Designing

The brake disc is designed to have enough mass so as to limit the maximum temperature reached by the disc under heavy braking from top speed to dead stop. The brake material is selected in order to remove brake dust and thus longevity of the rotor. The shape of the disc has been changed in order to allow easy installation. Where the first iteration has to be attached onto the wheel hub prior to assembly, the new rotor can be mounted onto the upright assembly after the system has been mounted onto the chassis. This also allows for easy brake disc swapping should that become necessary for maintenance. Moreover, the surface area of the surface in direct contact with the wheel hub has been reduced, this reduces the transfer of heat from the disc to the wheel hub during operation, improving the life of the wheel hub. Lastly, the final design was validated in ANSYS static structural.

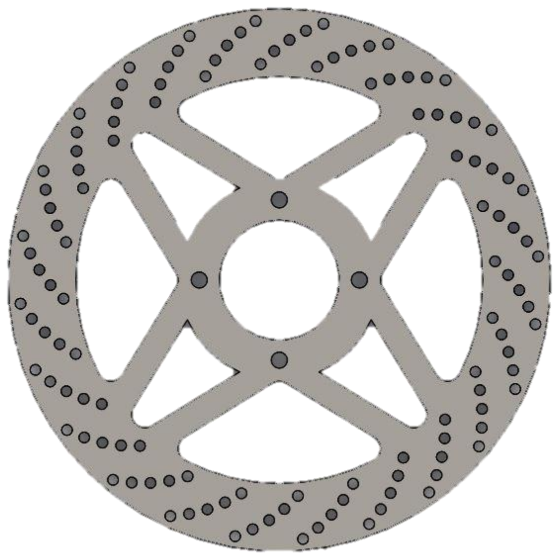


Figure 32: Brake Rotor – First Iteration

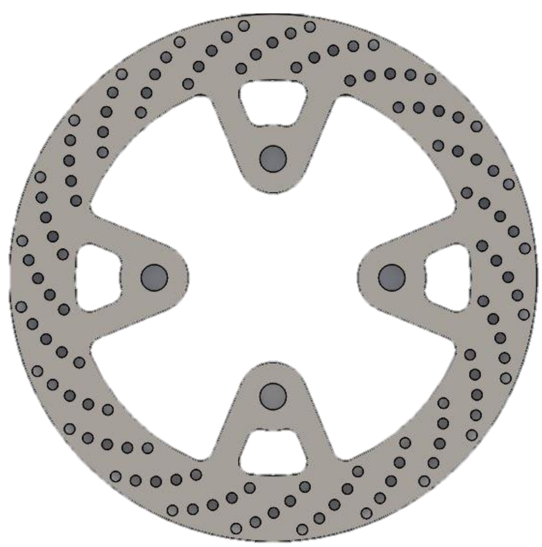


Figure 33: Brake Rotor – Second Iteration

The brake disc FEA was carried out on static structural with a 1mm size cartesian mesh which was able to achieve a quality of about 0.95. The disk was supported along its 4 bolt holes using cylindrical support feature and a torque was applied to the outer ring of the disc to simulate braking loads. These results were then used in topology optimization to achieve mass reduction while maintaining structural strength. In order to account for thermal stresses generated during braking and the safety critical nature of the part, a large factor of safety of 4 was used which was validated in the subsequent load simulation.

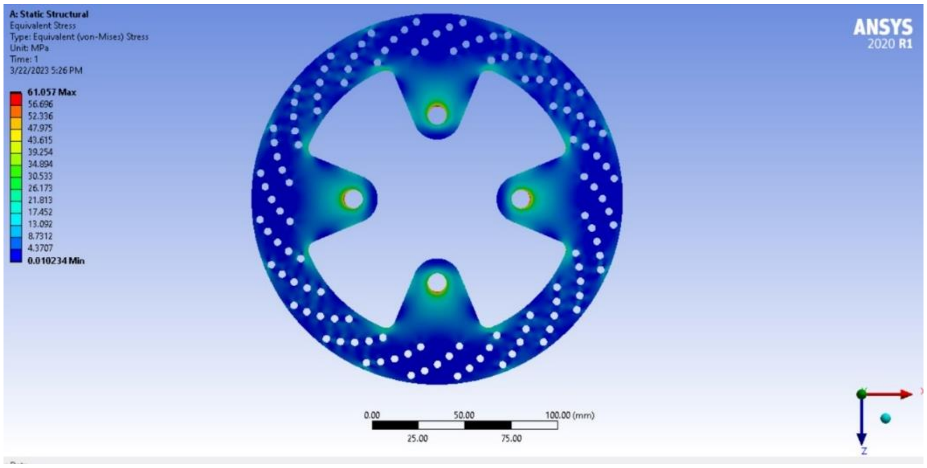


Figure 34: FEA of Brake Disk before optimization.

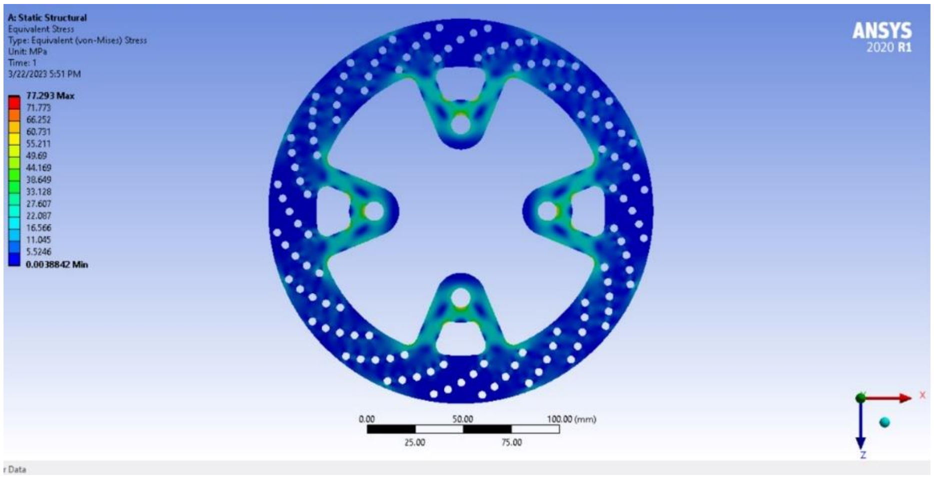


Figure 35: FEA of Brake Disc after optimization

Steering System

The steering geometry was optimized using a template created in Solidworks. A travel of 35 mm was given to the rack, and the wheels turned. The template showed whether Ackermann geometry is being followed or not. The geometry was modified until desired result was not achieved.

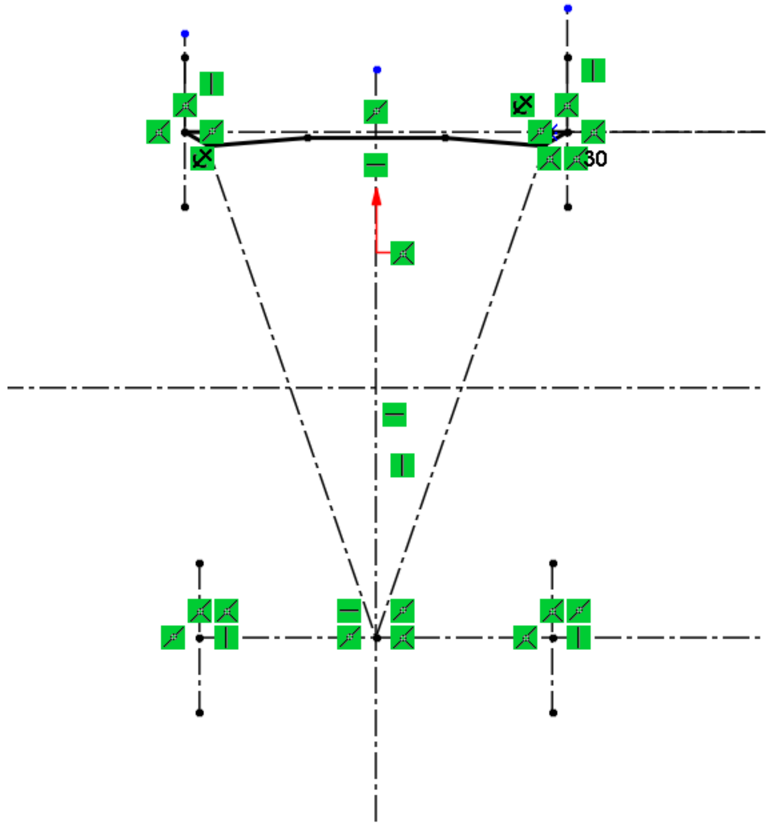


Figure 36: Steering Geometry Template

The following table shows the components of the Steering system being fabricated and those which are bought off the shelf.

Table 4: List of components of the Steering System being fabricated and bought off the shelf.

S. No.	Components	Fabricated/Off the Shelf
1.	Steering Wheel	Fabricated
2.	Steering Column	Fabricated
3.	Steering Rack	Off the shelf
4.	Tie Rods	Fabricated
5.	Ball Joints	Off the shelf
6.	Uprights	Fabricated

7.	Wishbones	Fabricated
8.	Wheel Bearings	Off the shelf

Material Selection

Table 5: Materials selected for the total components being fabricated.

S. No.	Components	Material Selected	Options considered
1.	Brake Disc	304 stainless steel	Aisi 4140, cast iron, 420, 410, 304, 316 steel
2.	Brake Bias Adjuster	Mild steel	Mild steel, Aluminium
3.	Steering Wheel	Aluminium	Mild steel, Aluminium
4.	Steering Column	Mild steel	Mild steel, chrome plated rod
5.	Tie Rods	A36 Steel	Carbon Fibre, A36, AISI 4130 chromoly tube
6.	Uprights	Al 6061	Mild Steel, Al6061, Al2219
7.	Wishbones	A36 Steel	Carbon Fibre, A36, AISI 4130
8.	Wheel Hubs	Mild steel	Al6061, Mild Steel
9.	Bushings	Nylon	Nylon, Polyurethane, rubber
10.	Trailing Arms	A36 Steel	Carbon Fibre, A36, AISI 4130
11.	Wheel Knuckle	Al 6061	Mild Steel, Al6061, Al2219

1. **Brake Disc**

Brake Disc is to be manufactured with 304 stainless steel. The choice of material was made on the basis of availability of material in the market.

2. Brake Bias Adjuster

The Brake Bias Adjuster can be made from both Aluminium and Mild Steel. We are going with Mild Steel because it is easily weldable, has low required yield stress and can be cut easily.

3. Steering Wheel

Aluminium is used for making steering wheel. Aluminium has low required yield stress and can be easily cut but it is also light weight. The factor to decide on the material for the steering wheel was the weight of the materials. Steering wheel can not be made heavy or else it would affect the performance of the driver during cornering and high speed situations.

4. Steering Column

Steering column is being made of Mild steel because of it being easily weldable, has low required yield stress and can be cut easily.

5. Tie Rods

Tie rods are to be fabricated using A36 steel as pipes are available in various sizes and it is weldable and machinable.

6. Uprights

Uprights are to be designed using Al 6061 as it has good strength to weight ratio, availability of material and machinability.

7. Wishbones

Wishbones are being designed using A36 Steel due to its Low cost, easy to weld good performance in heat affected zone so no need for normalization.

8. Wheel Hubs

Wheel Hubs are to be designed using Mild Steel because of its weldability and strength.

9. Bushings

Bushings will be designed using Nylon as Nylon is Stiff, has Low friction coefficient, and is resistant to wear along with being light weight

10. Trailing Arms

Trailing Arms are to be designed using A36 Steel. A36 Steel is Weldable, can be easily cut and has low required yield stress.

11. Wheel Knuckle

Wheel knuckles are to be manufactured from Al 6061 as it has good strength to weight ratio, availability of material and machinability.

Tyres Selection

Street car/passenger car tires were used on car, due to the unavailability of track car tyres in the market. Front tires are 165/70 R12 and rear tires are 165/65 R13. Rule book bounds us using tires greater than 8 inches in rim diameter. A smaller diameter tire is preferred in race cars, as it offers less rotational inertia. But, a smaller diameter tire also make the design of the suspension geometry, upright and wheel hub more complicated. In the R12 size rim, there is enough space to comfortably design upright and wheel hub. At rear, in-wheel motors are used, so in order to package them, we are using a slightly bigger rim (R13).

Final Design and Assembly of Suspension System:

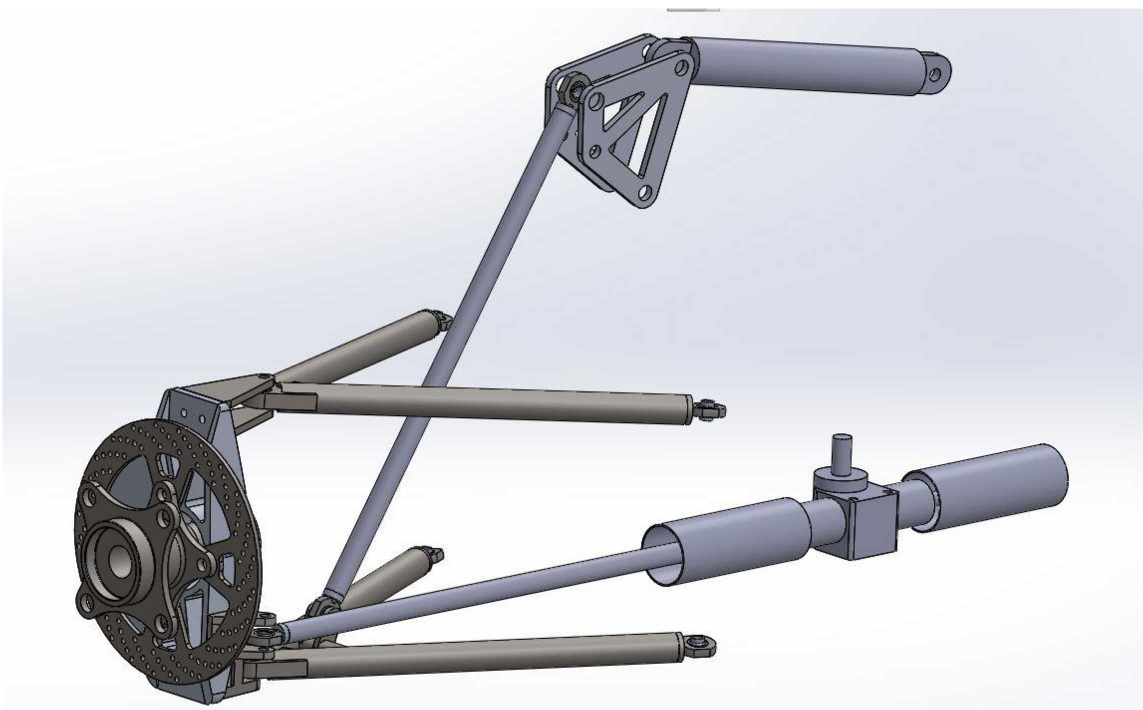


Figure 37: Assembly of suspension components

Manufacturing Process:

The manufacturing processes that are to be used for the manufacturing of these components are listed down in the table below:

Table 6: Manufacturing Processes for the components that are to be fabricated

S. No.	Components	Material Selected	Manufacturing Process
1.	Brake Disc	304 stainless steel	Laser Cutting
2.	Brake Bias Adjuster	Mild steel	Laser Cutting, Welding
3.	Steering Wheel	Aluminium	Laser Cutting
4.	Steering Column	Mild steel	Cutting, Welding
5.	Tie Rods	A36 Steel	Cutting, Welding
6.	Uprights	Al 6061	CNC Machining
7.	Wishbones	A36 Steel	Cutting, lathe, laser cutting, welding
8.	Wheel Hubs	Mild steel	Laser cutting, Lathe, welding
9.	Bushings	Nylon	Lathe
10.	Trailing Arms	A36 Steel	Cutting, lathe, welding
11.	Wheel Knuckle	Al 6061	CNC machined

CHAPTER 4: RESULTS AND DISCUSSIONS

The project resulted in design of a suspension system compatible with Team Alif's formula student electric car. The suspension was integrated with chassis and powertrain subsystem, as shown in the figures below:

Figure 38: Formula Student Car

Figure 39: Front Suspension

Figure 40: Front Suspension and Steering System

Figure 41: Rear Suspension

No problem was faced during integration of suspension subsystems with other systems of the car, which showed good inter-team coordination. The suspension system worked fine with the car, which depicted that the design process and methodology of the team was good.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Conclusion

This report provides a high-level overview of our project: Design and Manufacturing of a Suspension System for a Formula Student Car. We discussed what objectives are we trying to achieve and how are we achieving them. Designing and Structural Analysis of different components of the suspension, steering and braking system has been discussed in detail. The literature and existing designs reviewed as references for our project are also discussed. The report also mentions the reasoning and logic used to take design decisions for different systems. SolidWorks and ANSYS are the main tools used for designing and analysis of components. Lotus is used to get kinematic parameters.

Recommendation

Use of Slicks

Our Formula Car is using Street Tyres instead of Slicks due to unavailability of track tyres/slicks in the market. Slicks provide better grip and traction and have lower rolling resistance in comparison with Street tyres which is important for faster lap times. Slicks can perform good even when they get heated up during high speed maneuvers. Slicks are also lighter, on the other hand, street tyres are heavier which increases unsprung weight. In our case, the handling will not be as good as that in case of slicks. Using slicks, one can achieve good performance in the aspects of both handling and responsiveness of the car.

Anti Roll bars/Sway bars

Anti roll bar keeps the car’s body stable during turns by reducing the amount of body roll. These bars can also be used for even distribution of weight between the front and the rear wheels which can improve the overall balance of the car and reduces the possibility of understeer and oversteer. Formula Student cars are expected to responsive to driver inputs, using anti-roll bars one can achieve that.

Powerful Motors

The motors that are currently being used in our car are QS 260 3000W v4. If adequate funds were available, the motors could be replaced with any of the following motors. These motors are capable of providing more power and acceleration to the Formula Car compared with our QS 260 3000W v4 which has the maximum power output of only 3kW.

Table 7: Motor comparison

S. No.	Motor Model	Maximum Power Output
1.	QS 260 3000W v4	3kW
2.	Emrax 228	60kW
3.	Rinehart Motion Systems PM100DX	100kW
4.	AM Racing AMR Dual Stack	120kW
5.	YASA P400	150kW
6.	EVO Electric AFM-240	240kW

Aerodynamic Devices

For increased performance and stability, aerodynamic devices can be added with vehicle. For example, Front and Rear Wings, Diffuser and Side Tray.

1. Front Wing: It is attached on the front of the car. Increases downforce and reduces drag.
2. Rear Wing: It is attached on the rear of the car. It significantly increases downforce and improves traction during acceleration, braking and cornering.
3. Diffuser: Installed at the back of the car and accelerates the air underneath the car which creates a low-pressure zone that helps increase the drag.

These devices can significantly increase the performance of a Formula Student car by increasing stability, fuel efficiency and giving a competitive edge to the teams in the event.

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