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Design and Numerical Analysis of Suspension Geometry for a Formula Student Race Car

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Abstract

Formula Student (or Formula SAE (F-SAE)) is a worldwide university competition, organized by the Society of Automotive Engineers (SAE), which encourages university teams to design, build, and compete with a Formula-student race car. Design analysis of suspension especially for racecar is very crucial to achieve maximum performance and handling. Suspension design may vary depending on the road terrain and the vehicle purpose itself. The main objective of this project is to design and numerical analysis of a suspension system for a student formula car. We discussed the conditions, factors and FSAE rules that should be considered to design a student formula race car. According to the desired performance some packaging parameters are selected and other suspension and sprung parameters are calculated. Then according to the calculation the suspension geometry is determined with an optimized result by numerical simulation in Lotus Suspension Analysis. Further this process can be followed for designing suspension system for any kind of vehicles.

Keywords: Suspension design, Formula Student, Race car suspension, Lotus suspension analysis, Vehicle dynamics.

1. Introduction: The Formula Student event is a competition between schools that has built their own formula style race cars according to the Formula SAE rules. The overall goal of Formula student is to provide students with the opportunity and experience of taking part in all aspects of Engineering including; management, design, manufacturing, marketing and to increase the 'people skills' of the students by working as part of a large team. The way in which this is conducted is by enabling the students to design, develop and manufacture a single seated race car.

Student formula competition is not familiar in Bangladesh. Though it is one of the biggest automotive competition in the world for students, there is a few teams recently started participating in this type of competition from Bangladesh. A team from Rajshahi University of Engineering and Technology participated in Formula Student Japan 2017 as the first team from Bangladesh[1].

Design analysis of suspension especially for racecar is very crucial to achieve maximum performance and handling. Suspension design may vary depending on the road terrain and the vehicle purpose itself. In case of designing a suspension system for formula student competition lot of problems has been faced by the designers. There are many parameters that should be determined according to the required performance. A perfect guideline can help the designers to design the suspension system properly. Some steps should be followed to design a suspension system for a student formula car. The designers have to take some decisions based on experience in case of designing a formula student car. So a guideline can help new designers to take the decisions. In this paper a suspension designing process is described with numerical analysis.

2. Vehicle level targets: The main design requirements of the suspension design of a Formula Student race car may be like the followings:

i. The ability to keep all four wheels in contact with the ground at the correct angles in order to exploit the maximum tractive force of the tyres.
ii. Determining the suspension geometry according to packaging parameters.
iii. To ensure the expected camber change and toe change during bump; change of camber during roll and percent of anti-dive & anti-squat.
iv. Compliance with F-SAE rules.

3. SAE rules for Suspension System: For designing a suspension system firstly the suspension rules of SAE for student formula competition should be checked properly. The rules are the followings:
According to the rules of FSAE rule book 2017-2018,
Rule T6.1.1: The car must be equipped with a fully operational suspension system with shock absorbers, front and rear, with usable wheel travel of at least 50.8 mm (2 inches), 25.4 mm (1 inch) jounce and 25.4 mm (1 inch) rebound, with driver seated. The judges reserve the right to disqualify cars which do not represent a serious attempt at an operational suspension system or which demonstrate handling inappropriate for an autocross circuit [2].
Rule T6.1.2: All suspension mounting points must be visible at Technical Inspection, either by direct view or by removing any covers. [2]

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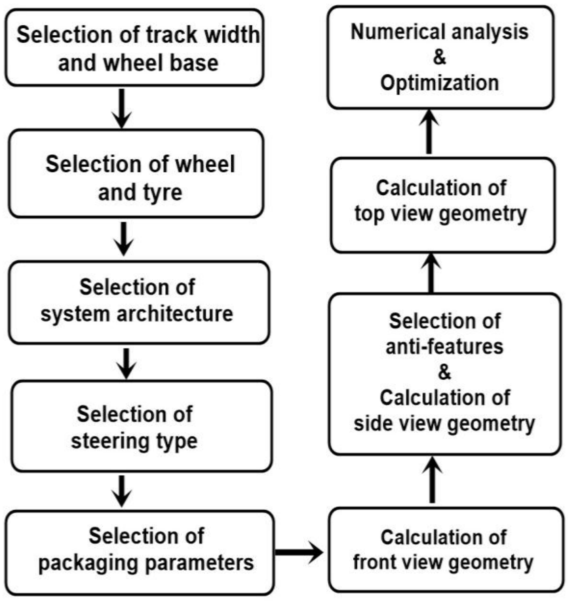
4.1 Work flow chart:



4.2 Deciding track width and wheel base: The wheel base and track width of both front and rare should be determined properly.

Wheel track B is determined by the empirical formula in following equation.

$$B = kL \quad (1)$$

Where L is the wheelbase and the k is the dimensionless unit. The optimum value of k is ranged from 0.90-0.96. But it depends on the required performance, conditions and factors[2].

4.3 Wheel and tyre selection: The FSAE rule 2017-2018 for wheel diameter for a student formula car are followings:

According to the rule **T6.3.1**, the wheels of the car must be 203.2 mm (8.0 inches) or more in diameter.

Generally two types of rim is used in student formula competition. They are 10 inch rim and 13 inch rim. The size of the rim is selected according to design perspective. Design of FSAE wheels is aimed at producing the lightest possible wheel with the lowest possible mass moment of inertia while maintaining a high level of lateral stiffness.

4.4 System architecture: For the front suspension the following need to be considered.

Type of suspension: There are generally following types of suspension for front.

1. Macpherson strut (Generally not used in FSAE car)
2. Double wishbone, damper to lower wishbone
3. Double wishbone, damper to upper wishbone
4. Double wishbone, pushrod/pull rod to damper
5. Double wishbone pushrod/pull rod to rocker arm
6. Double wishbone, anti-roll bar etc.

For the rear suspension there are many more possible suspension types, in practice.

A double wishbone, damper to upper or lower wishbone suspension system with its roll center little above the ground would give the best suspension geometry but due to their compact design and excellent rolling resistance, a push rod suspension or a pull rod suspension system is recommended for formula student car.

4.5 Type of steering: Steering system is strongly related with suspension system. The position of the track rod has impact on the combined performance with suspension system. The position of the tie rod ball joint should be perfect, otherwise bump steer will occur. The type of steering actuator should be determined. Such as 'Rack and pinion' or 'Recirculating ball' type steering. Rack and pinion is the most used steering system in formula student. Location of the steering actuator should be determined. It will be in front of or behind the wheel center.

4.6 Packaging Parameters Selection: There are some parameters which are called packaging parameters and they should be determined for designing the suspension geometry. The packaging parameters are tire size, rim diameter and width, wheel offset, kingpin inclination, mechanical trail, scrub radius, spindle length, the caster, the camber, tie rod position, rack location, track width, the upper and lower ball joint positions and tie rod outer position [Fig. 4.6.1 & 4.6.2]. Upright or knuckle geometry can be determined from these packaging parameters. In automotive suspension, a steering knuckle is that part which contains the wheel hub or spindle, and attaches to the suspension and steering components. It is variously called a steering knuckle, spindle, upright or hub as well.

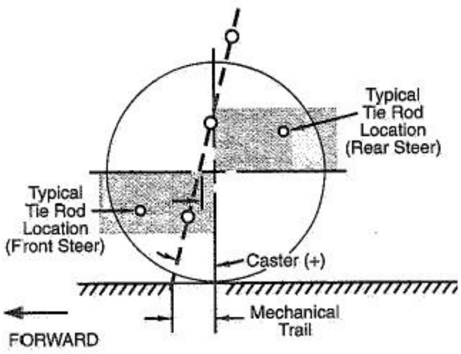


Fig.4.6.1 Packaging parameters [5]

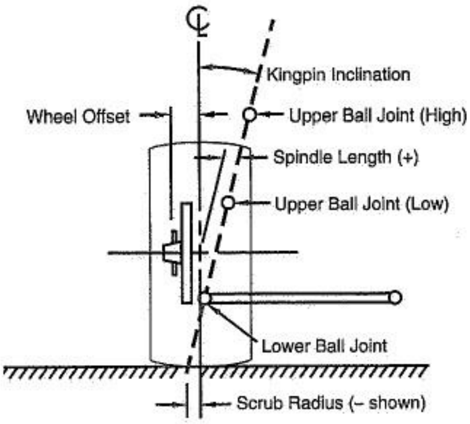


Fig.4.6.2 Packaging parameters [5]

Wheel offset: The offset of a wheel is the distance from the hub mounting surface to the center line of the wheel. The wheel offset is measured in millimeters and results in a positive, negative, or zero offset. Positive offset is when the hub mounting surface is toward the front or wheel side of the wheel. It is common to find a positive offset in newer and front wheel drive vehicles. Negative offset is when the hub mounting surface is toward the back or brake side of the wheels centerline. Zero offset is the hub mounting surface is even with the centerline of the wheel.
Kingpin inclination: In suspension systems, the kingpin is set at an angle to the vertical plane when viewed from the front or rear of the vehicle. This angle is known as the king pin inclination. The purpose of the KPI is to produce vertical displacement of the vehicle in during steering in an upward direction. The larger the KPI, the larger the effect. This lifting effect produces a self-centering torque similar to that of caster. The KPI also generates scrub radius.
Mechanical trail: Mechanical Trail (or Real Trail) refers to the length of the lever that, when combined with the contact patch, produces a self-righting effect on the steering.
Scrab radius: The scrub radius is the distance in front view between the king pin axis and the center of the contact patch of the wheel, where both would theoretically touch the road. The kingpin axis is the line between the upper and lower ball joints of the hub.
Track width: Track width is the distance between the centers of 2 tires mounted on same axle. There is front track width and rear track width in case of a 4 wheeled car.
Caster angle: The caster angle or castor angle is the angular displacement of the steering axis from the vertical axis of a steered wheel in a car measured in the longitudinal direction.
Camber: Camber angle is the angle made by the wheels of a vehicle; specifically, it is the angle between the vertical axis of the wheels used for steering and the vertical axis of the vehicle when viewed from the front or rear. It is used in the design of steering and suspension.
Roll center: The roll center of a vehicle is the notional point at which the cornering forces in the suspension are reacted to the vehicle body.

Based on the literature survey, knowledge about the cars from the Formula Student 2003 is at KTH an over view of static set up is given below.

• Kingpin inclination angle between 0° and 8°
• Scrub radius between 0mm and 10mm
• Caster angle between 3° and 7°
• Static camber adjustable from 0° to -4°
• Camber gain 0.2-0.3 degrees/roll angle at front axle
• Camber gain 0.5-0.8 degrees/roll angle at rear axle
• Maximum roll angle about 2°
• Roll center height between 0mm and 50mm in front and slightly higher at rear
• Well controlled and predictable movement of the roll axle
• Minimize bump steer
• 50% - 65% of the roll stiffness on the rear axle.[4]

4.7 Front view geometry: For designing front view geometry; roll center height, instant center position and fvsa length (Fig. 4.7.1) should be calculated. The lower wishbone length is kept larger than the upper wishbone to keep the camber rate low. Low camber rate ensure handling and stability. The roll center of a vehicle is the notional point at which the cornering forces in the suspension are reacted to the vehicle body.

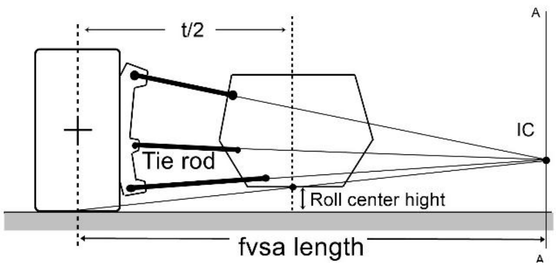


Fig.4.7.1 Front view geometry

The required parameters can be calculated from 2D drawing of the front view. The 2D design of the front view of the suspension system can be designed by the following steps:

1. Establish front view swing arm length (A-A)
2. Establish roll center location and project from ground contact point from RC to line A-A, establishing RC.
3. Project line from outer ball joint to IC.
4. Choose control arm length to get inner pivot locations.
5. Contact tie rod outer pivot to IC.
6. Establish tie rod length [5].

The fvsa length can be determined by the following equation: [5]

$$fvsa = \frac{t/2}{(1 - roll\ camber)} \quad (2)$$

Where t=track width.

$$Roll\ camber = \frac{\text{Wheel camber angle}}{\text{Chassis roll angle}} \quad (3)$$

4.8 Side view geometry: The side view geometry can be designed by the process that is described in the book 'Race Car Vehicle Dynamics' by William F. Milliken and Douglad L. Milliken [5]. The calculation can be develop through two steps.

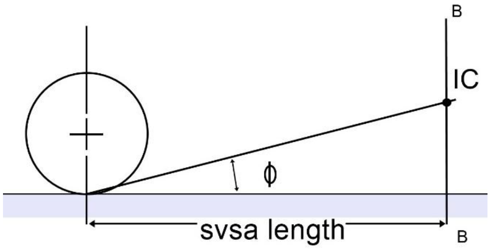


Fig.4.8.1 Side view geometry

1. Angle Φ that's establishes anti-dive. (Fig. 4.8.1)
2. Determining svsa length which gives line BB [5].

Anti-dive describes the amount the front of the vehicle Dives under breaking. As the brakes are applied, weight is transferred to the front and that forces the front to dive. Anti-squat is suspension's mechanical resistance to compression due to forces from the engine. Formula Student car is a rare wheel drive car with outboard braking. So, for a rare wheel drive car with outboard braking, the equation of determining anti-dive and anti-squat for independent suspension is following: [5]

$$\text{Anti-dive} = (\%\text{front braking}) \tan \Phi_F (l/h) \quad (4)$$

The equation for determining anti-squat in rare is following: [5]

$$Anti\ squat = \frac{\tan \Phi_R}{h/l} \quad (5)$$

Here l is wheel base and h is the height of CG.

Selecting anti-features: Before selecting the amount of anti-dive and anti-squat we should think about its effects. Mainly the side view instant center affects the wheel path. The wheel moves through a curve which has a center located on the same location with the instant center. Instant center affect the caster angle. For front suspension if the location of the IC in rearward and above or forward and below the wheel center then the wheel will move forward during bump. Otherwise if the IC is rearward and below or forward and above the wheel center then the wheel will move rearward during bump. In case of passenger car anti-dive is important. But for racing car though anti-dive and anti-squat has effect on grip, it can't change the performance much. But in case of drag racing anti-squat over 100% increase the grip of rare wheel which is called Pro-lift. So using anti-feature in drag racing car and passenger car is fruitful. To avoid complexity keeping 0% anti-dive is logical for FSAE car. Anti-dive will be 0% when the value of Φ will be zero. Here 0% anti-dive is used to design the suspension system. [5]

4.9 Top view geometry: There are two factors that are considered for designing the geometry of top view.

1. The maximum force on front wishbone occurs during maximum braking. The load on wishbone member reduces as the spread increases (fig. 4.9.1). So the wishbone should be spread as large as possible avoiding clash with rim.
2. If the chassis pivots are at some angle with the longitudinal center line of the car (fig.4.9.1), then there is a perpendicular component with the wishbone pivot axis of braking force which oppose the longitudinal weight transfer. For that reason some anti-dive is introduced [6].

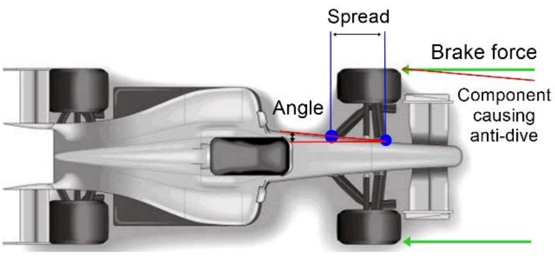


Fig. 4.9.1 Wishbones in top view

5. Data for front suspension: As we are designing and simulating a suspension system, so we have to select some parameters according to desired performance. The packaging parameters data and different vehicle data are collected from a student formula team from Rajshahi University of Engineering and Technology which participated in Formula Student Japan 2017. [1]

Table 1 Types of systems.

Systems	Types
Suspension system Architecture	Double wishbone, push rod to damper
Steering	Rack and pinion

Table 2 Packaging parameters data.

Parameters	Value
Wheel base	1570 mm
Wheel track	1200 mm
Rim diameter	10 inch
Rolling radius	177.8 mm
Kingpin inclination	7 degree
Scrab radius	9.5 mm
Caster angle	2 degree
Roll center height	25.4 mm
Static Camber	2 degree
Roll angle	5 degree
Bump	40 mm (FSAE rule T6.1.1)
Rebound/ Jounce	40 mm (FSAE rule T6.1.1)

From the packaging parameters data, the geometry for upright or knuckle is determined.

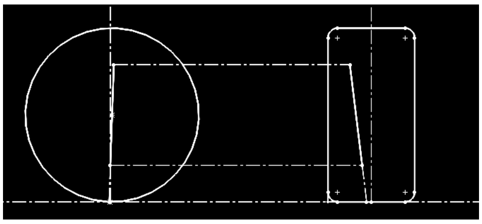


Fig. 5.1 knuckle/upright geometry

Table 3 Calculated data for fvsa of front suspension. From equation 2 and 3 and by 2D drawing of the geometry the following values are calculated.

Parameters	Value
Roll camber	0.59
Fvsa length	1670 mm
Fvsa height	71.4 mm
Roll center height	25.4 mm
Upper control arm length	293 mm
Lower Control arm length	387 mm
Tie rod length	309.5 mm

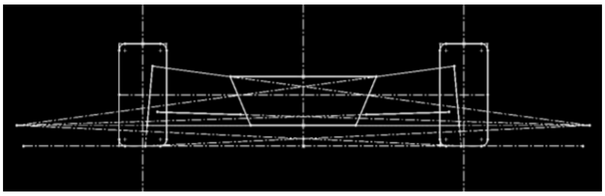


Fig. 5.2 Front view geometry 2D drawing

Table 4 Selected data for side view swing arm.

Parameters	Value
Vehicle mass	300 kg
Vehicle load on front axel	135 kg
Vehicle load on rare axel	165 kg
Percent of anti-dive	0%
Percent of front braking	60%
Height of CG	300 mm (approximately)
CG distance from front axel	900mm (approximately)
CG distance from rare axel	670 mm (approximately)
Deceleration for maximum braking	1.7 g

Table 5 Calculated data for svsa of front suspension: Formula student car is built to run on smooth and flat road. So there will be no bump in the race track. Also we need camber change during cornering. For 100% anti-dive there will be no camber change for rolling. So there is no need to keep anti-squat. In case of formula student car 0% anti-squat is perfect.

Parameters	Value
Angle Φ_R	0 degree
Svsa height	-
Svsa length	-

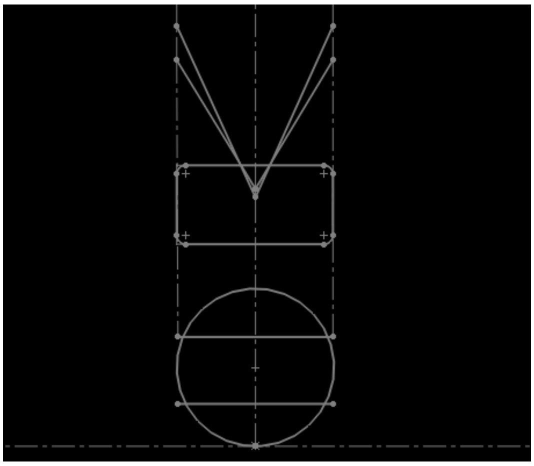


Fig. 5.3 Top and side view 2D drawing

6. Numerical analysis & optimization: From the assumed packaging parameters data and calculated data a model of suspension system is designed and simulated in 'Lotus Suspension Analysis' software. The roll angle, camber, toe and bump are plotted to analyze the performance of the system.
From the numerical analysis, the system can be optimized by changing the selected packaging parameters according to the required performance.

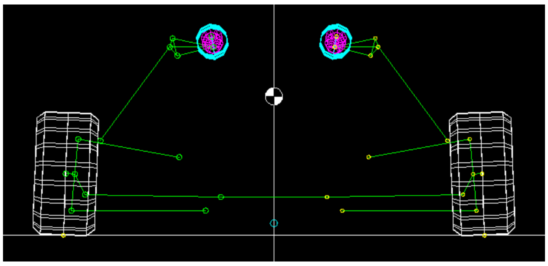


Fig. 6.1 Front view of front suspension

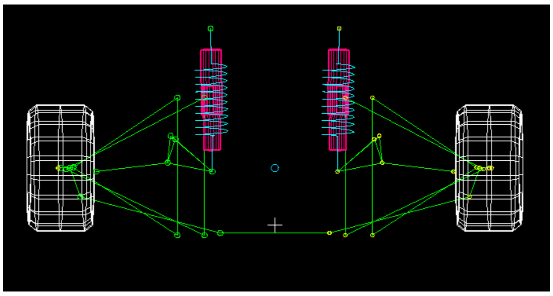


Fig. 6.2 Top view of front suspension

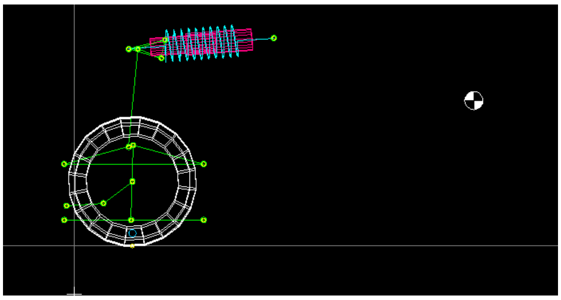


Fig. 6.3 Side view of front suspension

From roll vs camber graph (fig. 6.4) we can see that at maximum roll of 5 degree the camber is zero. So during cornering the inner tyre will be at maximum contact with the road. So the inner tyre friction will be maximum.

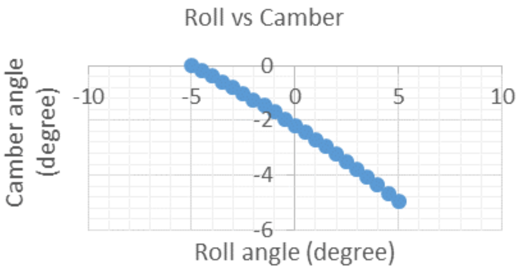


Fig. 6.4 Roll vs camber graph

From the bump vs camber graph (fig.6.5) there is some negative camber change for bump. As formula student car is an on road car, so camber change in bump will not affect the performance much.

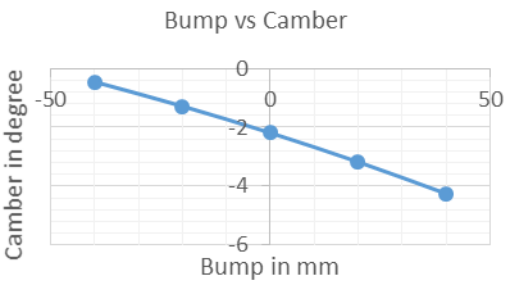


Fig. 6.5 Bump vs Camber graph

From the bump vs toe graph (fig.: 6.6) we can see that the toe angle has a little change for bump travel which will not affect much. The toe change for bump travel should be near zero.

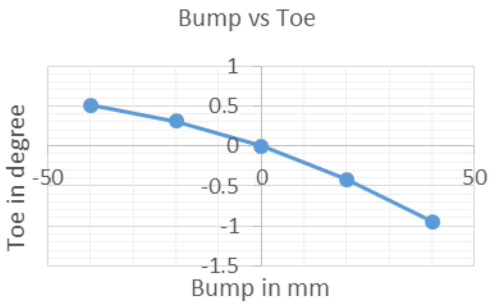


Fig. 6.6 Bump vs toe graph

Here, for the formula student car suspension system the percentage of anti-dive is proposed to keep zero. Here we can see in the bump vs % anti-dive graph (fig.:6.7) that the percentage of anti-dive is very low.

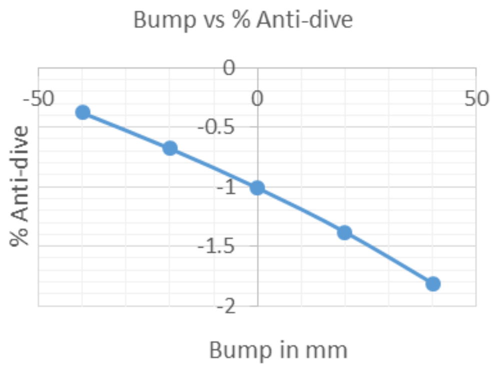


Fig. 6.7 Bump vs % anti-dive graph

7. Rear suspension: The rear suspension can be designed following the same procedure of front suspension. In case of rear suspension the anti-squat should be calculated instead of anti-dive and the track rod position should be determined instead of tie rod.

8. Discussion: For designing a suspension system of a formula student car, a process is described with the objectives to ensure the angle maximum tractive force between wheel and road; determining the suspension geometry and ensure the expected camber change and toe change during bump; camber change with rolling and percent of anti-dive & anti-squat. By numerical analysis in 'Lotus Suspension Analysis' software we showed that the all objectives are satisfied for the designed suspension system. Though there is some fluctuation from the expected result but that is not affect the expected performance. Also the system satisfy the SAE rule for formula student competition. Overall an optimize suspension system is designed for a formula student car according to required performance.

9. Conclusion: Suspension designing is depends on designer choice. A suspension should be designed according to the required performance. The suspension system for a road car and off road car won't be same. Designer should consider different suspension factors, road condition and purpose of the vehicle for designing a suspension system. By following the above process, suspension system for any kind of vehicle can be designed.

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