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Selection of tires based on Cornering stiffness for Formula Student Car

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Abstract: Tires, being the only medium between the road and any automotive vehicle, are important in driving and designing of an automotive vehicle. The paper emphasizes on the selection of tires for cornering stability of the vehicle. Though the term Tires are of great importance in FSAE competitions. Being a viscoelastic material tire performance is very hard to judge but some relationship can be thought, which is of great use to the designer. As the FSAE car aims to be quick and fast, the behavior of tire while turning becomes the main cause of study of such characteristics. The work assumes Cornering stiffness as the main idea for the selection of tires of similar category and also the design of steering system.
Keywords: Ackerman, Cornering stiffness, Formula student, Lateral force, R10, R13, Slip angle

I. INTRODUCTION

Tire mechanics is always surprising. It is engineering by itself and is very interesting. A lot of considerations we take while designing the FSAE car are of rigid body mechanics or Newtonian mechanics which describes the motion of macroscopic objects associated with physical laws. So while in vehicle design one must consider the tire mechanics along with rigid body mechanics. Viscoelasticity is defined as the property of material that exhibits both viscous and elastic characteristics while undergoing deformation [13]. This property of any formula tire is used while racing. The commercial tires are mainly made up of about 47% elastomers and 16.5 % metal, while most of the racing tires have more percentage of rubber in it which provides the elastic behavior. Having such differences the racing car looks upon selection of tire and its properties in a different manner. In India normally teams use three types of tires: wet tires, semi-slicks and slicks. Slick tires have the highest contact patch and viscous coefficient amongst all.

II. OUTLINE OF WORK

Generally teams use Hoosier Racing Tires as first preference. Presented graphs and results are of 10 inch and 13 inch Hoosier tires. Tire selection process requires a basic knowledge of slip angles, load transfer and cornering stiffness, which is explained ahead. Paper also discusses analytically, the comparison between performance of R13 and R10 individually. The methodology proposed here is based on the observations taken from the experience in a Formula Student Car of Veloce Racing Vishwakarma Institute of Technology Pune, and all the graphs represented are generated from actual tire data provided by "Formula SAE Tire Test Consortium (FSAE TTC)".

III. SLIP ANGLE AND LATERAL FORCE

As the tire rolls on road it experiences normal force (FZ), longitudinal force (FX) and lateral force (FY) simultaneously. Because of these forces the direction of travelling and direction of heading of the tire differs. This angle between the direction of travel and direction of heading is called slip angle [2]. It is important to consider the relationship between lateral forces and slip angles of tires, for a designer to predict the vehicle's behavior. Slip angles are nothing but tire deformations.

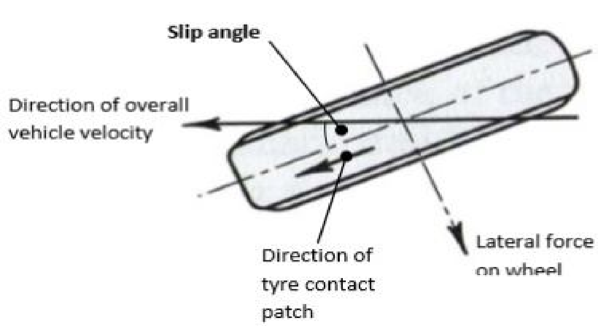

Fig.1: Slip angle[1]

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When the car is negotiating a turn, it has centrifugal force acting radially outwards. This force is balanced by lateral force of friction acting radially inwards. If car has to turn with higher velocity, the tires should generate more lateral force (FY). The cornering force can be considered as capacity of the tire to resist sliding in sideways while cornering. Whereas in some cases, both will increase by decreasing the vehicle's turning radius or increasing the linear speed.

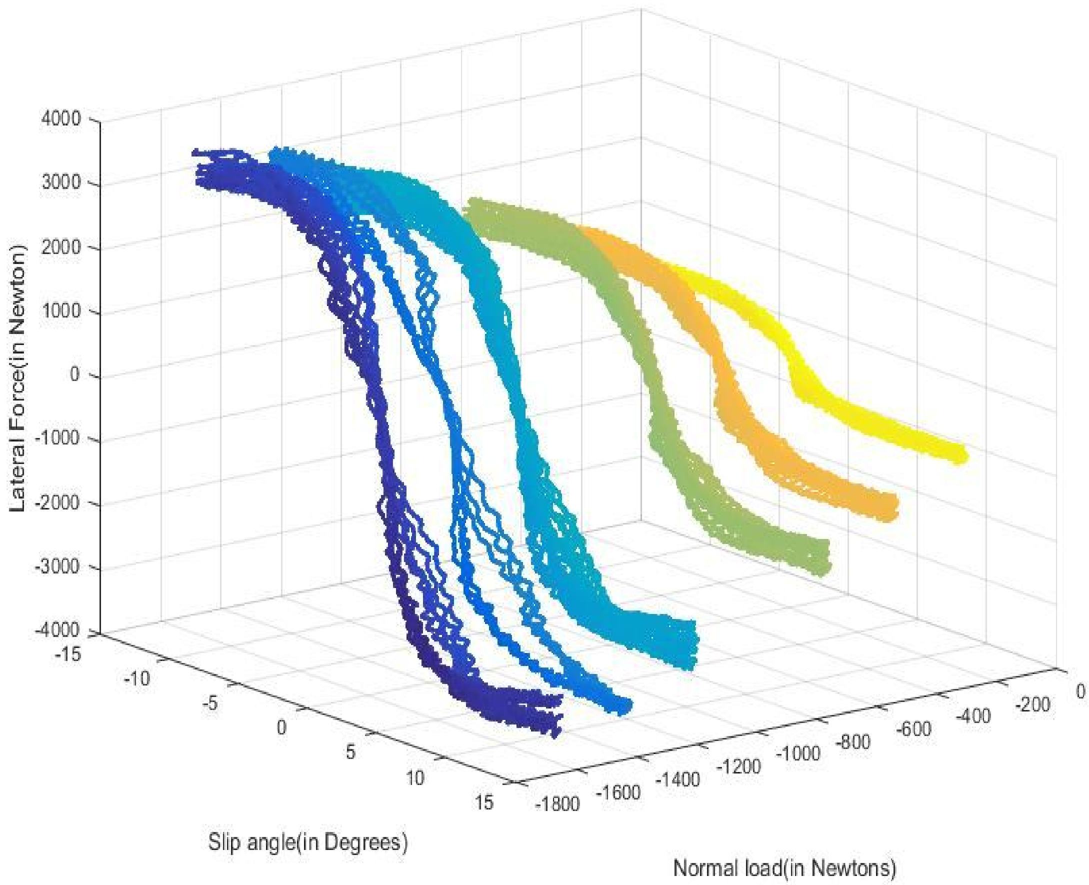

Fig.2: MATLAB plot of Lateral force versus Slip angle for different Normal load (R13)

From Fig.2, We can see that, for more lateral force tires produce more slip angle. The lateral force and slip angle both are interdependent, and can never be expressed independently. For a specified normal load, we can see from Fig.2 that the lateral force is increasing till a limiting value of slip angle and decreasing suddenly with higher slip angle. In case of racing tires this abrupt transition from grip to skid occurs in very small slip angles which can be experienced through steering system [4]. While cornering at higher slip angles, tires have significant resistance to forward motion which grows with slip angle due to increase in rolling resistance and tire temperature [6]. So at this time we have to give power to vehicle increasing its speed in turn. So one can have lesser lap time, increasing the car performance. Considering steering performance, for Ackerman geometry, low slip angles are involved due to low speeds. For Anti-Ackerman geometry higher slip angles (less than 6deg) are involved, significantly on outer tires which have more normal load due to higher speeds. So while cornering the vehicle, we know the outer tire will generate more slip angle, we have to steer the outer tire tighter than the inner one having low slip angles in order to compensate the lateral forces. But the Ackerman geometry provides the greater steer angle for inside wheel than the outer which is disadvantageous at high speeds which will result in low lateral force and sideways sliding of the vehicle. Thus Anti-Ackerman is recommended at higher speeds, creating a greater steer angle on the outer wheel than inner.

IV. COMPARISION BETWEEN R10 AND R13 HOOSIER TIRES

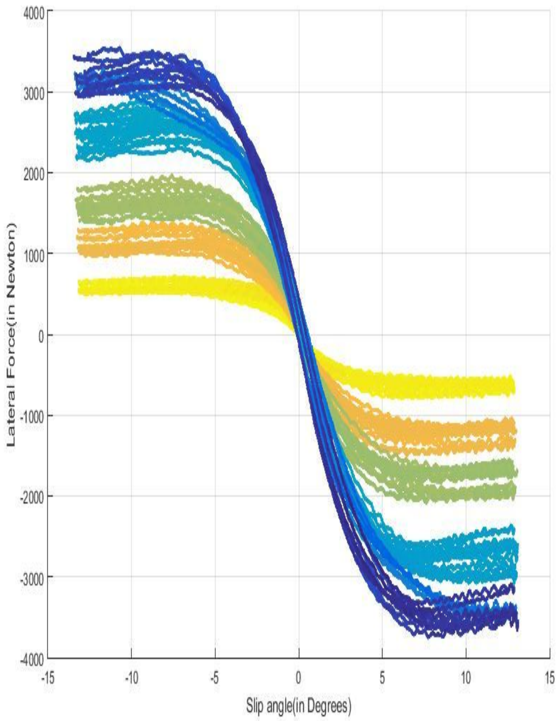

Fig.3: Lateral force versus Slip angle for R13

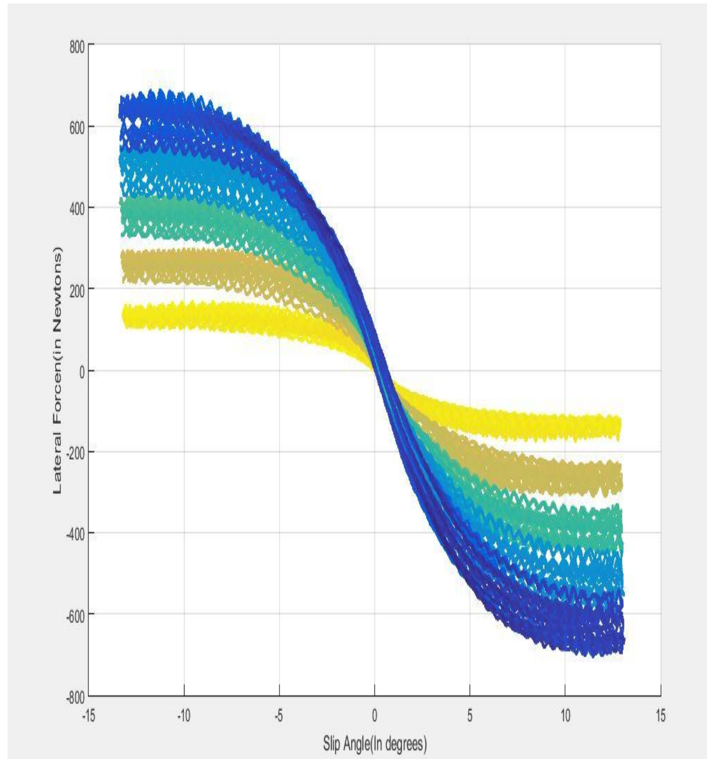

Fig.4: Lateral force versus Slip angle for R

The next step towards design is to find out the cornering coefficient for both, the R10 and R13 tires for comparison. The above graphs are plotted from the tire data of Round-5 in TTC discussion. The data available can be analyzed with the help of MATLAB and Excel. As the vehicle tires work at specific normal load range at particular time, we need to find out the cornering coefficient at a particular normal load. The data is sorted in excel for various normal load ranges and the graphs are plotted for that normal load separately for both tires. We can choose the value of normal load as per our vehicle's parameters. Normally, Formula student cars weigh around 2500N to 3000N. Weight on each tire for R13 and R10 in dynamic conditions can be easily calculated considering weight transfer as,

$$\text{Weight of vehicle=320kg=705lb}$$

$$\text{Static weight distribution} = 40:60 \;(\text{Front : Rear})$$

$$\text{Weight on front axle(Static)} = 320\times 0.4 = 128\text{kg} = 282.19\text{lb}$$

$$\text{Weight on each tire(static)} = \frac{282.19}{2} = 141lb$$

$$\text{Longitudinal weight transfer} = \frac{\text{Acceleration(g)}\times\text{Weight of vehicle(lb)}\times\text{Height of CG(mm)}}{\text{Wheelbase(mm)}} = \frac{1\times 705\times 320}{1550} = 145.54lb \quad [4]$$

$$\text{Weight on front axel in dynamic at 1g} = 282.19\text{-}145.54 = 136.64\text{lb}$$

$$\text{Lateral weight transfer on front axle} = \frac{\text{Lateral acceleration(g)}\times\text{Weight on front axle(lb)}\times\text{Height of CG(mm)}}{\text{Trackwidth(mm)}} = \frac{1\times 136.64\times 320}{1180} = 37.05lb \; [4]$$

$$\text{Weight on front tire each during linear acceleration} = \frac{136.64}{2} = 68.32lb$$

$$\text{Weight on outer tire in lateral acceleration} = 68.32\text{+}37.05 = 105.37\text{lb} = 47.79\text{kg} = 468.82\text{N}$$

$$\text{Weight on inner tire in lateral acceleration} = 68.32\text{-}35.07 = 31.27\text{lb} = 14.18\text{kg} = 139.1\text{N}$$

Similarly, for vehicle with R10 tires

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$$\text{Weight of vehicle} = 270\text{kg} = 595.25\text{lb}$$

$$\text{Static weight distribution} = 40:60 \ (\text{Front} : \text{Rear})$$

$$\text{Weight on front axle(Static)} = 595.25 \times 0.4 = 238.1\text{lb}$$

$$\text{Weight on each tire(static)} = \frac{238.1}{2} = 119.05lb$$

$$\text{Longitudinal weight transfer} = \frac{\text{Acceleration(g)} \times \text{Weight of vehicle(lb)} \times \text{Height of CG(mm)}}{\text{Wheelbase(mm)}} = \frac{1 \times 595.25 \times 250}{1550} = 96lb \text{ [4]}$$

$$\text{Weight on front axel in dynamic at 1g} = 238.1\text{-}96 = 142.1\text{lb}$$

$$\text{Lateral weight transfer on front axle} = \frac{\text{Lateral acceleration(g)} \times \text{Weight on front axle(lb)} \times \text{Height of CG(mm)}}{\text{Trackwidth(mm)}} = \frac{1 \times 142.1 \times 250}{1180} = 30.1lb \text{ [4]}$$

$$\text{Weight on front tire each during linear acceleration} = \frac{142.1}{2} = 71.05lb$$

$$\text{Weight on outer tire in lateral acceleration} = 71.05+30.1 = 101.15\text{lb} = 45.88\text{kg} = 450\text{N}$$

$$\text{Weight on inner tire in lateral acceleration} = 71.05\text{-}30.1 = 40.95\text{lb} = 18.57\text{kg} = 182.17\text{N}$$

As the outer tire has more weight it will dominate while turning. Cornering stiffness at this normal load is important point to calculate. The calculated cornering stiffness can be used to predict the behavior of vehicle in any dynamic simulation software.

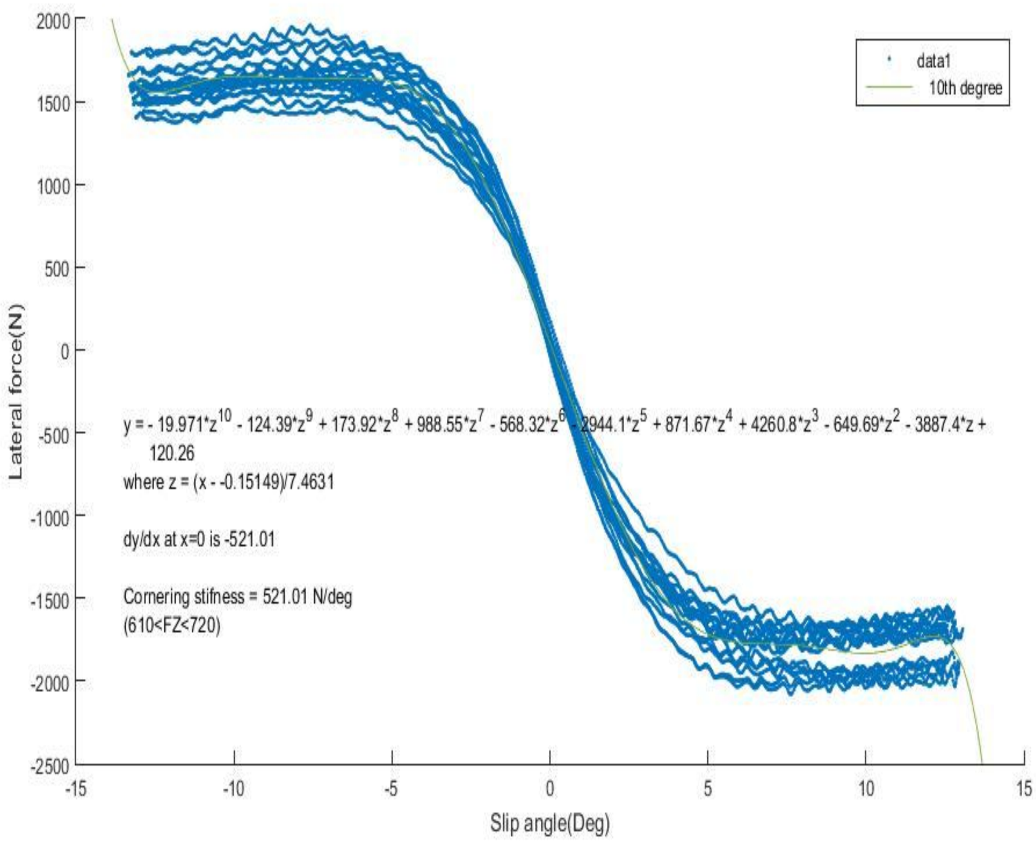

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Fig.5: Basic curve fitting in MATLAB for Normal load 610N < FZ < 720

V. CORNERING STIFFNESS

While turning at high speeds, the tire must develop cornering force to negotiate the turn without sliding. This cornering force is a cause of centrifugal acceleration and lateral friction generated between the tires and road. It is also dependent upon the material of tire, normal load acting on that tire and wheel alignment (i.e. camber, caster of that wheel.). At significant lateral acceleration the tire experiences lateral slip as it rolls. At certain tire load, the cornering force increases with slip angle till certain value and achieve the maximum limit which can be easily seen from Fig.3 and Fig.4. At low slip angles (less than 6deg) this relationship is assumed to be linear from the graph of tire data, hence cornering force can be defined as

$F_y = C_\alpha \times \alpha$ [2]

Where F_y = Cornering force

C_α =Cornering coefficient

α =Slip angle

We can find the cornering stiffness by taking the slope of plot between lateral force verses slip angle in elastic range of tire behavior. The peak limit of lateral force a tire can produce is called limit of adhesion. If we run the wheels up to this limit, specifically the outer ones, we can have maximum lateral force with considerably lesser slip angles, which will turn the vehicle with higher speeds while cornering, increasing the performance of the car. For Ackerman geometry the tires operate with low slip angles thus low lateral force acting, which decreases the performance of the car while turning. So as far as slip angles and lateral forces are considered, Anti-Ackerman geometry gives better performance achieving more slip angles on outside tires, if the tires have high cornering stiffness. Tire data is sorted in Excel and plotted in MATLAB for each set of normal load available. So cornering stiffness for specified normal load is calculated by fitting 10th degree polynomial and slope at zero slip angle is calculated from the equation given by basic curve fitting. The behavior of cornering stiffness can be studied. Cornering stiffness at given normal load of both the tires are tabulated as below in Table 1 and Table 2.

Table 1: Cornering force and Average normal force (R10)

Range of FZ(N)	Average FZ(N)	Cornering stiffness (N/deg)
40-60	50	41.27
90-110	100	70.4
130-160	150	95.78
180-220	200	113.32
220-270	250	130

Table 2: Cornering force and Average normal force (R13)

Range of FZ(N)	Average FZ(N)	Cornering stiffness (N/deg)
200-300	210.88	213.33
400-500	437.72	374.44
610-720	660.48	521.01
1000-1195	1102.56	757.41
1240-1460	1242.92	778.91
1460-1600	1552	904.58

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We can see from the tables how the cornering coefficient varies with normal loads. It increases with increase in normal load for both the tires. Also this increasing behavior is not linear. From the data we can get the values of cornering stiffness, but for the comparison we need the cornering stiffness at same condition of normal load. As the data is not accessible for all the normal loads, which is the actual requirement by the designer so that he can predict the tire behavior at any instance. So the cornering stiffness for tires can be extrapolated and then interpolated with spline interpolation in MATLAB as they are not linear. The cornering stiffness versus Average normal load is plotted in MATLAB and the cornering stiffness in dynamic working conditions is interpolated using MATLAB. The cornering stiffness in dynamic normal load of 450N can be calculated from the basic curve fitting equation obtained from the MATLAB solver

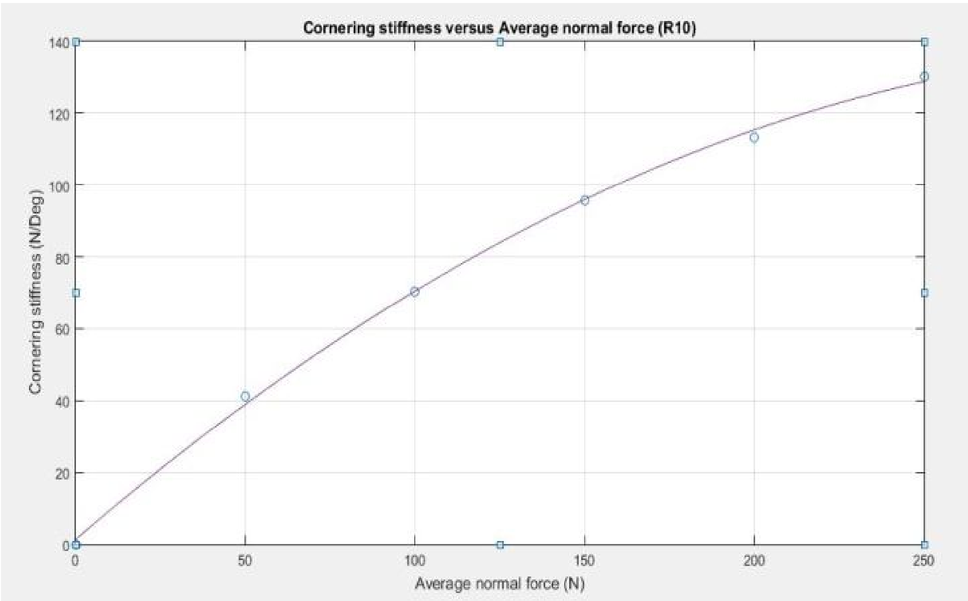

Fig 6: Plot of cornering stiffness versus average normal force (R10)

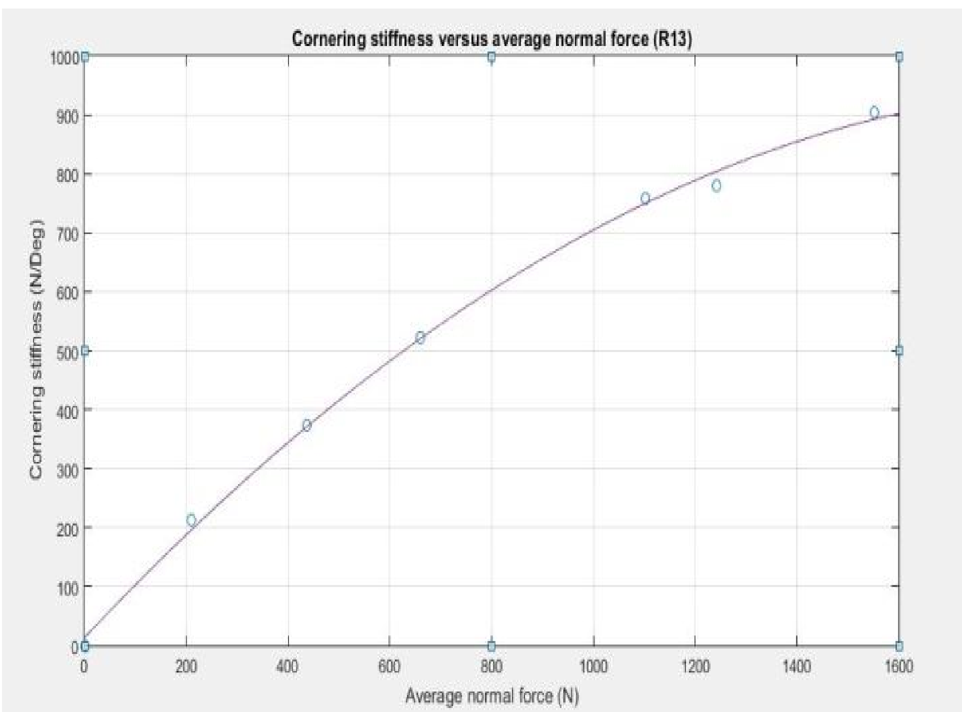

Fig 7: Plot of cornering stiffness versus average normal force (R13)

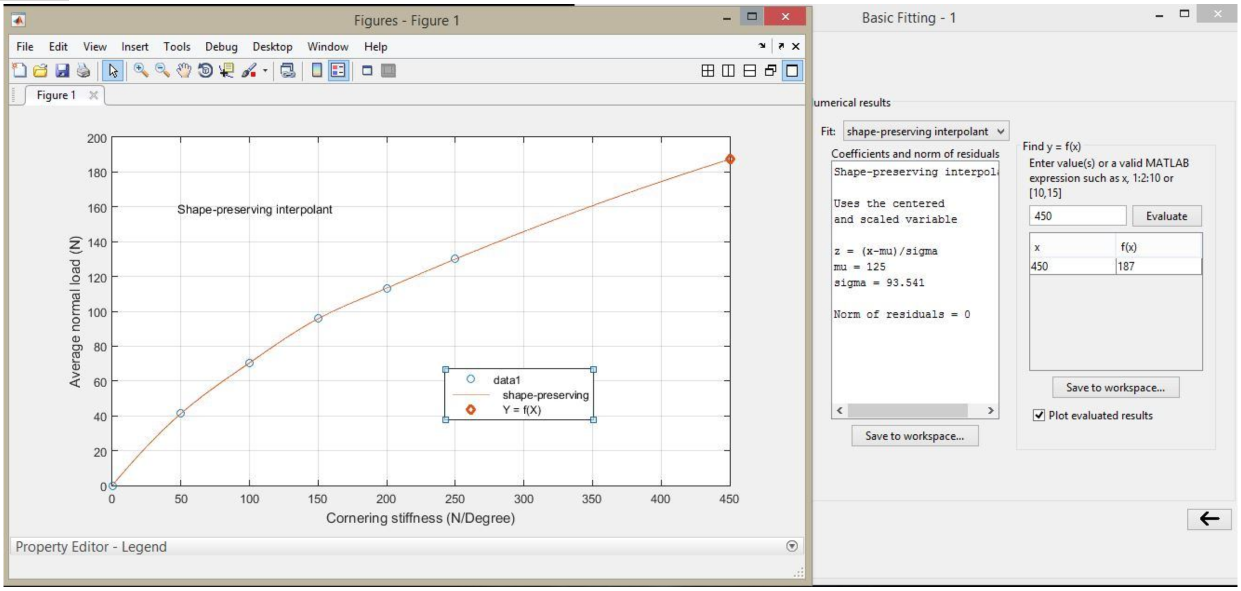

Fig.8: Shape preserving interpolation of cornering coefficient (R10)

So the value in dynamic normal load of the tire for R10 is 187N/deg whereas for R13 it is 395 N/deg. So the cornering stiffness of R10 tires is less than that of R13 tires at working normal load. The general formula for calculating the slip angle at Front and rear tires is,

$$\alpha_r = \frac{F_r}{C_{\alpha r}} = \frac{W_r}{C_{\alpha r}}\left(\frac{V^2}{g \times R}\right) \quad [2]$$

$$\alpha_f = \frac{F_f}{C_{\alpha f}} = \frac{W_f}{C_{\alpha f}}\left(\frac{V^2}{g \times R}\right) \quad [2]$$

For the same weight of car, velocity and radius of turn, the tire with greater cornering stiffness will have lesser slip angle. As the cornering stiffness is high tire could generate more lateral force at lower slip which in turn can help the vehicle to achieve greater velocity. R10 tires having cornering stiffness lower than R13, they could generate lesser lateral force even at higher slip angles which is undesirable in the cornering events of Formula SAE. So in this situation the vehicle with R10 slicks easily loses traction compared to R13 Slick tires. So the use of R13 tires at steering axle would be advantageous while cornering, which helps to increase the cornering performance of the vehicle. One more factor can be considered in selection of tires, which is the overall weight and weight distribution factor. Lower the weight higher will be acceleration of the car with some loss of normal force and cornering force.

VI. CONCLUSION

For winning of a racing competition the corners are the most challenging areas where the car can show the performance. Racing cars aim on higher velocities at corners with lower slip angles. Higher cornering stiffness is always preferred as it will lead to larger lateral forces while cornering. As R13 tire has more cornering stiffness (395N/deg) than R10 tire (187N/deg), so the vehicle with R13 tires will give lesser lap time keeping rest of the factors constant for the same vehicle. But as observed, with R13 tire the overall weight of the vehicle is greater than that of R10 tire, also the height of centre of gravity is slightly shifted away from the ground. It is up to the designer to make the choice between the tires, according to their working conditions and priorities.

VII. ACKNOWLEDGMENT

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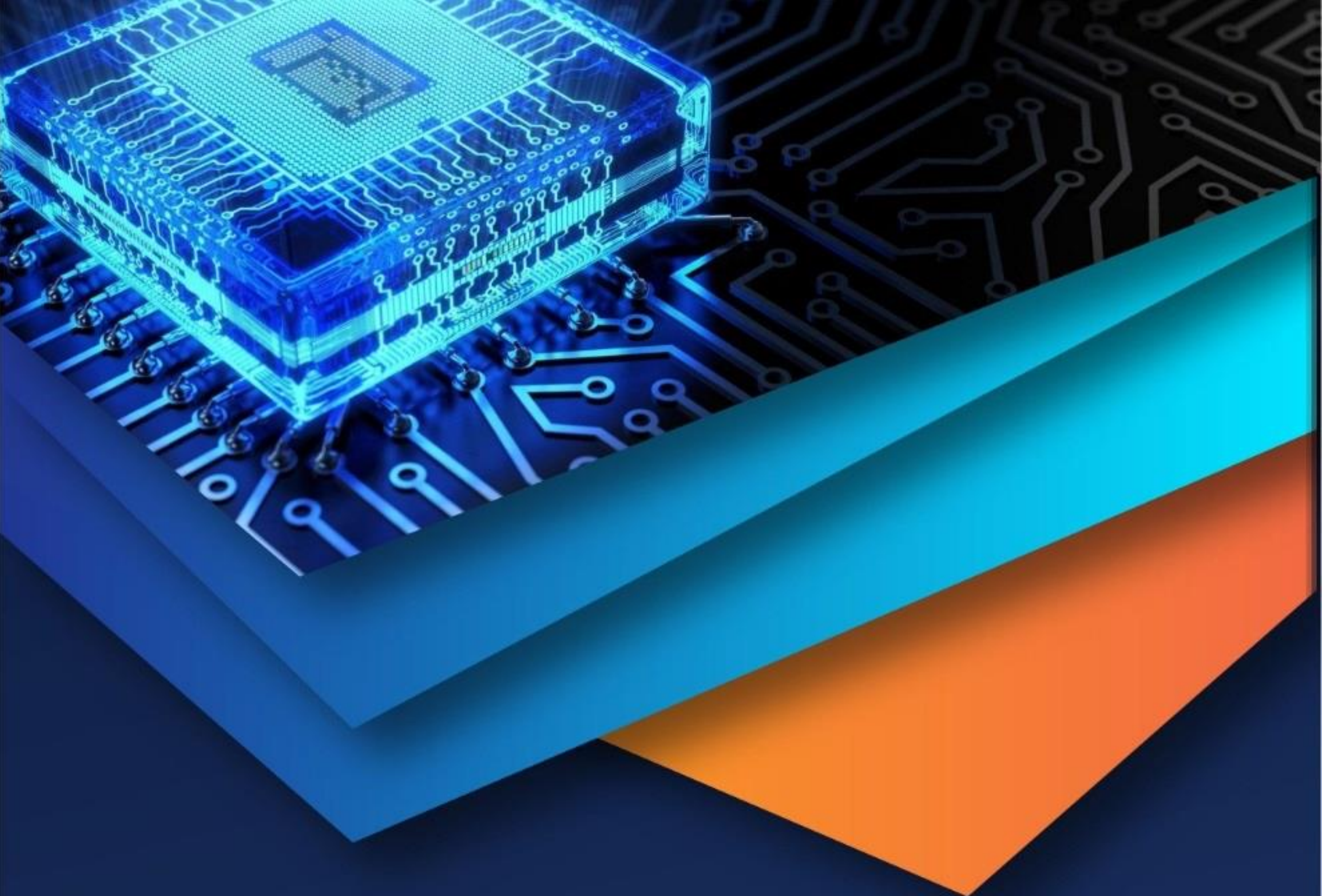

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