Tire Data Analysis to obtain Maximum Steady-State Lateral Performance of a Formula Student Vehicle

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Abstract

This paper describes an analytical study carried out to determine various parameters affecting a tire's lateral performance such as camber angle, toe angle, vertical normal load on the tire and tire pressure. A method to consider all of the mentioned parameters and find the optimum value of each parameter which makes vehicle fastest and neutral steer in nature is followed. This method may be called a beginner's method as, it does not involve any tire model. Being a simple method there are various factors which can be further involved in the process to increase accuracy. Such a discussion of further improvements possible is discussed towards the end. A constant radius turn is considered to simulate a steady-state condition, that occurs in the Skidpad Event. Primarily, these inputs may be useful to decide the suspension and steering geometries of the vehicle. Since the vertical normal load is a parameter in consideration the obtained result may also be useful for designing the aerodynamic nature of the vehicle.

Keywords— *Tire Data Analysis, Steady-State Vehicle Dynamics, Steady-State Cornering*

I. Introduction

The research performed in this paper is carried out during the design of a Formula Student vehicle of Stallion Motorsport a Formula Student Team. Formula Student is a engineering design competition held internationally among countries of the world at a student level. The vehicle is a open wheeled, SI engine driven race car, the specifications of which can be seen in Table I. The car was designed keeping in mind the Steady-State event i.e. Skidpad essentially a "figure 8 shaped" track having a layout as illustrated in Fig. 1.

As a result of the layout, a car running on the track undergoes pure cornering forces, hence qualifying as a Steady-State event considering the driver inputs remain constant too. For all further calculations in this paper the car is assumed to execute a right turn within the right circle of the Skidpad track shown in Fig. 1.The tires used are 16.0 x 6.0 -10 Hoosier Slicks designed specifically for track use only, having a rubber compound namely R25B. The tiredata utilized in this paper is provided by CalspanFSAE TTC.

Technical Specifications	
Weight with 65 kg Driver (kg)	294
Weight Distribution (F:R)	40 : 60
Wheelbase (mm)	1545
Trackwidth (mm)	1200
Tires	16*6*10
Tire Compound	R25B
Power Unit	Triumph Daytona 675R

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Table I

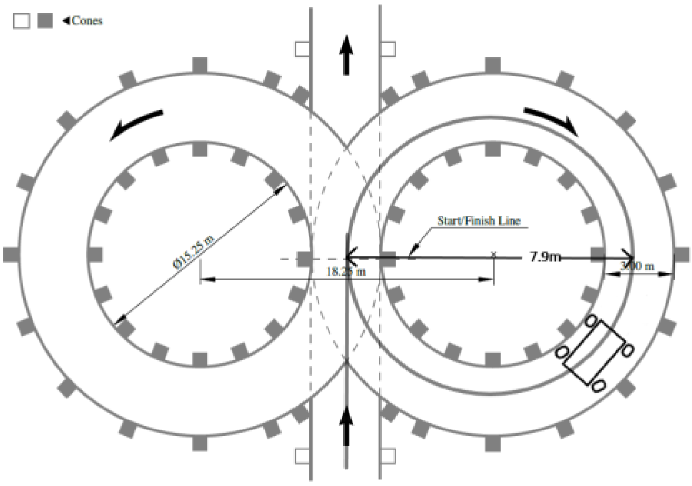

Fig. 1 Skidpad Track Layout

II. **Experimental Data**

Before starting work on the data, the target result that should be obtained at the end of all the analysis is defined. The result, includes values of Tire Pressure, Dynamic Camber, Roll Stiffness Distribution (Front:Rear), Aerodynamic CoP Location, Steering Angles, Maximum Lateral Force and the moment about CoG. The data available from CalspanFSAE TTC needs to be processed further, so that it can be readily available for performing multiple iterations. Originally, it consists of 21 channels or parameters out of which we will only be using Slip Angle, Inclination Angle, Tire Pressure, Longitudinal Force, Lateral Force, Normal Load, and the Self Aligning Moment.

A. *Importing the Data*

The data available is in .dat file format. It is already organized into 21 different columns that just need to be imported into a suitable application for viewing for e.g.MS Excel. However, for this method there are many columns of data that we will not be needing, hence the data needs to be processed and brought into a usable format. This processing includes, removing repeated or warm-up runs, storing the actual data to be used in variables in the form of arrays, identifying individual runs and segregating them, and interpolating the data so that it can be measured at any point of interest.

B. *Interpolating the Data*

The data measured is at 5 specific normal loads that are, 222.4 N, 444.8 N, 667.2 N, 889.6 N and 1112.06 N. Therefore if there is a normal load of 500 N on the wheel there is no data in existence to correlate with. This generates a need to interpolate the data across all the normal loads. After interpolating the data one must be able to take the value of any parameter of interest from the tire data corresponding to any normal load and any other parameter if involved.For instance as seen in Fig. 2. a graph of Lateral Force vs. Slip Angle at 444.8 N, this shows the nature of variation of lateral force over a specific range of slip angles. Unfortunately in the non – interpolated form, the data will only show such plots at the values of standard applied loads. After interpolating the data, we can create such plots at infinite values of normal load, as shown in the Fig. 3. Ultimately, the values for Longitudinal Force, Lateral Force and Self Aligning Moment are available at any particular combination of Normal Load and Slip Angle.

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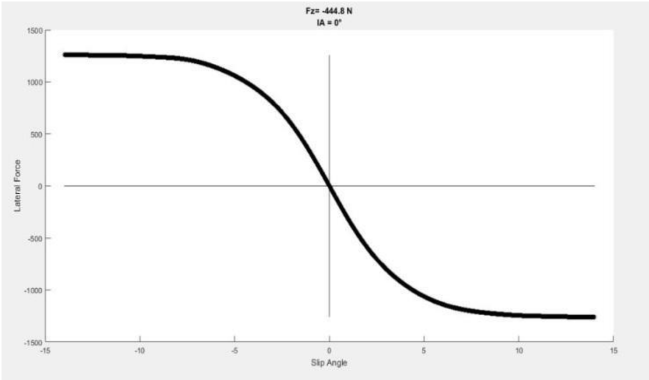

Fig. 2 Lateral Force vs. Slip Angle

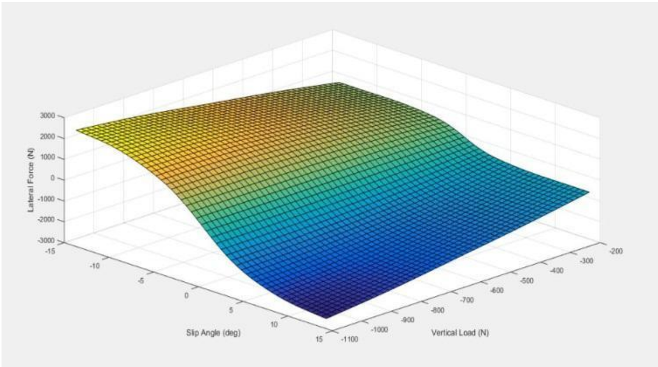

Fig. 3 Surface Plot

C. Calculating Lateral Load Transfer

The Normal Loads must be calculated under a condition such that the vehicle is undergoing the maximum possible lateral acceleration i.e. its peak lateral g. Since we have no idea of what this peak value is, we simply follow an iterative process to converge onto a single value for a particular vehicle setup(i.e. values of roll stiffness distribution, aerodynamic balance, weight distribution, etc).

D. Determining the Peak Performance i.e. Peak Slip Angles

Therefore, to use the tire data, we now need two parameters that is the Normal Load and the Slip Angle. Since we want to find the upper limit of the performance of the vehicle, we must consider calculating for the peak lateral acceleration possible. This peak lateral acceleration will be achieved when all four tires are applying their peak lateral forces onto the vehicle, provided they do not lose traction. To detect, such a loss of traction we use phenomenon due to which the Self Aligning Moment of the tire suddenly drops. A plot of Self Aligning Moment vs. Slip Angle as shown in Fig. 4 depicts the variation of the moment. But, when such drop in the Self Aligning Moment of the tire is observed, the vehicle is too close to losing traction, or has lost traction in most cases. To avoid this we take a value of Self Aligning Moment when it has stopped increasing, i.e. its peak value. The value of Slip Angle when the Self Aligning Moment is at its peak is considered.

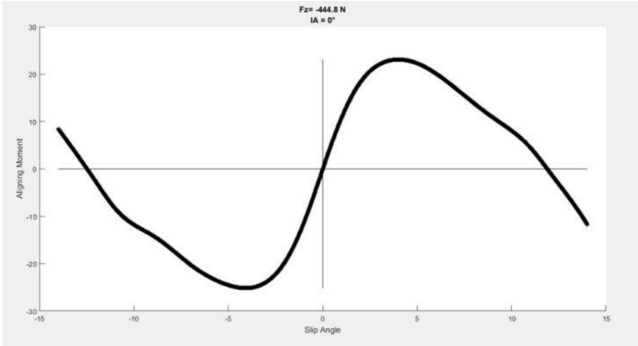

Fig. 4 Self Aligning Moment vs. Slip Angle

E. Determining Nature of Handing

To get a good estimate of the understeer or oversteer nature of the vehicle, the moment about the CoG of the vehicle is calculated. This moment is a resultant of the Longitudinal Force, Lateral Force and the Self Aligning Moment of each tire.To account the moment about the COG due to the Longitudinal Force(M_1),expression(1)is used:

$$M_1 = F_{xFR}\left(\frac{T cos(\delta_R)}{2} - a(sin\ sin\ (\delta_R)\ )\right) + F_{xRR}\cdot\frac{T}{2}$$

$$-F_{xFL}\left(\frac{T}{2\ cos\ cos\ (\delta_L)} + sin\ sin\ (\delta_L)\ \left(a - \frac{T tan(\delta_L)}{2}\right)\right) - F_{xRL}\cdot\frac{T}{2} \quad \ldots(1)$$

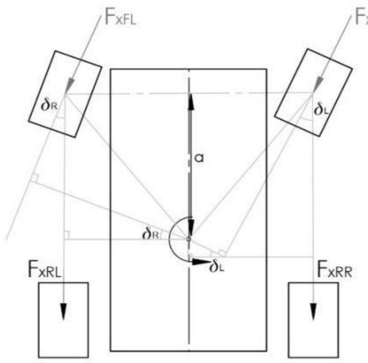

Fig. 5 Yaw Moment due to Longitudinal Forces

In top view the moment acting clockwise i.e. causing oversteer has a positive sign convention as opposed to the moment acting in anti-clockwise direction and causing understeer, which has a negative sign convention.Further considering the Lateral Force, the moment exerted by the Lateral Force about the CoG is taken by simply multiplying the magnitude of Lateral Force with the normal distance from the CoG. As all the four wheels of the vehicle tend to form a rectangle, the Lateral Force acting on both the front wheels apply a moment about the CoG that makes the vehicle oversteer, and the rear wheels, cause understeer as shown in Fig. 6.

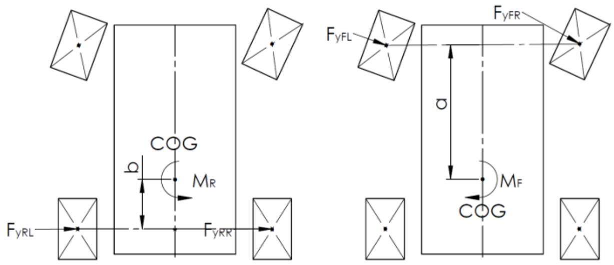

Fig. 6 Yaw Moment due to Lateral Forces

Therefore, the moment acting about the CoG due to Lateral Forces(M_2) is given by the expression(2).

$$M_2 = \left(F_{yFR}.cos\, cos\,(\delta_R)\ + F_{yFL}.cos(\delta_L)\right).a$$
$$+\left(F_{yFL}.sin(\delta_L) - F_{yFR}.sin\, sin\,(\delta_R)\ \right).\frac{T}{2}$$
$$-\left(F_{yRR} + F_{yRL}\right).b \quad ...(2)$$

Lastly, the Self Aligning Moment also exerts a moment about the CoG. To convert this moment about each tire to moment about CoG, we simply resolve the forces acting on the toe linkages or tie rods about the CoG. Expression(3) gives us the moment about CoG due to Self Aligning Moment(M_3).

$$M_3 = (F_{TRL} + F_{TRR})h_{TR} - (F_{TCL} + F_{TCR}).h_{TC} \quad ...(3)$$

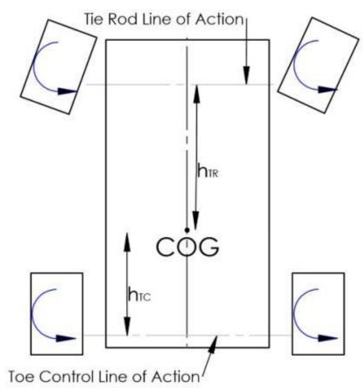

Fig. 7 Yaw Moment due to Self Aligning moment

The total moment acting about the CoG denoted by M is the sum of all the 3 moments calculated above i.e. M_1, M_2 and M_3.

The total number of calculations needed to perform increased to above 1400. Thus this procedure was converted to a code in Mathworks MATLAB, to reduce calculation time required and human error. The form of output of this code was the numerical results in a tabular form. The output numerical values were of parameters needed for further suspension and steering design such as, Iteration Number, Estimated Lateral G,AerodynamicDownforce, Downforce Distribution, Roll Stiffness Distribution, Normal Load on each Wheel, Lateral Force on each Wheel, Self Aligning Moment on each Wheel, Longitudinal Force on each Wheel, Slip Angles of each Wheel, Steering Angle Required of each Wheel,

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Moment about COG and the Calculated Lateral G. This tabulated data is imported into MS Excel to perform statistical analysis, and find the peak values of parameters desired.

III. RESULT

After analysing the MS Excel spreadheets, the minimum value of moment about CoG was found out. Simultaneously, the fastest configuration i.e. the iteration with maximum Lateral G was found out. Had there been a condition, where one would have to chose between, the peak Lateral G and the least moment about CoG, then in such a case, the iteration with least moment about CoG would be prioritised over the iteration with peak Lateral G. This would ensure the selection of a configuration of the vehicle that is easy to handle at high speed cornering. Out of all the iterations the iterations mentioned in Table II, were shortlisted to undergo the above mentioned selection criteria of the final vehicle configuration.

Table II

Sr. No.	**Tyre Pressure (psi)**	**Camber (deg)**	**Moment about CoG (mn)**	**Lateral G**
1	8	0	-85.2944	1.7121
2	8	0	239.488	1.7192
3	8	2	290.5182	1.6403
4	8	2	-177.664	1.6342
5	10	0	-8.04175	1.9316
6	10	2	-17.5659	1.815
7	10	2	-49.8728	1.8182
8	12	0	12.1994	1.9153
9	12	0	17.6888	1.94
10	12	2	5.0923	1.9119
11	12	2	48.5499	1.9395
12	14	0	12.8413	1.8269
13	14	0	65.1862	1.8527
14	14	2	-115.838	1.7672
15	14	2	-12.2868	1.7624

Out of all the above iterations the iteration no. 5 was selected and is highlighted in green colour. Some of the key parameters

IV. CONCLUSION

The purpose of this paper being to provide a way to utilize tire data in the design of a vehicle’s very basic but key parameters, is justified as seen in the result above. The vehicle further designed with this event proved to follow the design trends and won the Skidpad event in Formula Bharat 2020. The approach described is very basic and has a lot of room for further improvements. The no. of parameters considered can be increased as per any individual’s wish. Increasing the number of parameters considered not only increases the complexity of the method by increasing the number of calculations required but also increases the number of interdependencies of parameters, thereby increasing the time required to build a error free logic or method to use all the parameters. Even though the complexity is higher with increased number of parameters it is preferred as it increases the accuracy of the calculations tremendously.

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Abbreviations

SI	Spark Ignition
FSAE	Formula Society of Automative Engineers
TTC	Tire Test Consortium
CoP	Center of Presssure
CoG	Center of Gravity

Nomenclature

R	Right Wheel Steering Angle
F	Left Wheel Steering Angle
T	Trackwidth
a	Distance of CoG from Front Axle
b	Distance of CoG from Rear Axle
F_{xFR}	Longitudinal Tire Force Front Right
F_{xFL}	Longitudinal Tire Force Front Left
F_{xRR}	Longitudinal Tire Force Rear Right
F_{xRL}	Longitudinal Tire Force Rear Left
F_{yFR}	Lateral Tire Force Front Right
F_{yFL}	Lateral Tire Force Front Left
F_{yRR}	Lateral Tire Force Rear Right
F_{yRL}	Lateral Tire Force Rear Left
F_{TRR}	Tie Rod Force Right
F_{TRL}	Tie Rod Force Left
F_{TCR}	Toe Control Force Right
F_{TCL}	Toe Control Force Left
h_{TR}	Perpendicular Distance of Tie Rod From CoG
h_{TC}	Perpendicular Distance of Toe Control From CoG
M_1	Moment about CoG due to Longitudinal Force
M_2	Moment about CoG due to Lateral Force
M_3	Moment about CoG due to Self-Aligning Moment

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