FORCE AND MOMENT TIRE DATA MODELLING AND TEST REPORT GENERATION

by

Sudeep B. Agalgaonkar

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Mechanical Engineering

Charlotte

2019

Approved by:

Dr. Peter Tkacik

Dr. Russell Keanini

Dr. Jerry Dahlberg

ABSTRACT

SUDEEP B. AGALGAONKAR. Force and Moment Tire Data Modelling and Test Report Generation. (Under the direction of DR. PETER TKACIK)

For optimizing the performance of vehicles, tire force and moment data generated by a tire testing machine is crucial to automotive manufacturers. The data representation should involve more than the transmittal of raw data. Conceivable representation of data enables tire manufacturers to improve and optimize their tire design. It involves heavy post processing to generate tire curves and plots. This thesis report describes the development of an algorithm for tire data modelling and curve fitting. Later, it presents the layout design required for test report generation. The presented algorithm imports the data from a LabVIEW program. After post processing like, converting data files into a MATLAB readable format, rearranging it for creation of various tire curves and curve fitting using Pacejka equation, entire tire test is saved into a single computer file for circulation within the organization. A Simulink GUI called "MATLAB Report Generator" is used to generate reports. Before it can generate required reports, a specific layout is designed according to guidelines from SAE and insights from the research advisor. This comprehensive report can serve as a guide for tire data modelling and any improvements related to it. Finally, the processed data is compared to the actual tire data from a tire manufacturer. Ultimately it proves that, although 46 years old, the M-15 still is capable of 6 running tire tests with fairly good accuracy.

DEDICATION

To my parents, Mr. Balkrishna Kamble and Mrs. Manjushree Kamble

&

My sister, Mrs. Sneha Kanzaria

ACKNOWLEDGEMENTS

I would like to thank my research advisor and Professor at UNC Charlotte, Dr. Peter Tkacik for giving me the opportunity to work on this fantastic project. I am grateful to his incredible expertise and guidance throughout the project. I am also thankful to my committee members, Dr. Russell Keanini and Dr. Jerry Dahlberg, for their valuable time and guidance. I am thankful to my fellow graduate student Harish Nair, whose work on optimizing the Tire Test Protocol with PLC and LabVIEW enabled me to work on my research. I really appreciate the help from Dhiraj Muthiyala, Amol Dwivedi, Franklin Green and Luke Woroniecki for helping us rebuild the M-15 and making it fully operational. I would like to thank my family for the massive moral and financial support. That encouraged me to pursue this challenging project. I would also like to acknowledge Shraddha Chillal for her help in this project. At last, I would like to extend my gratitude to all faculty and staff members here at UNC Charlotte.

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CHAPTER 1: INTRODUCTION

1.1 Content Organization

This thesis introduces by talking about tire testing machines in general and specifics about the Michelin's M-15 Tire Testing Machine (TTM). As it progresses, it discusses the development of tire data MATLAB code and test report generation. Finally, it is concluded with results and analysis. It is systematically arranged as per chapters below.

Chapter 1: Introduction - This chapter provides brief history of tire testing machines and testing protocols with the SAE tire axis system. Later it explains specific details of the M-15 and ends with the problem statement of this research.

Chapter 2: Tire testing protocol - This chapter talks about the force and moment tire testing protocol as described by SAE. It briefly explains the required equipment, test procedure and calculation of gathered data. It also discusses the factors affecting tire testing.

Chapter 3: Parametric study of tire models - This chapter discusses available literature on different tire models and establishes that the Pacejka's magic formula tire model is the most efficient, hence most widely used. It also provides experimental data to back this inference.

Chapter 4: Development of MATLAB code - From importing tire test data files, rearranging and modifying the data and finally plotting it in a comprehending way is discussed in this chapter.

Chapter 5: Test report generation - The processed data should be available to customers in the simplest yet most detailed format possible. MATLAB report generation function is explained in this chapter.

Chapter 6: Results and analysis - All the data plots and tire curves are presented in this chapter. Some peculiarities about that data have been pointed out and pondered upon. This includes calculation of PRAT (Plysteer Residual Aligning Torque) originating from lateral tire pull. It also discusses some ply steer literature review.

Chapter 7: Conclusions - This chapter discusses on results and analysis from the previous chapter and summarizes some facts from it by quantifying the data. In the end, it discusses about the future scope for this research.

1.2 Tire Force and Moment (F&M) Test Machines (TTM)

The pneumatic tire was first invented in 1845. But it was not until 1925 that Broulhiet advanced the concept of slip angle which is the cornerstone idea behind current understanding of mechanics of tire force and moment generation. This was also the subject of subsequent investigations in Germany which gave rise to the testing tires on a drum type roller, by Fromm, in circa 1931. More extensive drum type testing was performed in late 1930's by Evans and Bull. The latter investigations examined conditions of combined longitudinal and side slip. Then Bradley, Allen and Forster examined tire testing on flat surfaces. Differences between flat and drum-type testing was established and documented first by Bull.[1]

These analyses, however, did not take into account carcass deformation. The modern analytical treatment of the elastic deformation of the rubber band theory was developed by Schlippe and Hadekel. Its assumption is that the tire's characteristics can be determined by considering the deformation of the equatorial line, which is the intersection of tire surface. All these theoretical tire models are in fact semi-empirical, which means they involve one or more parameters whose values must be obtained by calculating tire forces and moments under controlled test conditions. Recent developments in tire force and moment testing methodology involve new and innovative ways of measuring required forces. Vehicle-towed dynamometers allowed for tire forces and moments measurements in broadest range of dynamic and environmental conditions.

Dunlop Tire Company has developed a modern laboratory equipment in England, which is called flat-plank tester designed and built in-house. Better technologies for data processing, instrumentation and simulation have been in development and are getting simpler and better. A more widespread understanding of vehicle dynamics related to the tire-road contact patch has enabled several independent research organizations to innovate new test protocols. The industry appears to be entering a time of rapid expansion in the application of tire force and moment technology.[1]

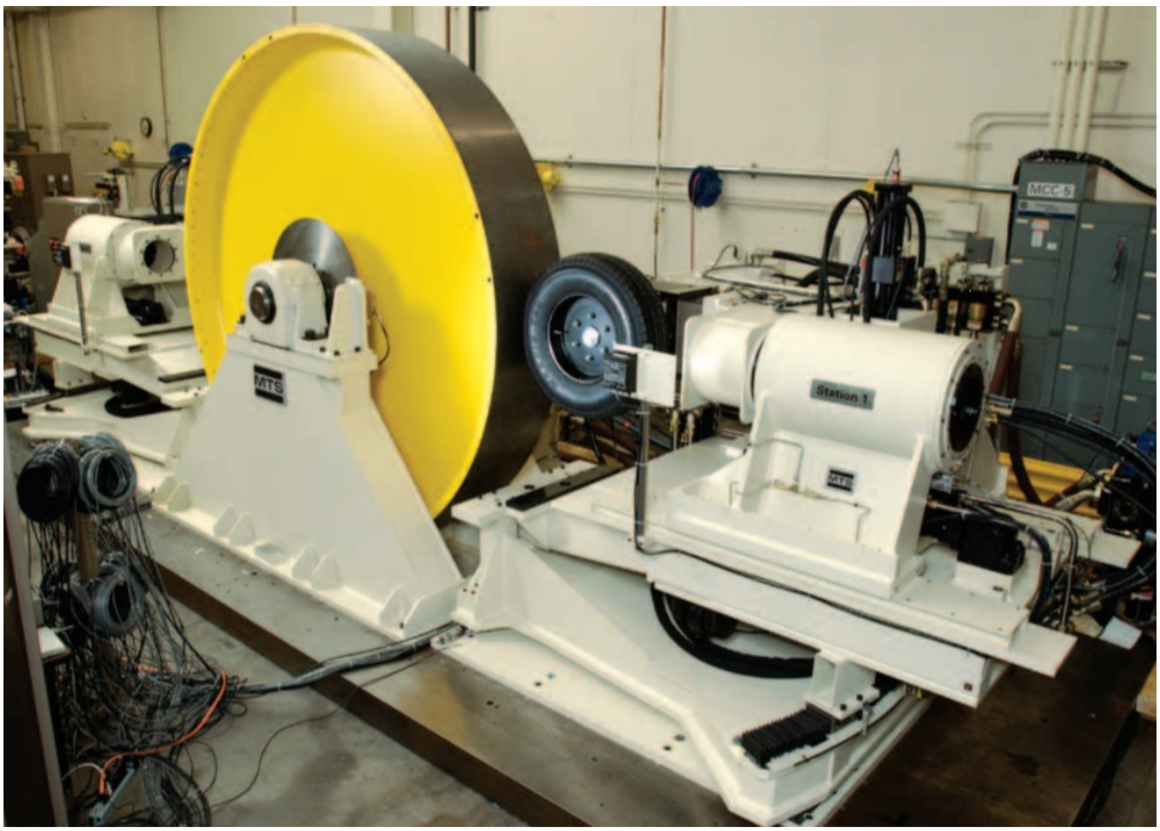

Figure 1.1: MTS Drum-type TTM

The force and moment TTM dates back the to the 1930's and It played an important role in the analysis of vehicle dynamics. The idea behind the tire testing machines was to test the tires in a controlled environment in an indoor setting. This was particularly important for the growth of tire technology, as the tire behavior is not just a linear or a simple non-linear relation. It is a complicated phenomenon that changes its behavior significantly, based on many parameters such as rubber compound, tire cross section, temperature, pressure, inclination angle, steering angle, vertical load, tread pattern, contact area, tread wear, age, road surface properties, etcetera. Therefore, very few tire models exist till date that can predict a tire's behavior with confidence and be applied in the vehicle dynamic simulations or analysis. [2]

The tire data from a Tire Testing Machine (TTM) contains a series of test conditions simulated in the lab. The data of number of relevant parameters are then collected at equal time increments. This data is then supplied to the tire companies, Automotive companies, Race teams, Researchers, etcetera. to help them understand the tire behavior. The famous tire model given by Hans B. Pacejka known as the "Pacejka Model" or "Magic Formula" helps to curve fit the tire data into a useful relation to work with.[3] Thus, the tire data is helpful in quantifying and predicting the tire performance with a reasonable accuracy.

A thorough understanding of the cornering force and aligning moment TTMs is needed for this research, to design a suitable calibration system for it. The three main parts involved in the machine are the roadway, tire manipulating system and sensors for collecting data. However, it is also important to note that not all TTMs are made equally. For instance, there are three different types of TTMs based on the type of roadway being used - concave drum, convex drum, flat track. [4] They are used judicially depending on the purpose of tire tests being done. The TTMs with a drum type roadway have a simpler design and are cost effective compared to the flat roadway machines.[5] However, they are regarded as producing less accurate tire data because of the complications due to the curvature of the roadway and tire contact patch. The ratio of tire diameter to the road-wheel diameter is an important parameter in this analysis. There exists no simple way to convert the data from a drum type TTM to a flat surface. Despite the inaccuracy of the drum type machines, they are still widely used in the industry to study tire endurance and performance at high-speeds.[6]

Figure 1.2: MTS Flat Trac TTM

On the contrary the flat-surface machine can generate data accurately matched to flat road conditions but fails to maintain the simplicity of design. The construction of high-speed flat-surface machine is complicated and expensive to maintain. They are also not as durable as the drum type machines.[7] They are essentially configured like a belt sander and typically consist of a steel belt for the roadway, that is running over two drums and a flat bearing in between. For example, the MTS Flat Trac machine shown in the figure 1.2[8] uses a special type of hydro-static air bearing to maintain the flat contact surface in between the two drums. Also, the steel belt needs a controller to maintain its lateral position throughout the test regardless of lateral force generation. [9]

Most TTMs employ various types of hydraulically actuated tire manipulators for increased loading speed. This consists of a carriage, on to which the tire is mounted, and hydraulic pistons used to manipulate the tire's vertical position, inclination angle, steering angle, etc, with respect to the roadway. The M-15 used hydraulic loading at MARC. But, due to advantages of electric linear actuators, it has been converted to electric load. The M-15 currently is in the process of getting automated steer.However, it doesn't have variable camber capability.

1.3 SAE Tire Axis System

To allow a standardized way to understand the data, a widely accepted terminology is developed for all the parameters involved in the force and moment measurements. Two main platforms developed for this purpose are - SAE Tire Axis System and the ISO Wheel Axis System. Throughout this research, the SAE tire axis system is followed. As shown below in the figure 1.3[10], the SAE Tire Axis System is defined at the contact patch. Some of the definitions are as follows. [11]

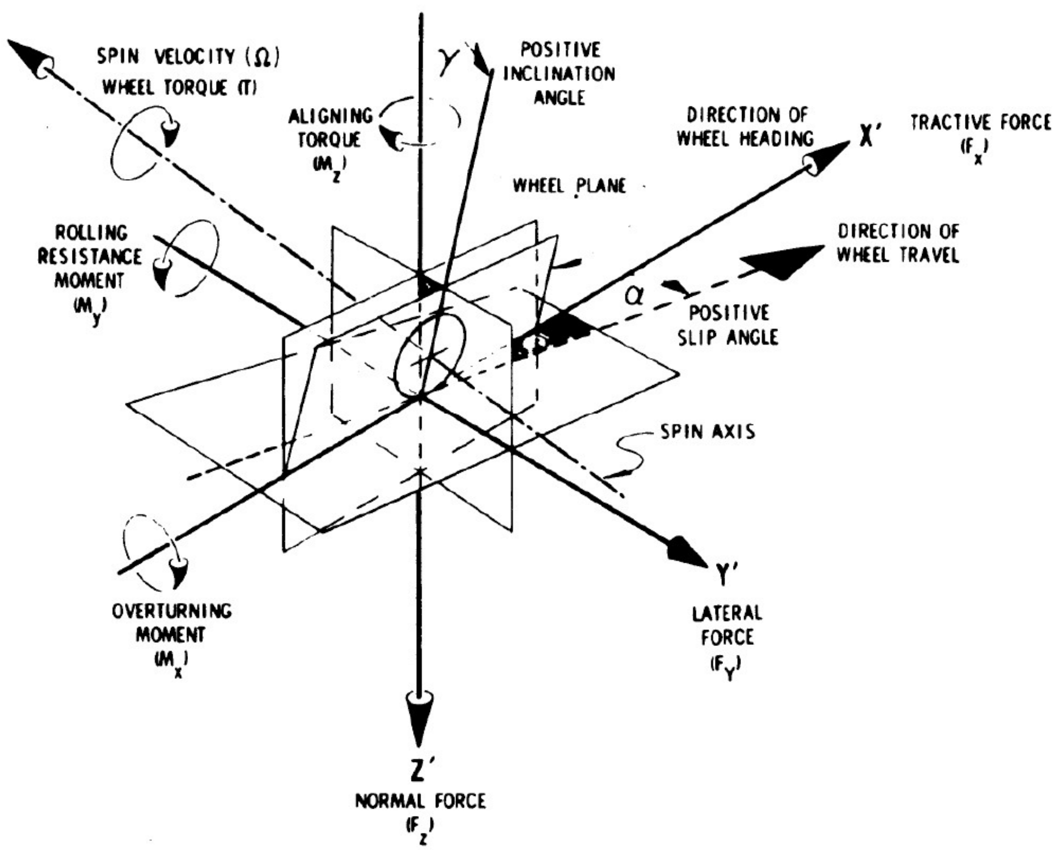

Figure 1.3: SAE Tire Axis System

Aligning Stiffness: First derivative of aligning moment of a free-rolling tire with respect to slip angle, evaluated at zero angle.

Aligning Moment: Moment about the Z'-axis on the tire by the road. It is shown in the figure. The aligning moment is positive in the given figure.

Inclination Angle: Angle between the X-Z plane and the wheel plane. Figure shows a positive inclination angle. The X'-axis is into the paper. Include figure

Cornering Stiffness: Absolute value for the derivative of the lateral force of the free-rolling tire with respect to slip angle, evaluated at zero slip angle.

Center of tire contact: Intersection of the wheel plane and the normal projection of the spin axis onto the road plane. It is shown as the origin of tire axis system in the figure.

Lateral Force: Component of the tire force vector in the Y'-direction acting on the tire by the road. The lateral force shown in the figure is positive.

Loaded Radius: Distance from the wheel center to the center of tire contact measured in the wheel plane.

Longitudinal Force: Component of the force vector in the X'-direction acting on the tire by the road. Positive force is shown in the figure.

Normal Force: Normal component of force between the tire and the road acting on the tire by the road and directed into the road plane. The positive direction of normal force is shown in the figure.

Rolling Moment: Moment about Y'- axis acting on the tire by the road. Positive rolling moment is shown in the figure.

Slip Angle: Angle between the X'- axis and the direction of travel of the center of tire contact. Include figure.

Spin Axis: Axis rotation of the wheel.

Tire Face: Outward side of a tire mounted on a vehicle according to the vehicle manufacturer's specification or general practice. Currently in the United States, the tire face usually the side without the serial number. Other examples commonly used to define the tire face are the side of the tire with the white sidewall or other decoration. In doubtful cases, the tire face selected should be marked and recorded as such. [10]

1.4 Michelin's M-15 Force and Moment TTM

The M-15 Tire Testing Machine was built in-house by Michelin in Clermont Ferrand, France in 1973. It was originally used by Michelin Americas Research and Development Corporation (MARC) in their Greenville, SC facility for F&M tire testing. In 2015, it was donated to the Motorsports Research Laboratory of the University of North Carolina at Charlotte (UNCC). Since then it was rebuilt to today's fully operating state with the help of modern electronics by Dr. Peter Tkacik, Professor at Mechanical Engineering and Engineering Sciences at UNCC, along with many undergraduate and graduate students.

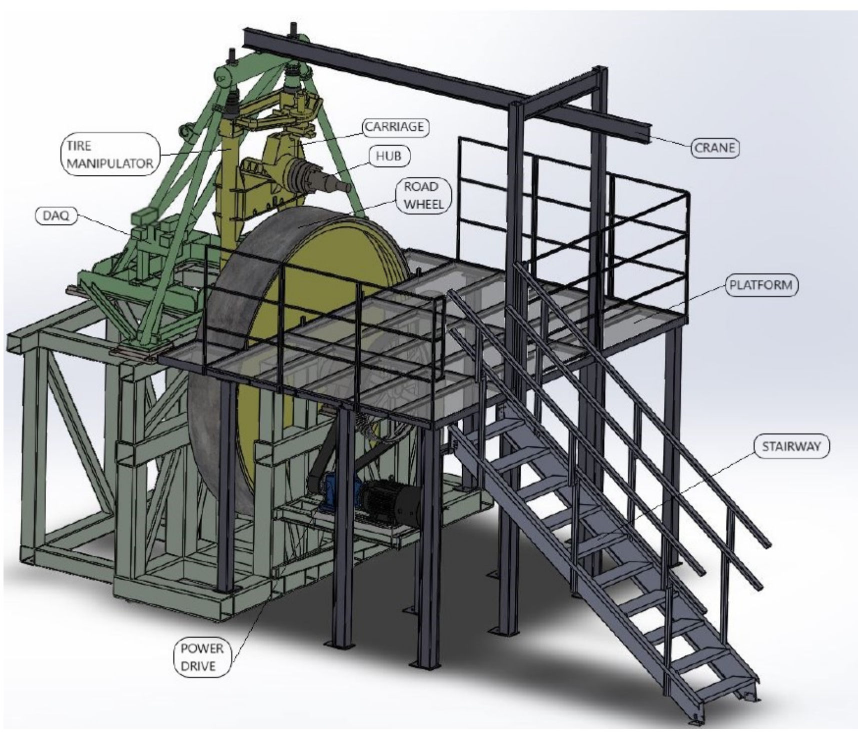

Figure 1.4: Isometric view of the M-15

Michelin's M-15 is a force and moment, convex-drum type tire testing machine (TTM). The tire mounted above the 8.5 m circumference road wheel as in the figure 1.4[12]. The primary components of the M-15 are the Carriage, Tire manipulator, Force and Moment Measurement System, Main Drive and Road Wheel.

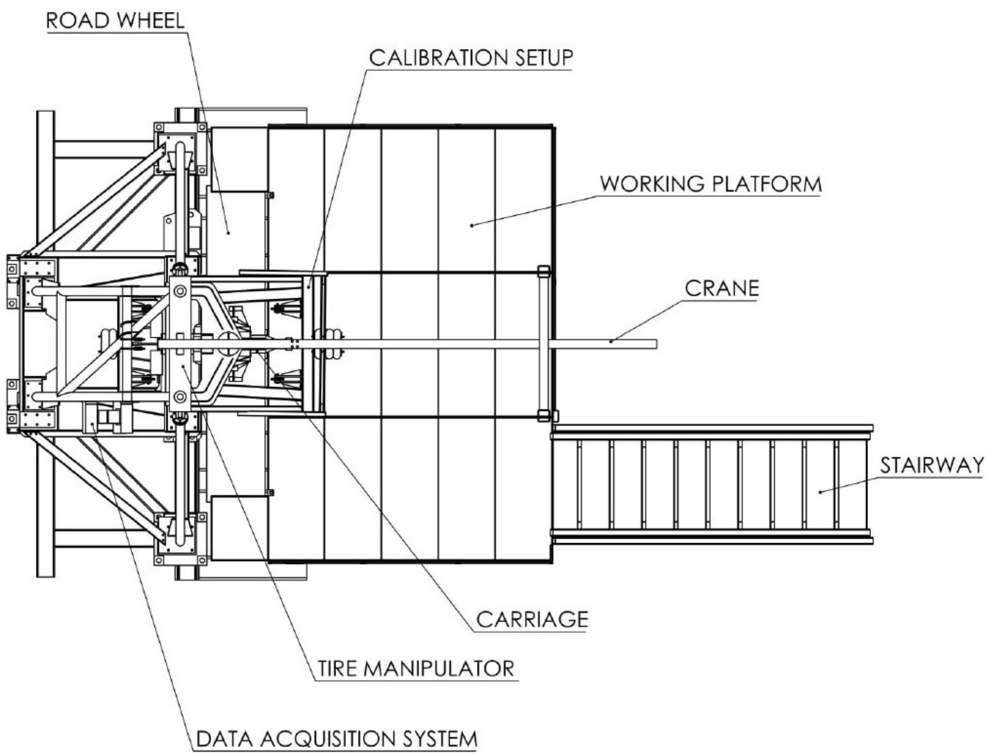

Figure 1.5: Top view of the M-15

Carriage: A heavy steel frame standing about 27 m (9 ft) tall. The heavy steel frame is then mounted on a heavier steel frame that has working platform about 2.2 m (7 ft) high, which is where the tire operator works. It acts as a connection between force and measurement system and the actuators. The carriage is the most vital part of the system as tires are mounted directly on the carriage while testing. A steering system is attached to the carriage through a rack and pinion mechanism with 1 deg increments.

Tire Manipulator: A hydraulic actuator was attached to the carriage for applying vertical load in Z direction. Due to the advantages of an electronic linear actuator over a hydraulic one, it was changed to an electronic one. It has been calibrated in vertical direction using a reference load cell. A DL-06 Programmable Logic Controller (PLC) system is used, along with a PLC program, to properly operate and control the whole machine including the linear actuator for the precise vertical motion.

Force and Moment Measurement System: A special wheel has been designed and manufactured for mounting tires. It can be then attached to the hub with six lug nuts. Six custom made full-bridge strain gauge load cells are situated strategically in the hub as shown in the figure 1.6[12].

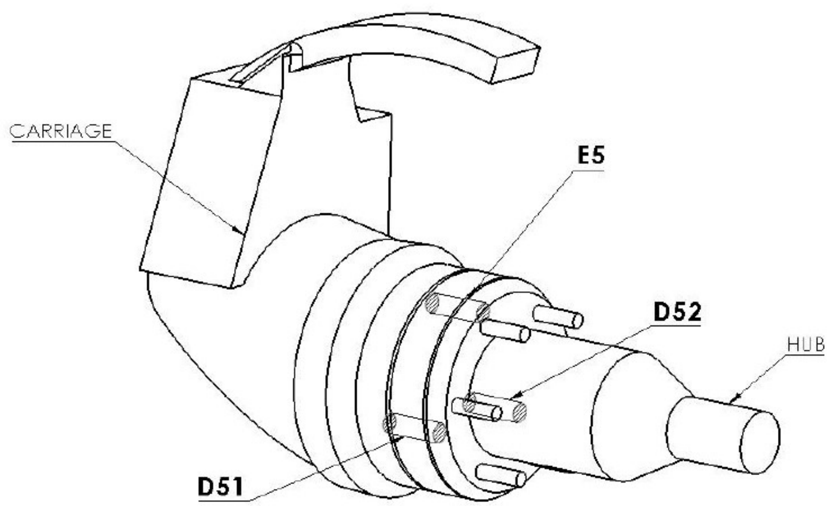

Figure 1.6: Load Cell Positions in the Carriage

They are placed at vertices of an equilateral triangle just behind the part where the wheel is attached. Many of the required forces and moments can be measured using this setup. As mentioned above, there are two load cells at each vertex of the triangle on the circle with pitch diameter of 200 mm. Second set of load cells serves as a backup in case the primary set is damaged. These load cells were manufactured in-house by Michelin in France. The triangular structure of this setup allows the machine to calculate lateral force (F_y), overturning moment (M_x) and aligning moment (M_z)

due to the interaction between three load cells. However, the setup cannot be used to calculate longitudinal force (F_x), rolling resistance moment (M_y). The vertical force (F_z) is calculated using a separately calibrated load cell which is located in the carriage.

Steering System: To facilitate the steering of the carriage and thereby the wheel, rack and pinion system has been attached the machine. This way, the wheel can be set at various slip angles.

Power Drive: A 20 hp vector motor powered by a 430 VAC three phase frequency drive is used to drive the huge road wheel. A motor with a 4.76:1 gear reducer is attached to a timing belt with an additional 5:1 speed reduction is used to drive the road wheel at desired speeds, 7.66 kph to be precise. The assembly is mounted on the main frame. Like the tire manipulator, the main drive is controlled using the DL-06 PLC.

Figure 1.7: Road wheel when it was being installed in the MSR

Road Wheel: This TTM uses an 8.5 m road wheel, 8.5 m being the circumference. To simulate the flat tire-road contact patch as closely as possible, the size of wheel this big as per in the figure 1.7[12]. Due to this size, light truck tires can also be tested with good accuracy on the M-15. The entire road wheel assembly is mounted on a heavy steel frame. For the smooth movement, large spherical roller bearings are utilized. One can get a better idea with the help of the figure shown above.

1.5 Problem statement

Representing the data output in a conceivable way is an important aspect in any testing machine. Only after comprehending the data, one can rectify and modify the input data accordingly. The development of codes for data analysis and representation is an integral part of tire testing protocol. For the same purpose, the motive of this research is to develop a tire data calculation and representation protocol in such a way that, the tire data requester should be able to interpret the performance of the tire in the simplest way possible.

The research can be broken down into two parts. First part is to develop a MATLAB code to generate tire curves and plots which would work with the data files created with a LabVIEW program. The code should import these data files, which contains vertical force (F_z), lateral force (F_y), slip angle (SA) and aligning moment (M_z), modify these data files in a readable form if needed and ultimately plot lateral force vs slip angle & aligning moment vs slip angle curves.

Second part is representing the generated plots into a single, readable PDF format. Both computer file and a printed version can be procured as needed. For this part. MATLAB has a report generation function. The report should consist of basic details such as, name of the requester, tire type, date, tire pressure, tire size, and etcetera. After these details tire plots should be included as requested. This particular part plays a vital role in tire testing, as the quality and accuracy of a tire testing report can be regarded as a final step in the entire process.

CHAPTER 2: FORCE AND MOMENT TIRE TESTING PROTOCOL

2.1 Apparatus

The indoor tire testing machine facility consists of three basic components: A simulated roadway with driving mechanism, a loading and positioning system, and a measuring system. [10]

Simulated Roadway:

- It should be coated with a stable non-polishing material like "Safety Walk or 3-Mite". The roadway surface shall be maintained free from loose material or deposit.
- The surface area shall be wide enough to support the entire tire footprint.
- The supporting structure shall be sufficiently rigid to ensure the specifications for angular accuracy are met.
- The surface must be checked periodically for cracks, tears, dimples, contamination, and etcetera.
- The drive system must be capable of operating the simulated roadway at the speed specified within an accuracy of $\pm$ 1 km/h. 3.5 km/h is the minimum recommended test speed.

Loading and Positioning System:

- A fixture is provided for positioning the tire with respect to the track surface and loading it against the simulated roadway at specified normal forces. It shall accommodate all sizes of tires to be tested.

- The machine shall accommodate rims with diameters and widths required by the user.
- The loading mechanism shall have the provision for changing the normal force on the tire test from zero to 160 % of the normal load.

Measuring System: It shall be capable of measuring these data for a free-rolling tire: Aligning moment, lateral force, longitudinal force, normal force, overturning moment, slip angle, inclination angle, and loaded radius. Individual load cell values shall be corrected to tare. [13]

2.2 Test Procedure

- Adjust the tire pressure to the test pressure with the tire unloaded and the machine locked to prevent danger to the operator. Tire pressure shall be controlled as specified during test.
- Set the roadway speed to 3.5 km/h (2 mph).
- Obtain test data for the listed slip angles at the listed loads.
- Slip angle sequences: 0, +1, -1, -2, +2, +4, -4, -6, +6, +8, -8, -10, +10 degrees
- Normal Force Sequence: 250, 567, 833, 1101, 1372 lb
- The tire shall complete 2.5 revolutions after each load change prior to starting data acquisition. Data acquisition shall continue for 1 revolution. The reported data for a load and a slip angle will be the average of the data points taken at that condition. [10]

2.3 Calculation of Test Results

Owing to the many uses of these data files, the manipulation to be performed is correction of the data for load cell tare, interactions and transformation form machine to SAE coordinates. Further data analysis must be performed for understanding of it in the form of graphs and tire curves. The corrected data file must be saved in the form of a computer file. [10]

2.4 Factors affecting Indoor Tire Testing

The pneumatic tire is the primary control element and probably the most crucial aspect in ground vehicle systems. The tire-road interface develops forces and moments which provides functions of support, directional control, braking and acceleration capabilities. Tire design plays a vital role in the manner these forces and moments affect the performance of a tire. The ride quality ultimately depends upon tire design. These tire forces and moments are analogous to airfoil characteristics used in the design of aircraft. [1]

Speed: The steady state elastic properties of a tire are dependent on threshold speed. The threshold test speed has not been directly specified, but several test facilities have run successfully at 1 mph.

Temperature: Some rubber properties of rubber are known to vary with temperature. So, elastic properties of tire are expected to vary with temperature. However, these effects have not been carefully investigated yet.

Road Surface: The elastic response of a pneumatic tire is dictated by the compliance of its constituent parts (cords, tread, etcetera) and by the relative configuration of these parts under the conditions of external loading. One of the major determinants of a loaded tire's configuration is its shape of the road surface. It is found experimentally that the distortions produced when a tire is loaded against a curved (either concave or convex) surface are different from those produced by a flat surface as to exert an influence on the tire's elastic response. The significance of this influence depends on the degree of curvature. Consequently, laboratory machines employed to measure tire force and moment properties for vehicle design and tire selection purposes frequently incorporate flat, rigid test surfaces.

Contaminants: The presence of contaminants (such as water, dust, or oil) at the tire-roadway interface may exert a substantial effect on the interfacial friction coefficient. Immaculate care must be taken to eliminate the possibility of contamination during tire force and moment testing.

CHAPTER 3: COMPARATIVE STUDY OF TIRE MODELS

To make use of force and moment data in vehicle design, tire characterizations must be put into mathematical terms, that is, as models. At present, there are two practical limitations that affect the use of tire models as part of a vehicle model. First, a tire model must not consume so many computer resources that the vehicle model does not run at a reasonable speed. This means that the tire model cannot be too complex. Moreover, it must become simpler as the requirement for operational speed increases, for example, in using real-time models for hardware-in-the-loop-testing. Second, a model must not require major engineering input so that the effects of different tire designs can be compared and evaluated on vehicle models for a rational cost. [14]

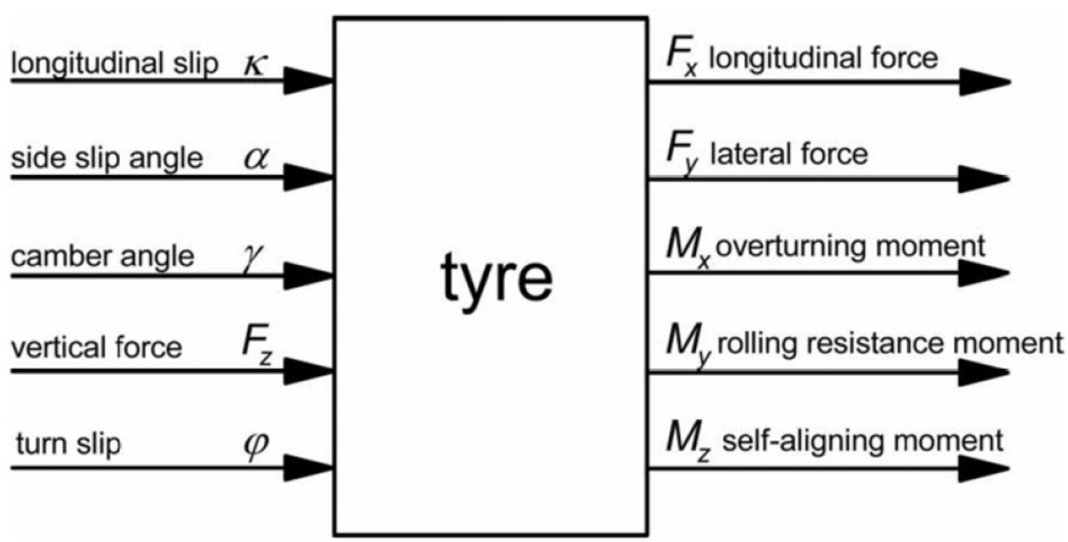

Figure 3.1: Tire inputs and outputs

There are three basic ways to model force and moment behavior: purely structural consideration (finite element analysis), using lumped parameters (structurally based), or empirical (or semi-empirically) by fitting a relationship ("curve") to experimental data. Generally, FEA models are not satisfactory as substructure elements of vehicle models because they do not meet the criteria stated in the previous paragraph. Empirical models with prudent insertion of some lumped parameter aspects (making them semi-empirical) are the current models of choice for evaluating tire forces and moments in vehicle modeling. [3]

Empirical models began as curve fits. That is the way tire force and moment data is most commonly used in vehicle modeling. In order to deal efficiently with combined operations, such as simultaneous driving or braking, and cornering or transients, certain elements from lumped-parameter models have been incorporated into empirical models in recent years. Thus, various initially-empirical models might now be regarded as semi-empirical models. [3]

3.1 The Magic Formula Tire Model

It is one of the most widely used semi-empirical tire model. It is used to calculate steady-state tire forces and moments in vehicle dynamic studies. The development of this model began in the mid 80's. In 1993 using the magic formula based on weighing functions was introduced for describing the horizontal tire force generation at combined slip. This approach was adopted by Hans Pacejka and developed even further.

Six important properties of the "Magic Formula" are noted in a subsequent paper by Bakker, Pacejka, and Lidner. The two that seem most important are: a) the formula can match the experimentally observed characteristics of lateral force, aligning torque, and longitudinal force quite well and b) the coefficients can be related to actual physical tire data in a recognizable way.

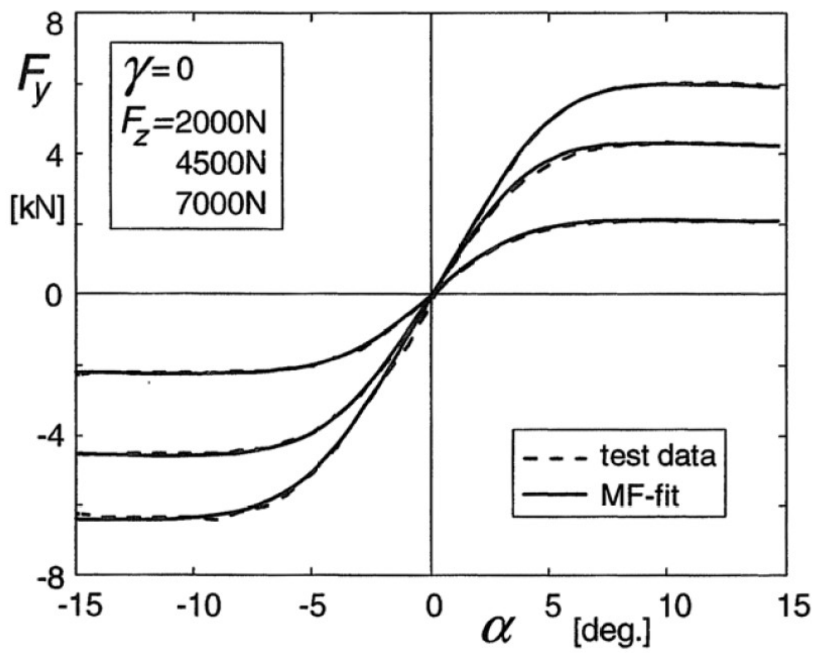

Figure 3.2: Magic Formula sample plot (F_y vs SA)

Today, the most common empirical or semi-empirical models are derived from the "Magic Formula", introduced in a 1987 paper by Bakker, Nyborg, and Pacejka.[3]

$$y = D \sin[C \arctan (Bx - E(Bx - \arctan(Bx)))] + S_V$$

y: Lateral force or aligning moment

x: Slip angle

B: Stiffness factor

C: Shape factor

D: Peak Value

E: Curvature factor

arctan(BCD): Slope of the curve at origin

S_V: Vertical Shift

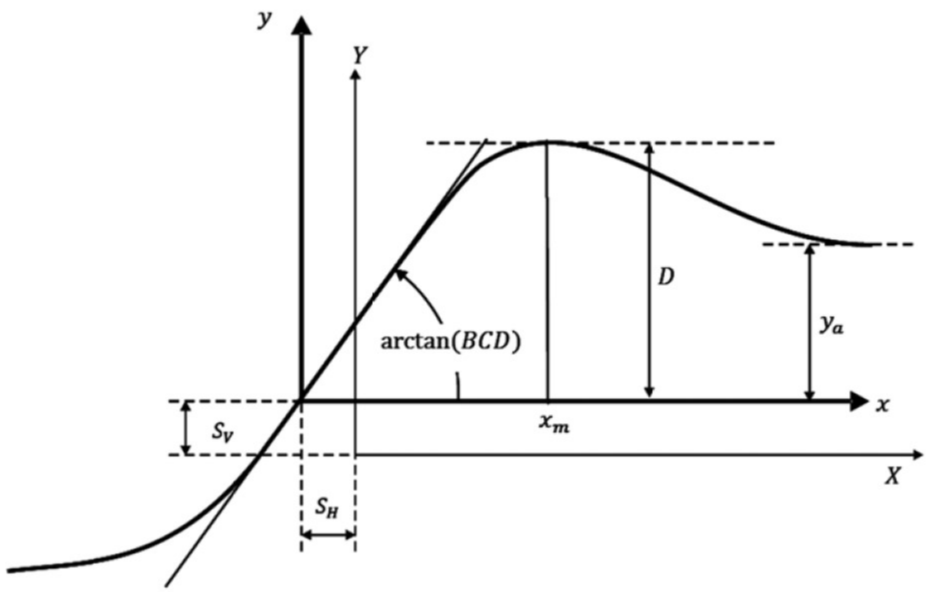

Figure 3.3: Sample Magic Formula Equation

Each of these factors must be approximated from measured data from experiments for the respective tire and environment. It is also possible to apply an offset in x and y with respect to the origin to this general formula. An offset can arise due to ply-steer and conicity effects as well as wheel camber. The shift in x and y can be performed by using the modified coordinates,

$$Y(X) = y(x) + S_V$$

$$x = X + S_H$$

S_V : Vertical Shift

S_H : Horizontal Shift

The discussion in Schuring, Pelz, and Pottinger is very helpful for understanding the mathematical features of the "Magic Formula" and sheds light on both the interpretation of the coefficients B, C, D, E, S_H and S_V and the consequences of the values chosen for C and E.

S_V and S_H simply locate the center point of the Magic Formula curve with respect to the origin when the traditional representation of tire data is used. For example, in the case of lateral force S_V and S_H arise from ply steer and conicity.

arctan(BCD) is the initial slope of the curve. In practice, this product is the cornering stiffness, aligning stiffness, or longitudinal stiffness depending on which force or moment is being modeled.

B and D are size factors. D can be estimated from the maximum value of y when the curve has a definite peak. The fact that y cannot exceed D leads immediately to this relationship. C and E are shape factors.

3.2 The TMeasy Tire model

The TMeasy tire model belongs to the class of semi-empirical tire models, where the description of forces and moments relies also on measured and observed force-slip characteristics which contrasts with purely physical models. In the semi-empirical tire models, the tire contact patch is considered as an even plane and the tire forces and moments can be approximated by specific mathematical functions. The semi-empirical tire model TMeasy has originally been used for vehicle dynamic calculations of agricultural tractors.[3]

Conclusions: There is not enough literature review available on the TMeasy tire model. From the available literature, it can be said that, the tire model shows an asymmetric tire behavior. With relatively fewer model parameters, gives a reasonable approximation of the pure longitudinal and lateral tire force characteristics. Inaccuracy of the tire model occurs in the aligning torque and combined slip characteristics.

3.3 The TreadSim Tire Model

The TreadSim (a tread simulation) tire model falls in the category of physical tire models. This model is developed to investigate different aspects of the tire model which were impossible to include in semi-empirical tire models. Some of these difficult to calculate features are, Arbitrary pressure distribution, finite tread width at turn slip or camber, velocity and pressure dependent friction coefficient, anisotropic stiffness properties, combined lateral, longitudinal and camber or turn slip, lateral bending and yaw compliance of the carcass and belt, finite tread width at turn slip or camber. [3]

Conclusions: The outcome of the model reveals that the tire properties shows unrealistic values, especially the overall low bending and lateral belt stiffness and the resulting large magnitude of the lateral carcass deformation. Thus, it is concluded that for high vertical forces the TreadSim model has problems to give a good approximation of the measurement results. TreadSim generates a peak friction coefficient that is generally higher than the measured peak friction. It is possible due to the result of the poorly modelled contact patch shape and the unrealistic normal pressure distribution. Improvements for the TreadSim tire model are the improvement of the contact shape deformation, also under the influence of a camber angle. Other improvements that could be studied further are the normal pressure distribution and the possibility to derive the pressure distribution from a FEM model.

3.4 Dynamic Tire Friction Model (LuGre friction model)

The LuGre friction model was developed as a cooperation between the Department of Automatic Control at Lund University (Sweden) and Laboratoire d'Automatique de Grenoble (France). The model describes a dynamic force characteristic which arises when frictional surfaces are sliding onto each other. Thereafter, there have been several investigations to make the LuGre dynamic friction model suitable for the tire-road contact problem. An extension of the LuGre tire model is proposed by Deur. The model describes the dynamics of longitudinal and lateral tire friction forces, as well as the self-aligning torque dynamics.

Conclusions: The model validation has shown that the LuGre tyre model with an asymmetric non-uniform normal pressure distribution over the tire/road contact patch shows reasonable accurate static behavior of the longitudinal and lateral tire forces. Overall the dynamic tire friction model based on the LuGre friction model gives promising results for the steady-state tire behavior. However, physical tire models still need tire parameters that are optimized with respect to measurements to reach the same level of accuracy of empirical tire models.

3.5 Significance of Pacejka Tire Model

Table 3.1: Errors of the optimization results of the tire models

No camber	MF (%)	TMeasy (%)	TreadSim (%)	LuGre (%)
Pure F_y	1.33	2.12	4.50	4.85
Pure M_z	7.02	17.20	25.29	24.28
Combined F_y	3.84	20.71	12.12	8.58

From the fit results it can be concluded that the Magic Formula tire model gives the best approximation of the steady-state tire characteristics. For both the optimization with and without camber influence, the magnitude of the fit errors is considerably smaller with respect to the other tire models.[3]

It can be concluded that the physically oriented tire models cannot achieve the same accuracy as the semi-empirical based tire models. In the physical tire models, some assumptions are made to decrease the computational effort. For example, the poor approximation of the normal pressure distribution, the rectangular shape of the contact patch, empirical formulae to improve the aligning torque behavior, etc.

CHAPTER 4: DEVELOPMENT OF MATLAB CODE

4.1 Curve fit equations

These curve fit equations were developed by the graduate students working on the machine before the current team.[15][12] The equations developed by them proved to be accurate with curve fitting provided depicted in figures below.

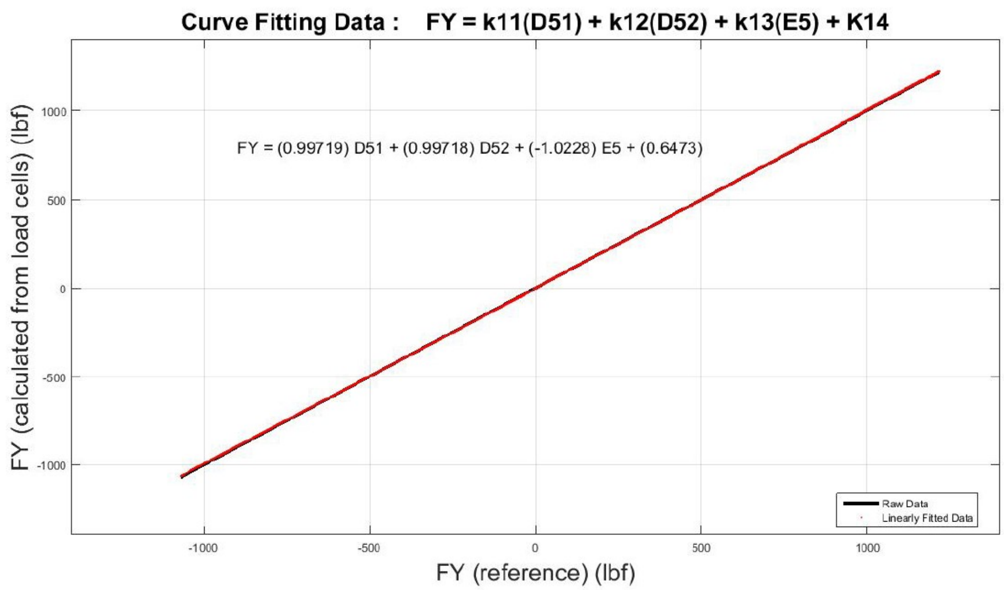

Figure 4.1: F_y equation after curve fitting

From the graph shown above for Fy (lb) vs Fy calculated, it can be inferred that by using the three-dimensional, first order curve fit, the accuracy of the curve fit equation has improved quite significantly. The reason for this is that now, the data from all the three load cells are considered for developing the curve fit equation and not only the load cell which seemed most appropriate.

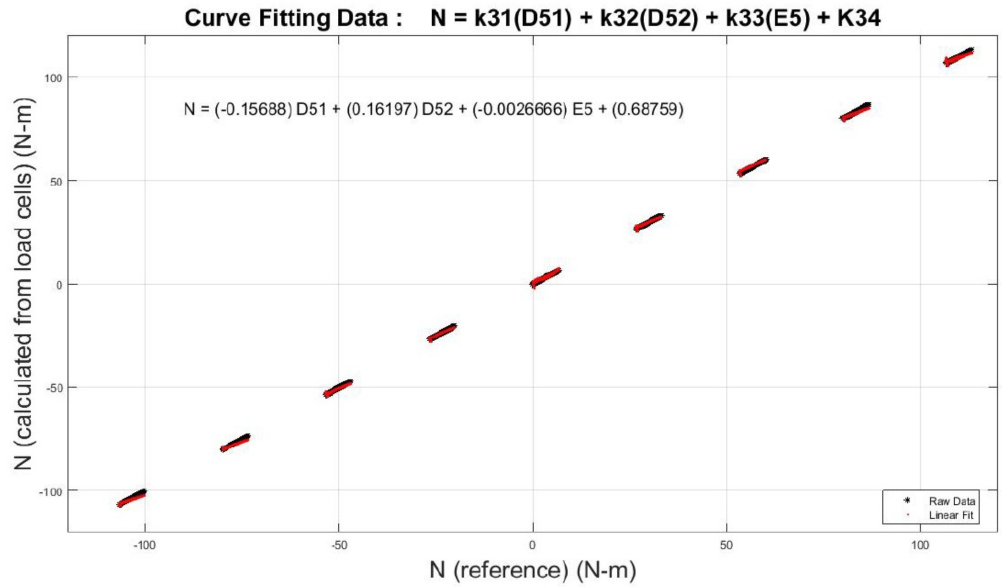

Figure 4.2: M_z equation after curve fitting

A similar improvement can be seen in the graph of Aligning Moment(lb-ft) vs Aligning Moment Calculated. In this case, too, a similar curve fit equation was developed, and significant improvements were seen here.

According to the curve fitting, equations for F_y (lb) and M_z (lb-ft) are as follows.

$$F_y(lb) = (0.99719)D51 + (0.99718)D52 + (1.0228)E5 + (0.6473))$$

$$M_z(lb - ft) = (-0.15688)D51 + (0.16197)D52 + (0.0026666)E5 + (0.68759))$$

A major error in these equations was pointed out and then rectified. Third term which is positive was taken as negative as per the old calibration, which gave incomprehensible values. After correction, output data is used for post-processing.

4.2 Structure of Algorithm

4.2.1 Data Acquisition

From the LabVIEW program, multiple data files are generated, according to slip angle sequence. If they are saved into any other order but this, file names have to be changed manually which is time consuming and should be avoided. It can be seen in the figure, that LabVIEW increments the file names with numbers. It can be seen in the figure, different columns of data. These locations are of crucial importance, since the MATLAB algorithm works specifically on cell locations. The entire procedure is explained below.

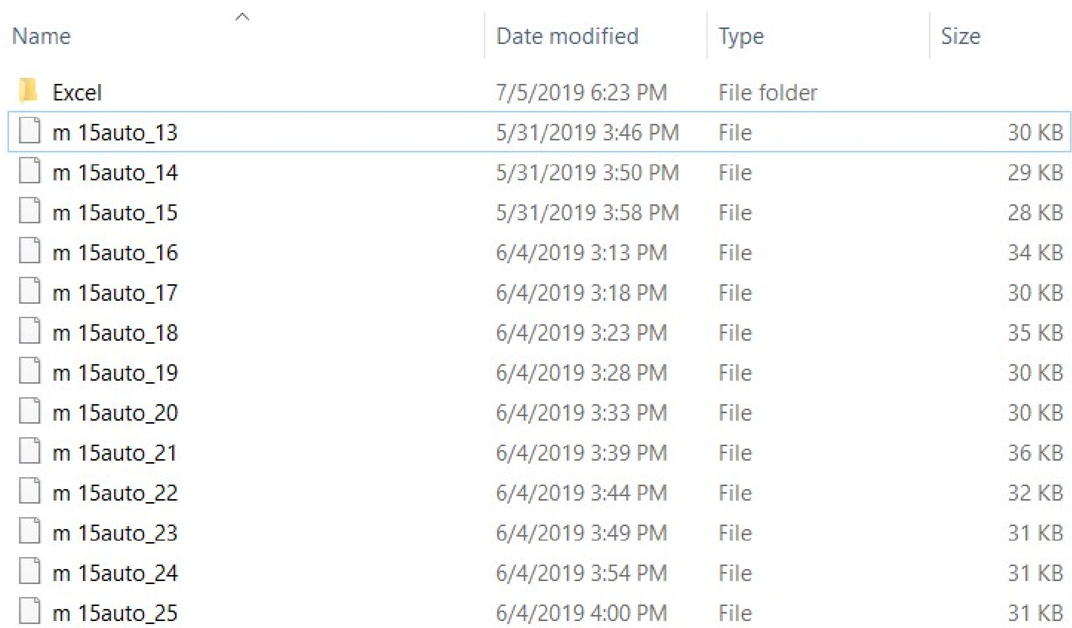

Figure 4.3: Data files from LabVIEW

- Files generated from the LabVIEW program are .xlsx files. They are saved in a folder on computer.
- As per the tire testing protocol mentioned in the chapter above, these files must be in a specific sequence in order to post process later.
- The sequence is according to slip angles as follows: 0, +1, -1, -2, +2, +4, -4, -6, +6, +8, -8, -10, +10 degrees.
- The files need to be renamed to arrange them into the sequence. If they are not in a specific order, the plots would be rendered irrelevant.
- After that is done, MATLAB import for the files is initiated using files = dir('*.xlsx')

- The imported files are then populated with N = length(files)

	A	B	C	D	E	F	G
1	FZ load	D52 (Filter	D51 (Filter	E5 (Filtere	SA (Filtere	Fy	Mz
2	248.8146	86.06072	98.59261	-182.415	-0.30197	371.3554	-0.35393
3	250.0319	86.05929	98.59098	-182.414	-0.30197	371.3506	-0.35392
102	587.4521	178.8015	211.9537	-289.719	-0.3018	686.6269	-2.83066
103	586.4783	178.8021	211.9551	-289.72	-0.3018	686.63	-2.83078
202	835.0397	246.0777	317.8654	-379.184	-0.30167	950.8327	-8.31079
203	834.5528	246.0772	317.8647	-379.184	-0.30168	950.8312	-8.31077
302	1112.572	287.6001	413.911	-449.088	-0.30804	1159.511	-16.4666
303	1111.841	287.5996	413.9121	-449.088	-0.30804	1159.512	-16.4669
402	1376.714	300.6323	495.981	-497.59	-0.30607	1303.954	-27.1016
403	1375.496	300.6326	495.9822	-497.591	-0.30607	1303.956	-27.1018

Figure 4.4: Excel data file

4.2.2 Rearrangement of data

- The data still needs to be properly arranged in columns for post-processing. It is done using xlsread command.
- Specific range of columns is imported and saved into appropriate variables according to vertical load cycles, 250, 567, 833, 1101, 1372 lb.
- After the data is taken out of data files according to load cycles, specific column arrays are created for slip angle (SA), lateral force (Fy) and aligning moment (Mz). For example, for 250 lb vertical load, SA250, FY250, and MZ250 arrays are created and populated.

4.2.3 Magic formula curve fitting

All detailed engineering measurements are subject to a degree of variability due to phenomena that cannot be controlled. Tabulation or plotting of raw engineering data is frequently of limited usefulness since statistical variability tend to hinder application and interpretation. Tire force and moment tests are run on a very few samples of a particular design under idealized conditions. The data must be treated as a statistical estimate of tire design performance to be used mainly for comparison purposes although test accuracy and test conditions are controlled to the extent possible. Final processing, curve fitting and plotting must be selected to facilitate interpretation and proper application of test results.

Most tire data in raw form contain a degree of asymmetry between positive and negative slip angle information as well as left and right rotation mode. Some tires are constructed with a controlled degree of asymmetry for special reasons. Alternatively, the curves may be forced through the origin. Curve fitting is done to eliminate this asymmetry.

When all these arrays are created, F_y vs SA and M_z vs SA plots for each load are generated. Later they are combined onto a single graph. Different colors are assigned to distinguish each load. Tire curves are generally fitted using the Pacejka equation (magic formula), as it provides a good fit.

The Pacejka formula, also called simply Magic Formula "MF" or "MF-tire", is a function, which is used to predict and simulate the forces developed by a tire. Given an input x and a list of coefficients, the function calculates the force y developed by the tire. Three different functions are used, one for longitudinal forces, other for lateral forces, and the last one for the self-aligning torque (the feedback force that can be experimented on a car's steering wheel). Each function has its own set of coefficients.

Dependence of curve on coefficients: The goal is fitting the curve with the results obtained in the empiric experiments on the specific tire the curve is being calculated for. Once the proper coefficients for the curve are found, the behavior of that tire can be easy and realistically predicted without having to use the real tire. One can imagine using a tire testing facility, testing a specific tire in a wide variety of conditions and measuring the results.[16]

Table 4.1: Pacejka '94 Lateral Force parameters

Coefficient	Name	Parameters	Formula
C	Shape factor	a0	C = a0
D	Peak factor	a1, a2, a15	$D = Fz.(a1.Fz + a2).(1 - a15.\gamma 2)$
BCD	Stiffness	a3, a4, a5	$BCD = a3.sin(atan(Fz/a4).2).(1 - a5.\lvert\gamma\rvert)$
B	Stiffness factor	BCD, C, D	$B = BCD/(C.D)$
E	Curvature factor	a6, a7, a16, a17	$E = (a6.Fz + a7).(1 - (a16.\gamma + a17).sign(slip + H))$
SH	Horizontal shift	a8, a9, a10	$H = a8.Fz + a9 + a10.\gamma$
SV	Vertical shift	a11, a12, a13, a14	$V = a11.Fz + a12 + (a13.Fz + a14).\gamma.Fz$

Then, based on those results, one could start experimenting with the coefficients of the Pacejka curves until getting a curve that acceptably fits the experimental results. Pacejka and other models are developed by and for the automotive industry. Real coefficient sets are scarce and difficult to find, as they are heavily protected intellectual data. [14]

The equation used for the same is as following:

$$y = D\sin[C\arctan\left(Bx - E(Bx - \arctan(Bx))\right)] + S_V$$

The coefficients, as mentioned before in this report, can be related to actual physical tire data in a recognizable way. These coefficients or start points can be changed for each curve, in order to fit them. The set of values will be different for each tire and should be changed in the MATLAB program accordingly.

CHAPTER 5: REPORT GENERATION

Two problems related to tire force and moment data concern the automotive and tire industries. The first is the problem of computer storage of force and moment data as a compact form is needed to aid vehicle directional control simulations. This problem particularly concerns the automotive companies and is somewhat an in-house task since its solution is directly dependent on a particular company's computer resources and capabilities.

The second is, that of developing a standard format for tire force and moment data to facilitate adequate communication between the tire and automotive companies. Force and moment characteristics of the free-rolling tire are influenced by vertical load, slip angle and inclination angle. The usual test procedure is to set two of the variables constant and vary the third. The quantities being, raw test data, the force and moment measurements, and recorded data.

When the quantity being varied has run through the desired range of values. In addition to holding two of vertical load, slip angle or inclination angle constant, there are test variables such as inflation pressure and speed of rotation. These can be varied for each combination of values of slip angle, inclination pressure and vertical load. It is obvious that unless test variables are clearly identified and a systematic procedure for variation is developed, any data transfer between companies can be confusing and inefficient.

Tire force and moment data should include following:

1. Tire identification, to include size, brand and construction features.
2. Inflation pressure

3. Test speed (depending on machine concept)

4. Tabular printout/pdf of test data and graphical representation (tire curves) can be as follows:

    - Lateral force vs slip angle at five different loads (in range of 40-160% rated load).
    - Aligning torque vs slip angle at five different loads (in range of 40-160% rated load).
    - Lateral force vs vertical load at different slip angles ($\pm$ 1 deg, 2 deg, 4 deg, 6 deg, 8 deg and 10 deg).
    - Aligning torque vs vertical load at different slip angles ($\pm$ 1 deg, 2 deg, 4 deg, 6 deg, 8 deg and 10 deg).
    - Lateral force vs aligning torque at different vertical loads from 40-160% rated load and at slip angles ranging from $+1$ deg to 10 deg (Gough plots).

This data representation method should involve more than the transmittal of raw data. It requires post processing to generate tire curves and plots. Raw mathematical data is not expected here.

The lateral force has been recognized as the principal force and moment characteristic affecting vehicle handling, and it is known as a function of large number of variables. The variable having the most effect on lateral force is the slip angle. To study the lateral force-slip angle relationship, a tire property termed cornering stiffness has been defined. It is the magnitude of the derivative of lateral force with respect to slip angle.

The relationship of lateral force to inclination angle is described by the tire property known as camber stiffness, which is the derivative of the lateral force with respect to inclination angle. It has significant effect on vehicle understeer, and suspension geometry depends on this parameter. As the M-15 does not have varying inclination angle capabilities, camber stiffness is not considered in this research.

5.1 Requirements of Tire Test Report

Dr. Tkacik came up with a basic idea of a test report as following. It contains information about test condition, tire designation, etcetera as shown in the figure 5.1[17] below.

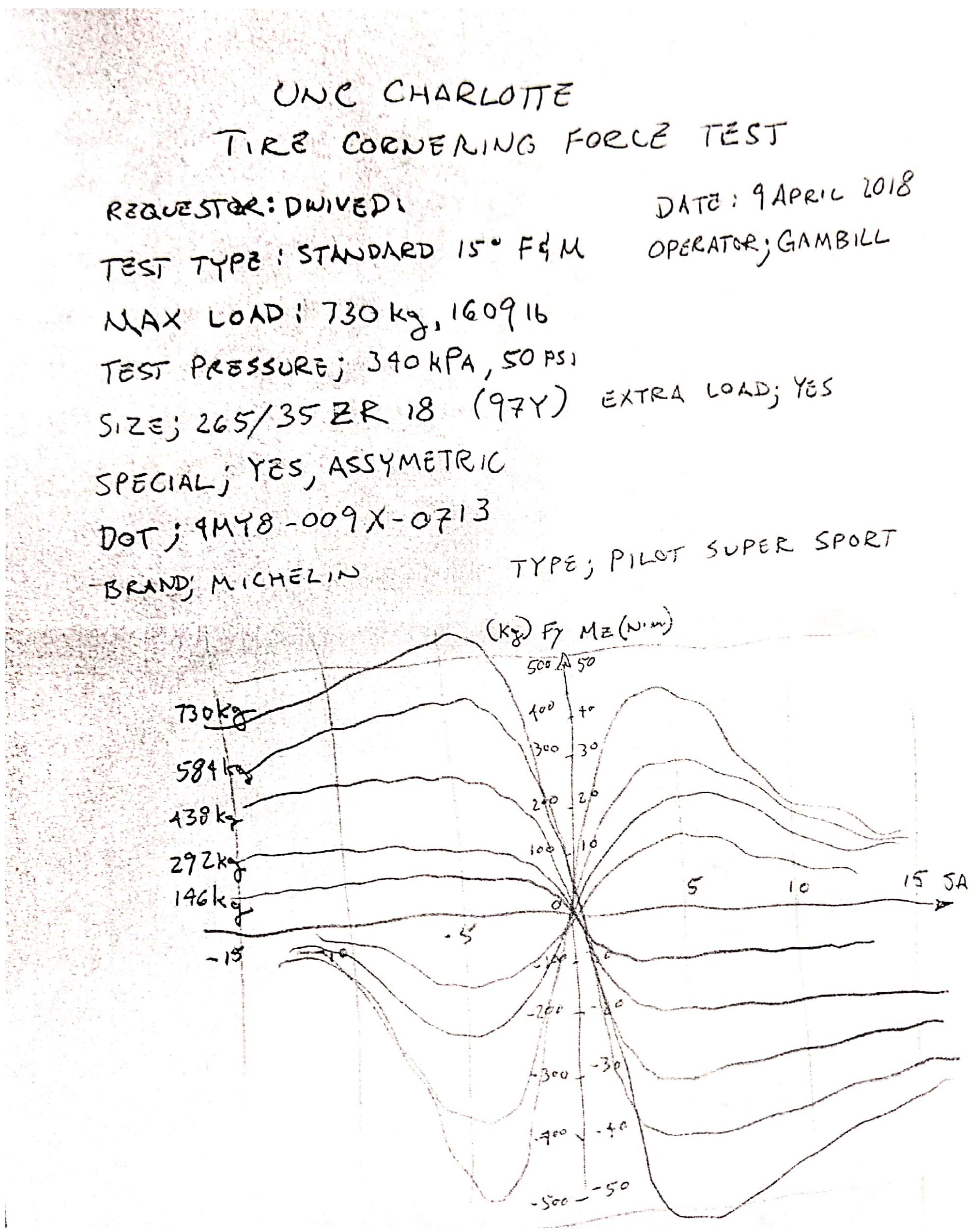
UNC CHARLOTTE
TIRE CORNERING FORCE TEST
REQUESTOR: DWIVEDI
DATE: 9 APRIL 2018
TEST TYPE: STANDARD 15° F&M
OPERATOR; GAMBILL
MAX LOAD: 730 kg, 1609 lb
TEST PRESSURE; 340 kPA, 50 PSI
SIZE; 265/35 ZR 18 (97Y)
EXTRA LOAD; YES
SPECIAL; YES, ASSYMETRIC
DOT; 4MY8-009X-0713
BRAND; MICHELIN
TYPE; PILOT SUPER SPORT

Figure 5.1: Initial Test Report Idea

5.2 MATLAB Report Generator

MATLAB Report Generator provides functions and APIs that integrate reporting capabilities into MATLAB applications. One can develop programs that generate reports in PDF, Microsoft Word, Microsoft PowerPoint, and HTML. MATLAB Report Generator enables dynamic capture of results and figures from the MATLAB code and document those results in a single report that can be shared with others. One can use the prebuilt, customizable Word and HTML templates or design reports based on organization's templates and standards. The user interface of the software and the output title page are shown below.

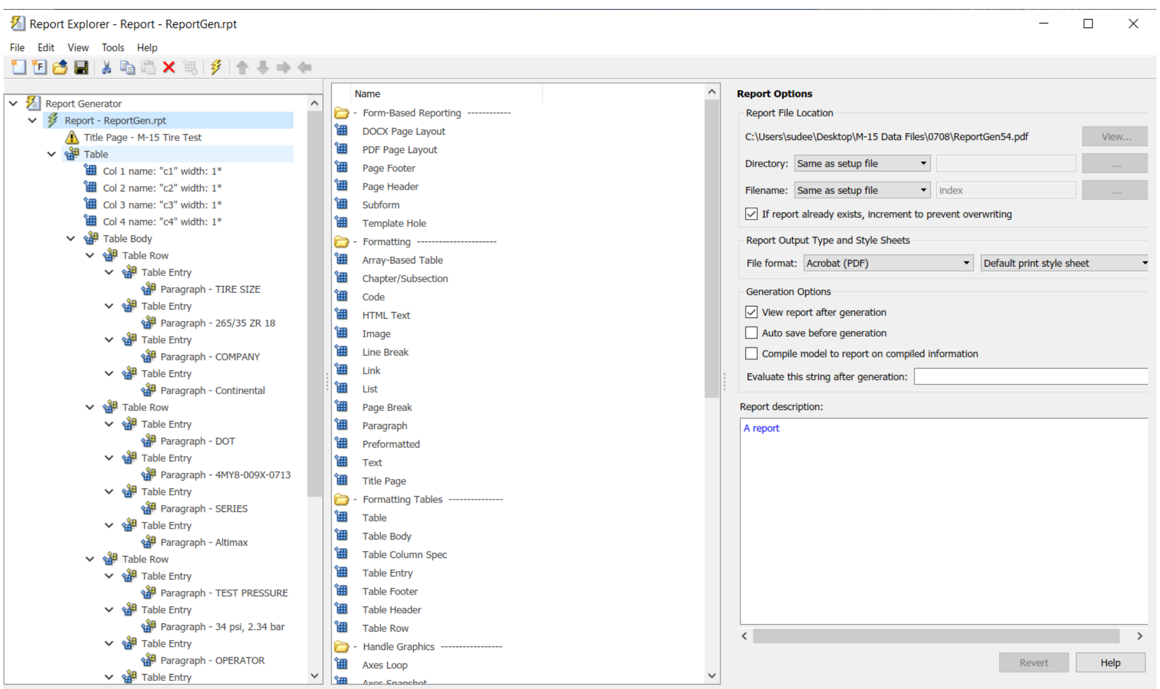

Figure 5.2: MATLAB Report Generator User Interface

As seen in the figure, the report contains various parameters like tire size, brand, test pressure, etcetera. The layout is completely customizable to include required information.

M-15 Tire Test

Force and Moment

UNC CHARLOTTE

07/10/19

TIRE SIZE	265/35 ZR 18	**COMPANY**	Continental
DOT	4MY8-009X-0713	**SERIES**	Altimax
TEST PRESSURE	34 psi, 2.34 bar	**OPERATOR**	Harish Nair
REQUESTOR	Dr. Tkacik		
SPECIAL	Asymmteric		

Figure 5.3: Tire Test Report Title Page

CHAPTER 6: RESULTS AND ANALYSIS

6.1 Post-processing

6.1.1 Ply Steer

Major parameters causing pull problem consists of ply steer, conicity of tires, road crown, cross camber, cross caster and other manufacturing non-uniformity of the vehicle. Force and moment behaviors are function of tire body parameters (profile, belt angle, belt constructions etc.) and contact behavior of tread pattern by the geometry of tread pattern. This part describes the effect of pattern in particular and influences of shoulder lateral groove angle on ply steer residual aligning torque.

A typical radial tire is constructed with multiple layers of plies bonded together. The individual plies have various prescribed orientations of carcass layer which are parallel to the meridional direction and anti-symmetric belt package in the crown region. The classical lamination theory misconception is that the orthotropic layers are perfectly bonded together with an infinitely thin bond line and the deformations across the bond line are continuous. Usually, the multi-ply systems twist and bend when subjected to simple tensile load. The result is a combination of bending, shearing and stretching of the laminate. [18]

Moreover, if the tire is free rolling, the toroidal shape of tire becomes flat at the contact patch, so lateral and longitudinal shear stresses are generated in the contact area and additional in plane shear also occurs due to change in belt tension at contact patch. These shear stresses when applied to the individual tread blocks, create coupled reaction forces resulting in an aligning torque. Thus, radial tires generate measurable lateral force and self-aligning moment under straight rolling condition.

Ply steer side force is an inherent property of a belted radial tire which is the nonzero side force at zero slip angles.

PRAT (Plysteer Residual Aligning Torque) is defined as the level of tire aligning torque at the slip angle where the lateral force is zero. The phenomenon is governed by the structural parameters of both tire body and treads pattern as well as the frictional dynamics of rolling tire. Conventionally, tire PRAT is adjusted through the classical approach. In this approach, trial productions of tires by adjusting the construction and tread design parameters are too costly and time-consuming and there has been a demand for a new approach to address the above method.

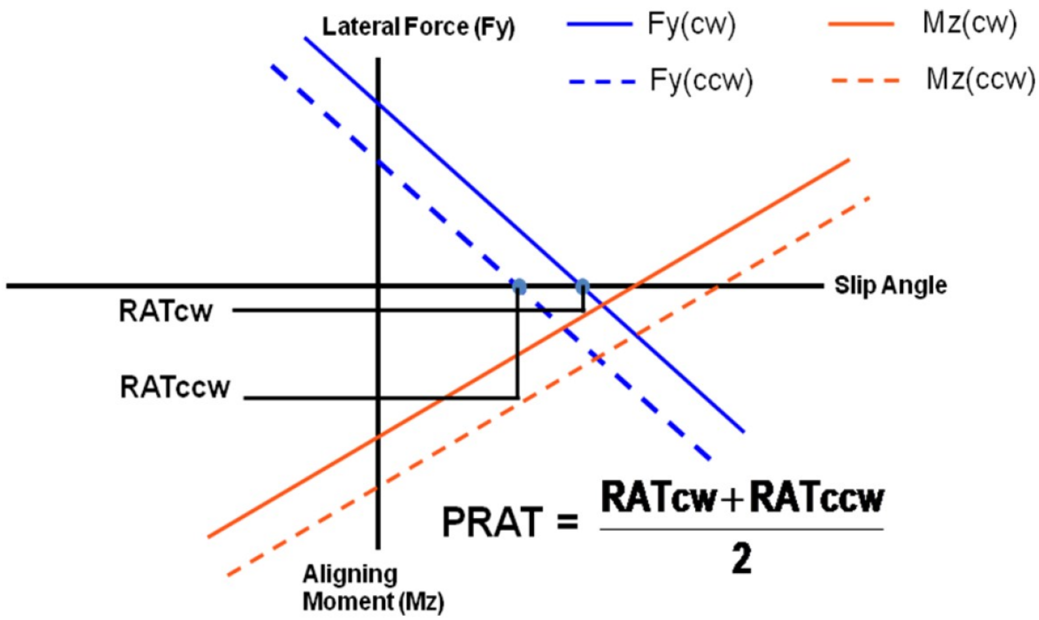

Figure 6.1: PRAT calculation using plots

The phenomenon of PRAT can be decomposed into two effects, first, the pattern effect and second, the body effect. The pattern effect is usually extracted by changing the signs of belt cord angle about a particular tread design. The pattern effect is can be calculated by below formula.

The pattern effect = (PRAT1 + PRAT2)/2

PRAT1: PRAT evaluated at Regular belt cord orientation

PRAT2: PRAT evaluated at Reverse belt cord orientation

PRAT can also be calculated using a mathematical formula which is mentioned later into this report.

6.1.2 Conicity

It is a parameter based on lateral force behavior. Describes the tire's tendency to roll like a cone. It is also called as pseudo-camber. Usually, it is introduced by the tire manufacturer to counteract road crown. CRAT is defined as the conicity residual aligning torque.

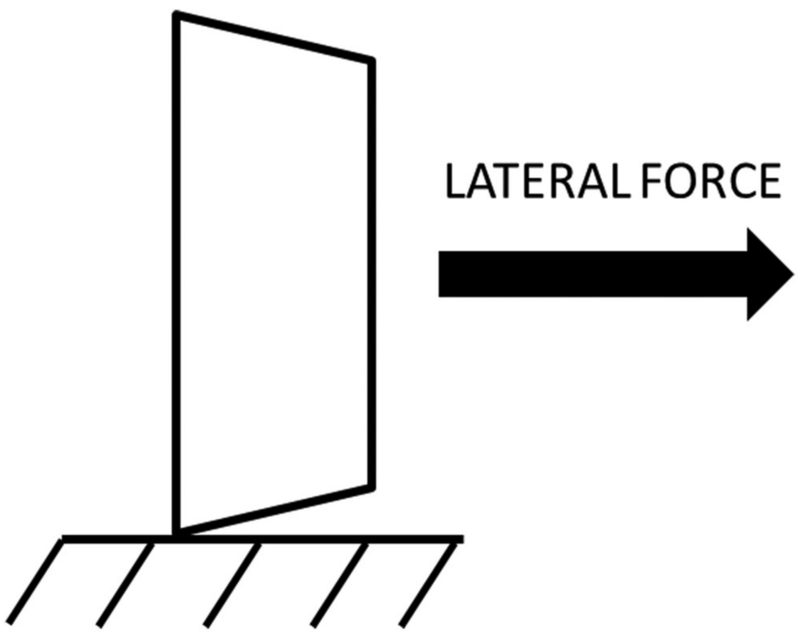

Figure 6.2: Conicity of tire

6.1.3 Cornering Stiffness

At a given tire load, the cornering force increases with a slip angle. At low slip angles values (less than 8°), this relationship is linear, hence, the cornering force is defined as:

$$F_y = C_\alpha.\alpha$$

The proportionality constant C_α is known as the cornering stiffness and is defined as the slope of the curve for F_y versus α at $\alpha = 0$. A positive slip angle produces a negative force (to the left) on the tire, implying that C_α must be negative; however, SAE defines cornering stiffness as the negative of the slope, such that C_α takes on a positive value.[19]

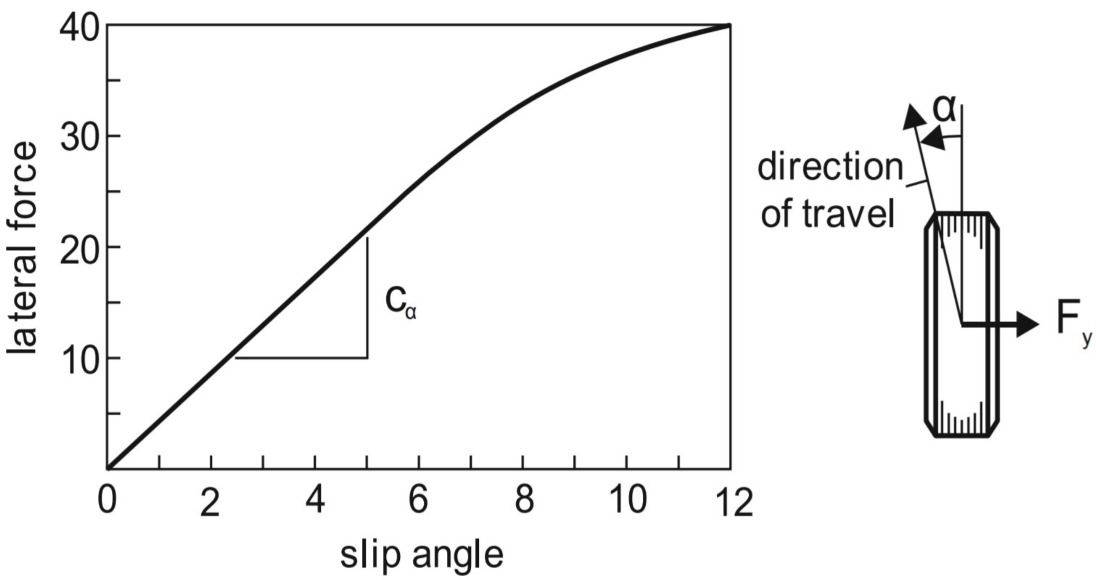

Figure 6.3: Cornering Stiffness

The cornering stiffness depends on many variables like tire size and type (radial or bias ply construction), number of plies, cord angles, tire width and tread are significant factors. For a given tire, the load and inflation pressure are the main factors affecting the cornering stiffness.

6.1.4 Aligning Stiffness

Aligning moment is a similar phenomenon to cornering stiffness and is defined as:

$$M_z = A_\alpha . \alpha$$

The proportionality constant A_α known as the aligning stiffness and is defined as the slope of the curve for M_z versus at SA $= 0$. SAE defines aligning stiffness as the negative of the slope, such that A_α takes on a positive value.

6.2 Plots and Discussion

6.2.1 Pacejka Fitted Curves

After the curve fitting the raw data with Pacejka equation, resulting plots like F_y vs SA and M_z vs SA for all loads, for the Altimax 89 (205/55 R16 091T) look as follows. Tire pressure was kept at 34 psi (2.34 bar) throughout the test. Tire engineers can then estimate performance of their tires and tweak the design if needed. These plots along with many other parameters mentioned in the report later can be included in the tire test report.

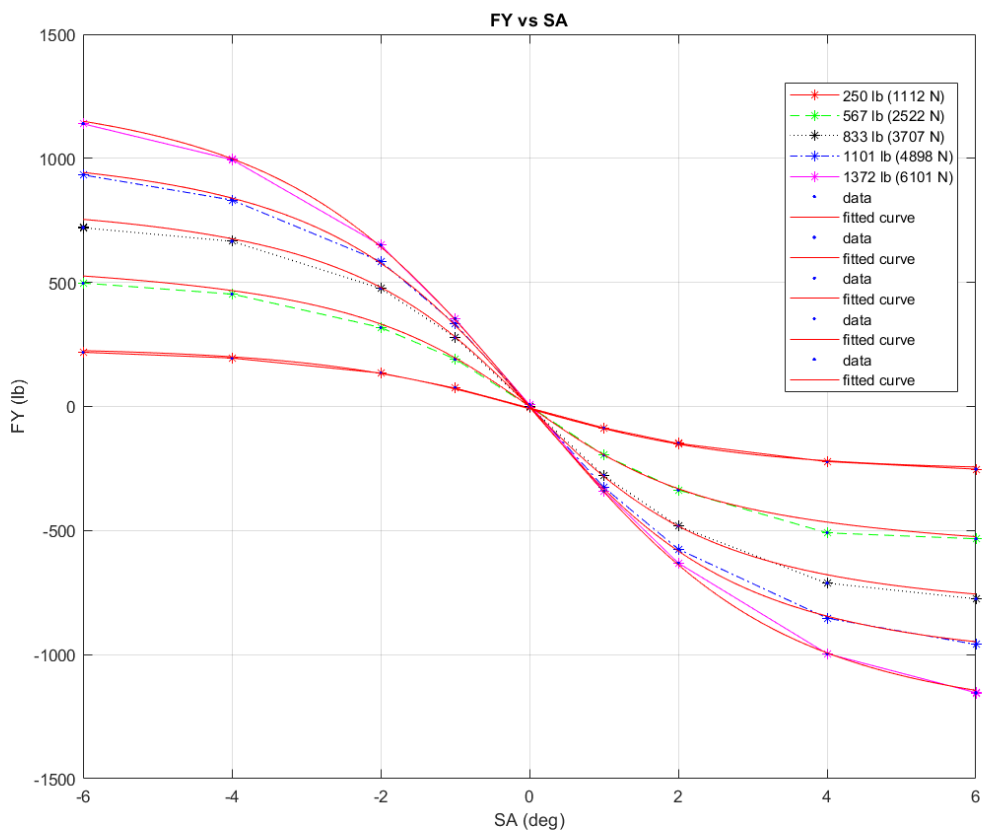

Figure 6.4: F_y vs SA for all vertical loads

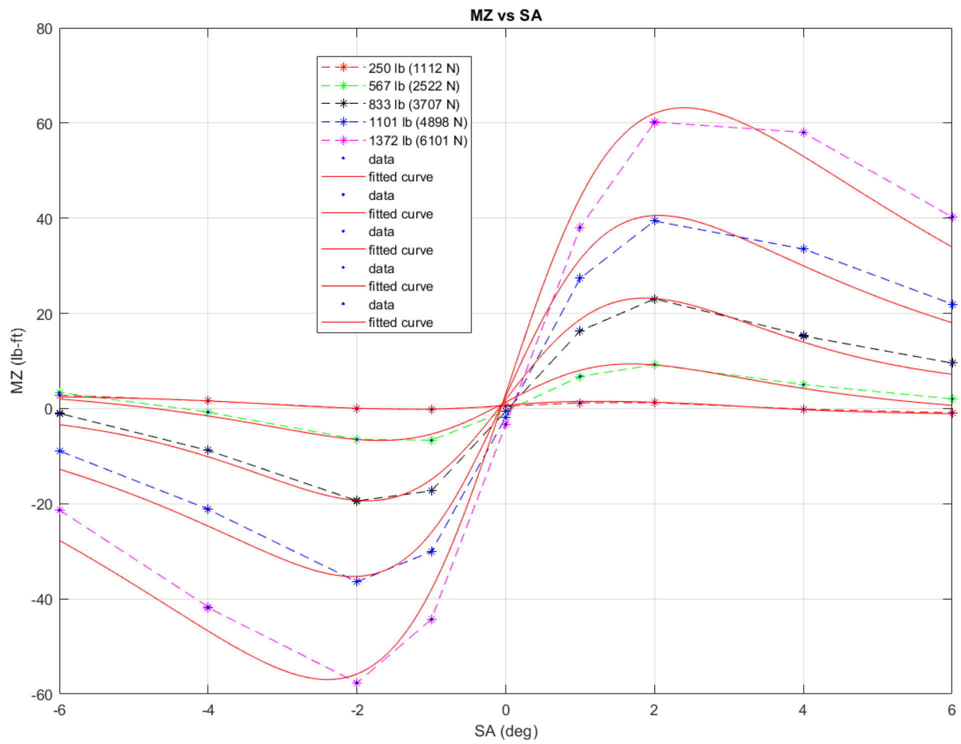

Figure 6.5: M_z vs SA for all vertical loads

Following formulae are used throughout this research. However, the data obtained is in lb and lb-ft. SAE prescribes the data to be in N and N-m. Required conversion is done every time.

$$Conicity(N) = (FY_{OF} + FY_{OR})/2$$

$$Plysteer(N) = (FY_{OF} - FY_{OR})/2$$

$$CRAT(N-m) = (MZ_{OF} + MZ_{OR})/2$$

$$PRAT(N-m) = (MZ_{OF} - MZ_{OR})/2$$

$$Cornering\ Stiffness(N/deg) = (FY_1 - FY_{-1})/2$$

$$Aligning\ Stiffness(N-m/deg) = (MZ_1 - MZ_{-1})/2$$

FY_{0F} = Lateral force at 0° slip angle with forward velocity

FY_{0R} = Lateral force at 0° slip angle with reverse velocity

MZ_{0F} = Aligning moment at 0° slip angle with forward velocity

MZ_{0R} = Aligning moment at 0° slip angle with reverse velocity

FY_1 = Lateral force at 1° slip angle

FY_{-1} = Lateral force at −1° slip angle

6.2.2 Comparison of the Altimax Data

Altimax 89 (205/55 R16 091T) is ran on the M-15 and the data generated is compared with the data provided by the company. Resulting plots are given below.

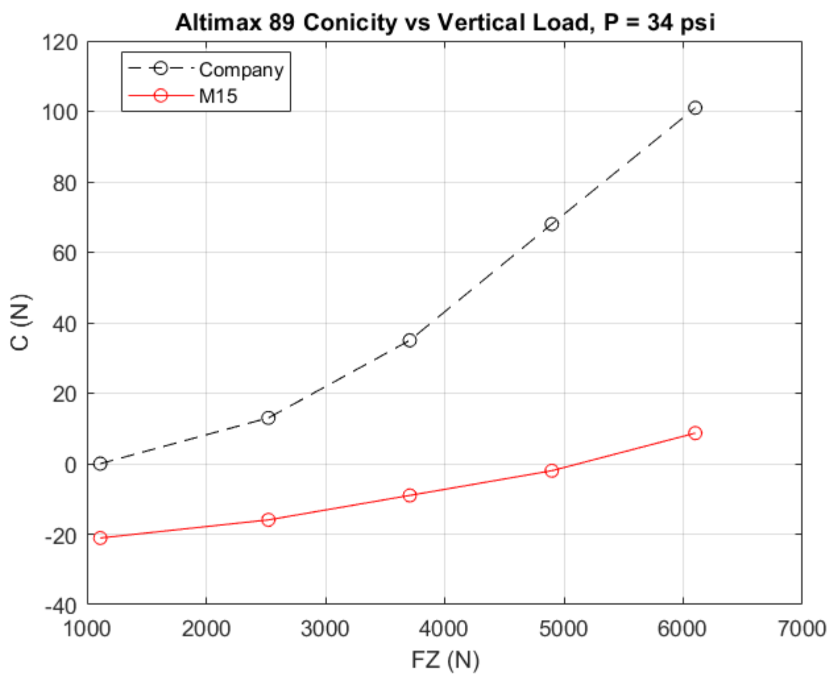

Figure 6.6: Conicity vs vertical load (Altimax 89)

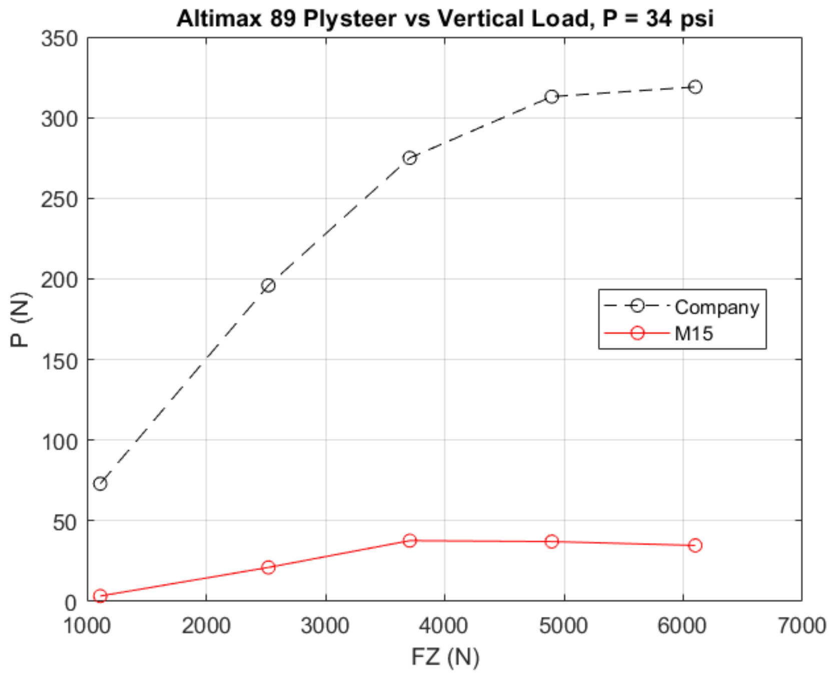

Figure 6.7: Ply Steer vs vertical load (Altimax 89)

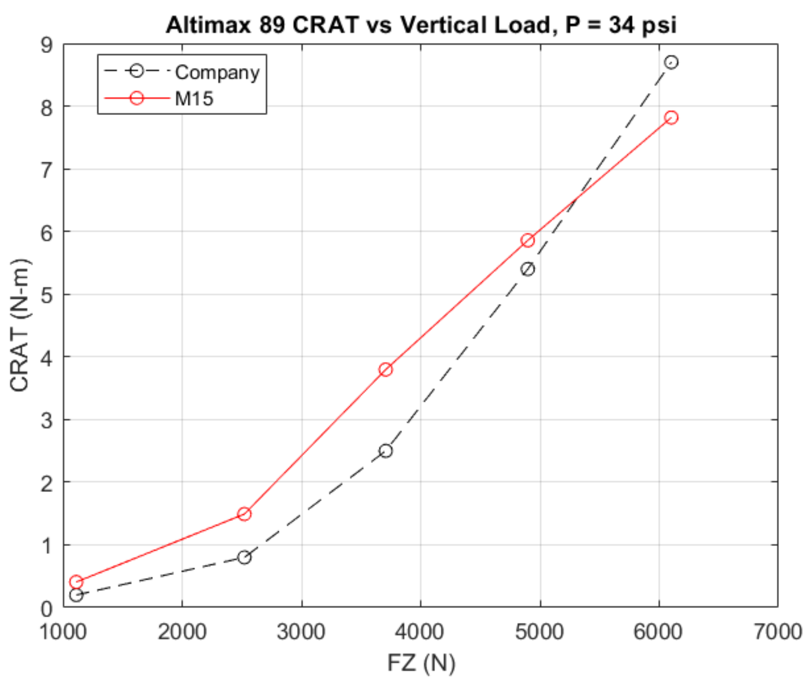

Figure 6.8: CRAT vs vertical load (Altimax 89)

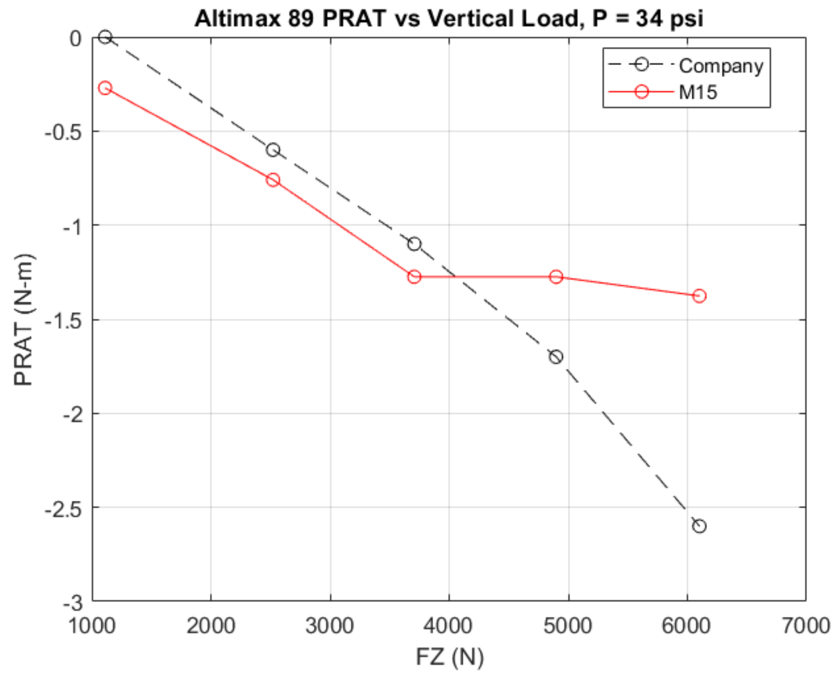

Figure 6.9: PRAT vs vertical load (Altimax 89)

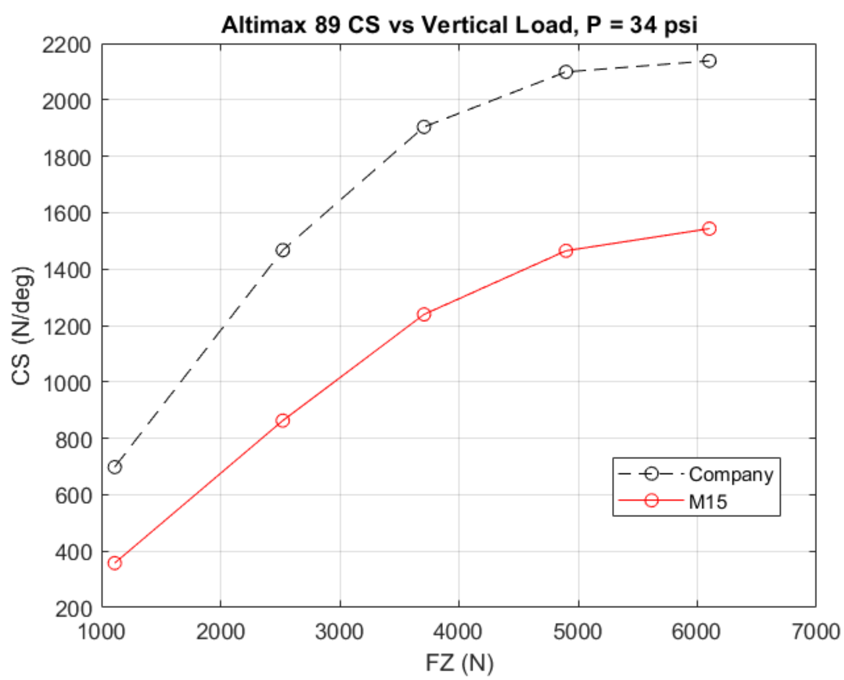

Figure 6.10: Cornering Stiffness vs vertical load (Altimax 89)

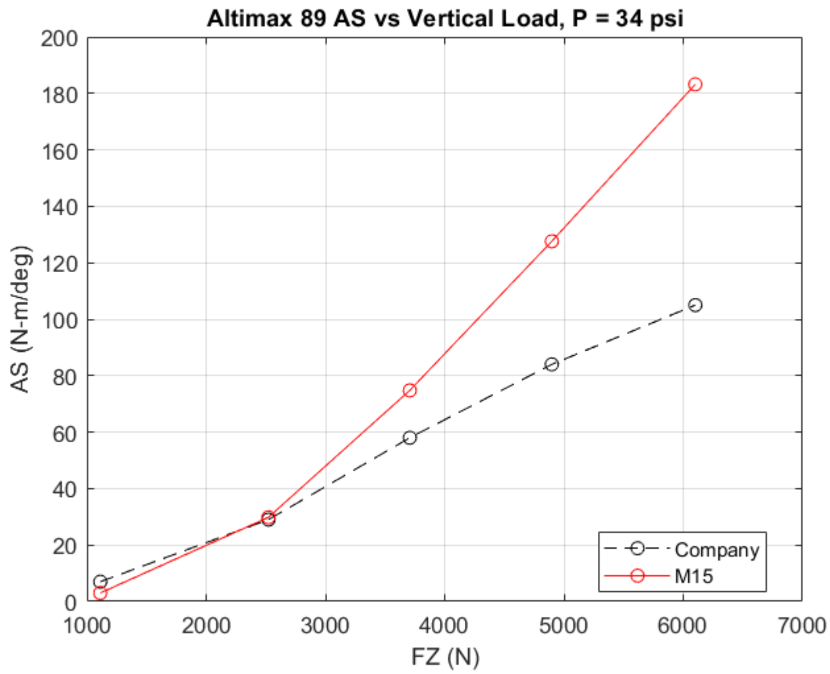

Figure 6.11: Aligning Stiffness vs vertical load (Altimax 89)

It is evident from the graphs that, the M-15 data gives significantly low numbers than the company data. This is due to different test conditions for both the test conducted. These parameters are discussed below.

A major determinant of loaded tire's forces and moments is the shape of road surface. Tire's response varies significantly when it is subjected to concave or convex surfaces other then flat surface, especially the convex surface. Significance of this influence depends on the curvature of the road wheel. The relative motion between tire and roadway is a function of frictional coefficient, hence material of both tire and roadway affect the tire data. Inflation pressure affects the performance of tires. Physical properties of rubber vary with temperature.[20] Hence, elastic properties are expected to vary.

6.2.3 Bridgestone's Tire Data

To check if the road surface makes difference in the test data, two tests were compared, with sand paper surface and with steel surface. The resulting plots are as follows. It can be concurred that, the road surface makes a significant difference in conicity and PRAT.

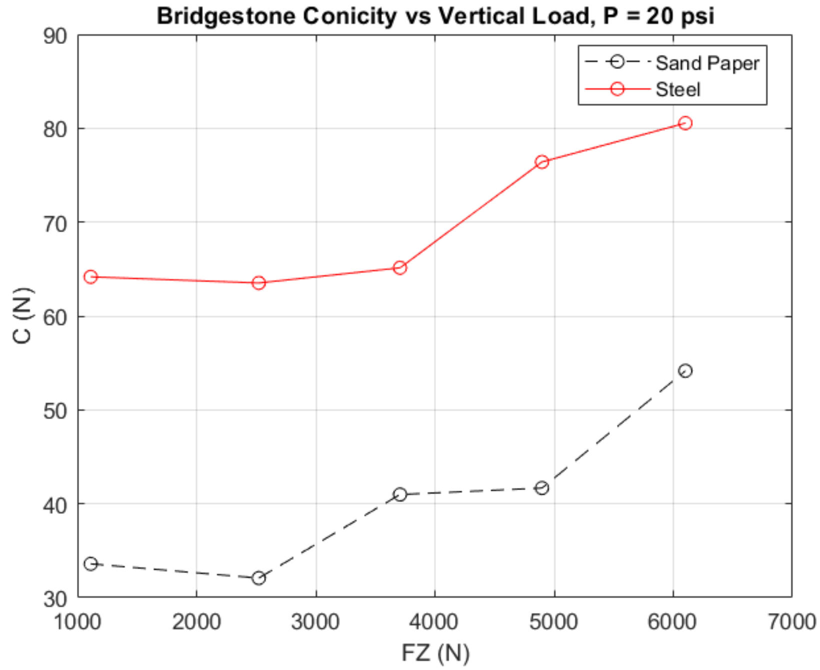

Figure 6.12: Conicity (Sand paper vs Steel)

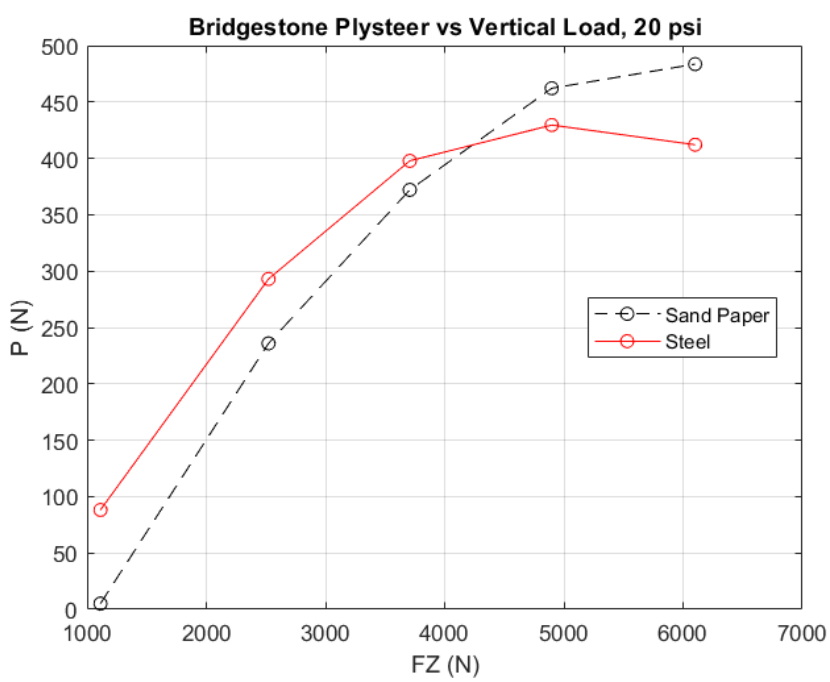

Figure 6.13: Ply Steer (Sand paper vs Steel)

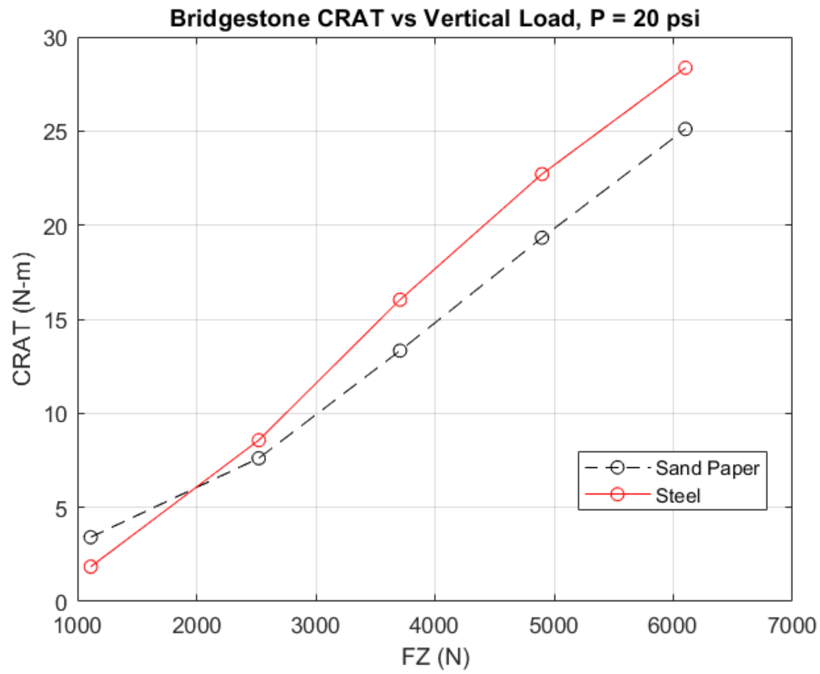

Figure 6.14: CRAT (Sand paper vs Steel)

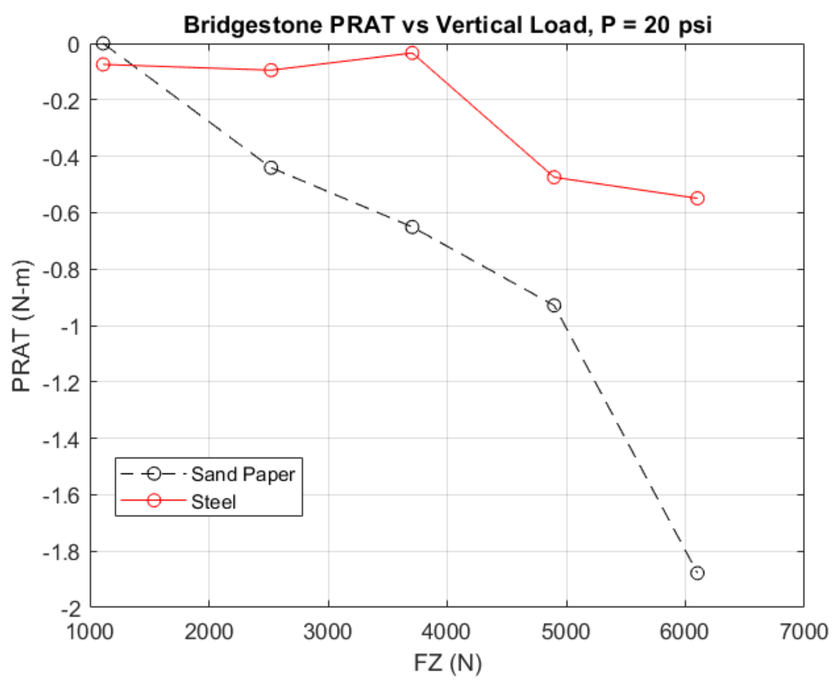

Figure 6.15: PRAT (Sand paper vs Steel)

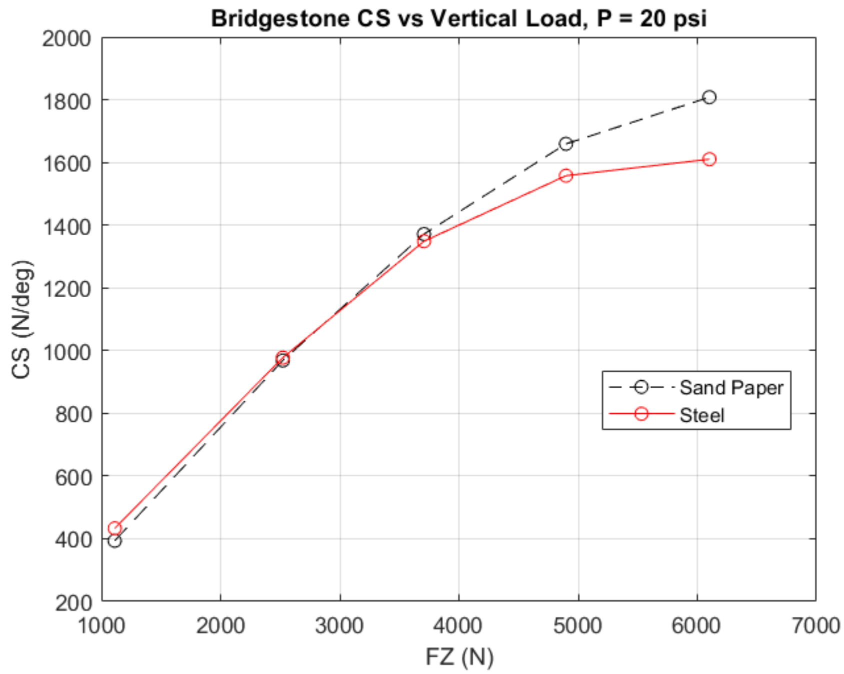

Figure 6.16: Cornering Stiffness (Sand paper vs Steel)

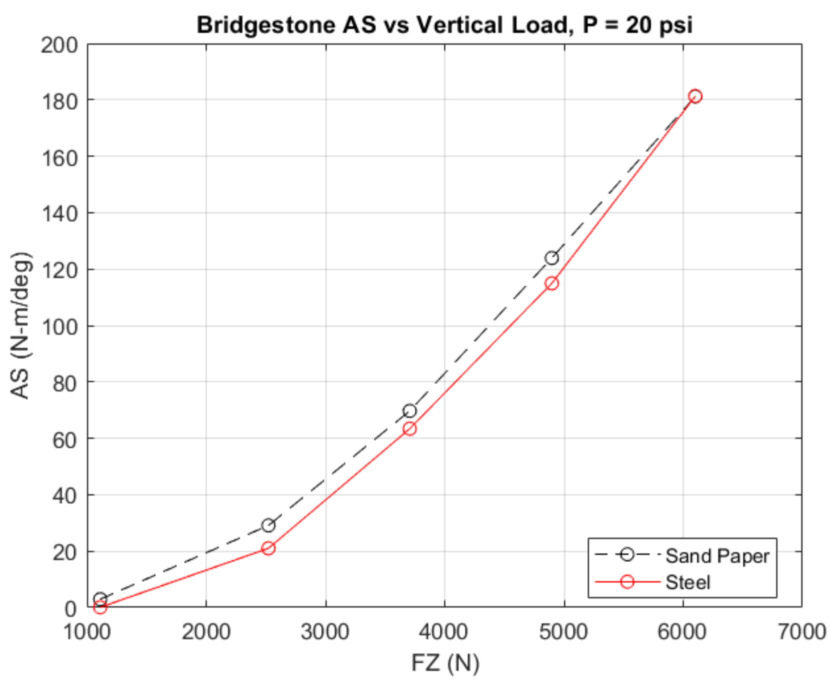

Figure 6.17: Aligning Stiffness (Sand paper vs Steel)

6.2.4 Comparison of different Altimax tires

Due to differences between company data and the M-15 data, multiple tests were conducted on different Altimax tires with different load ratings to see if the trend of anomalies continues. Except conicity, the trend continues with all parameters.

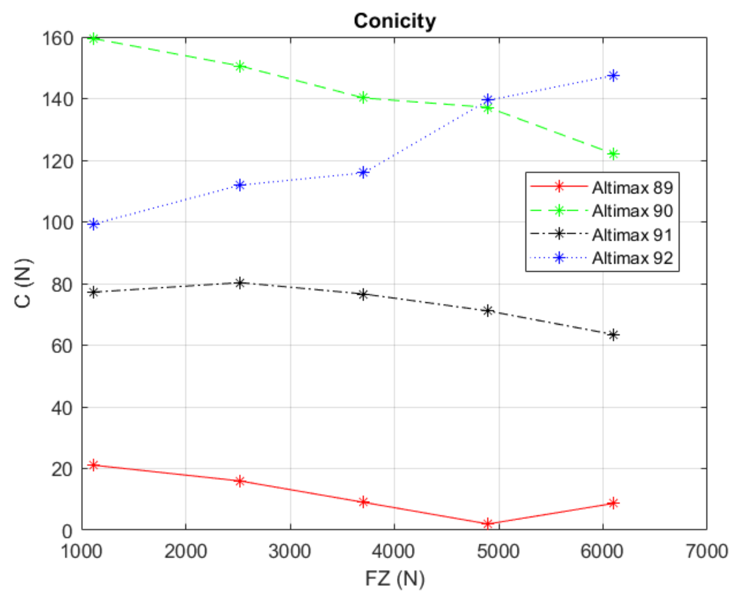

Figure 6.18: Conicity for all Altimax tires

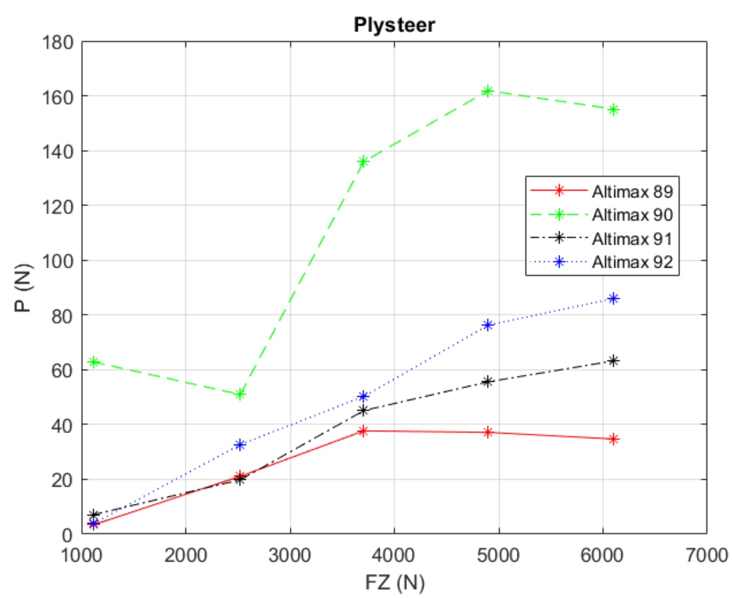

Figure 6.19: Ply Steer for all Altimax tires

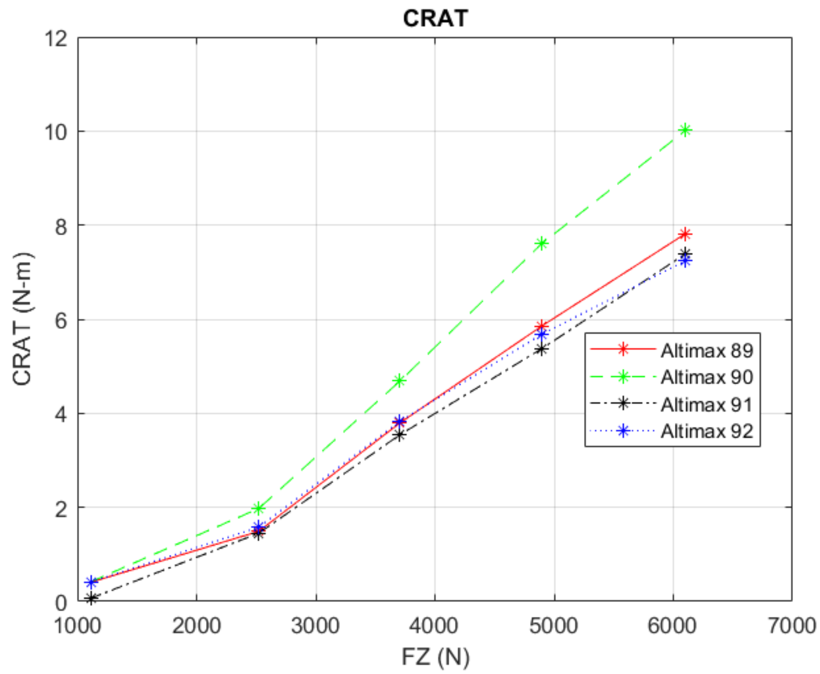

Figure 6.20: CRAT for all Altimax tires

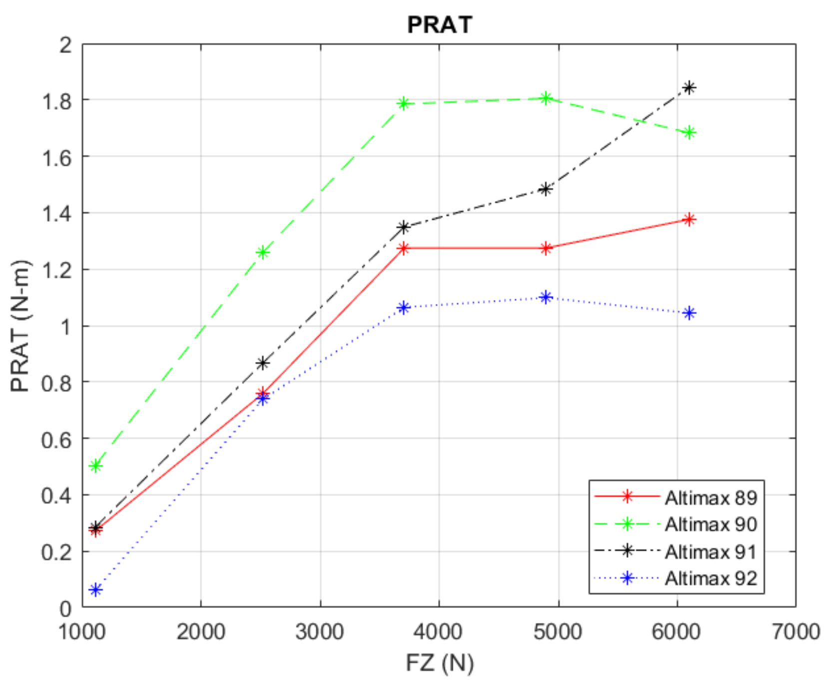

Figure 6.21: PRAT for all Altimax tires

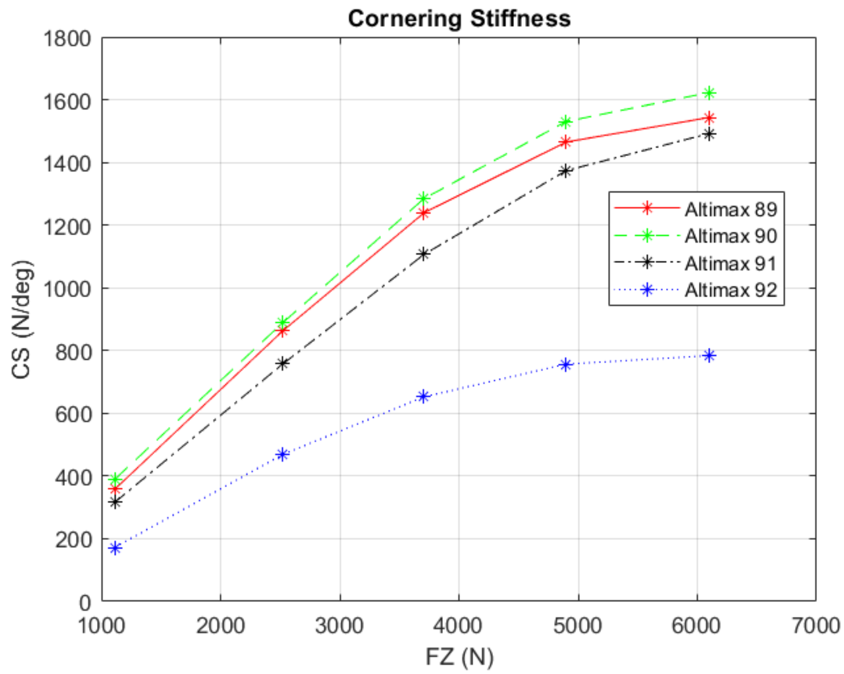

Figure 6.22: Cornering Stiffness for all Altimax tires

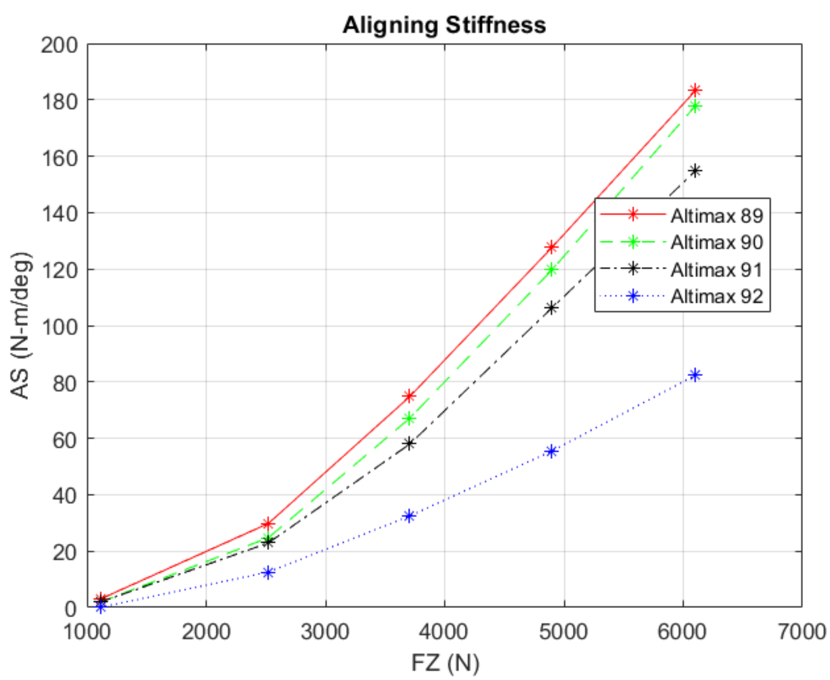

Figure 6.23: Aligning Stiffness for all Altimax tires

6.3 Test for Repeatability

For any test machine, repeatability is an important aspect, as it decides the reliability of the test protocol and the machine itself. Five tests were run on Altimax 89 (205/55 R16 091T).

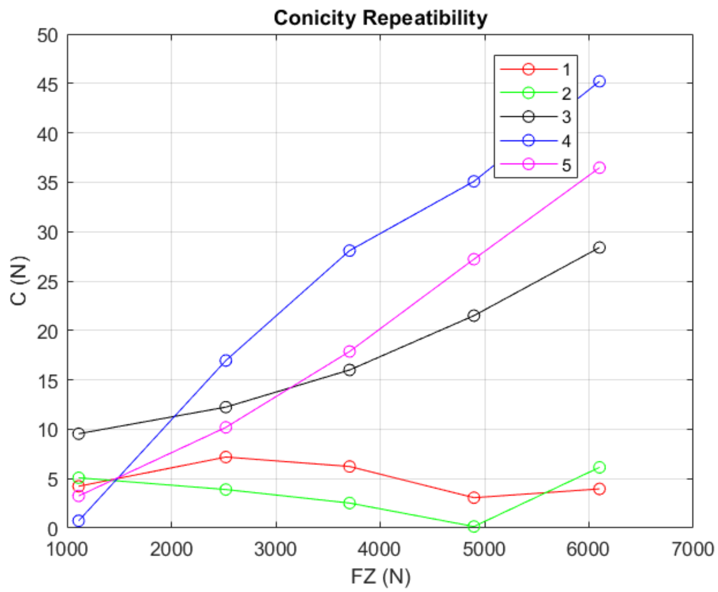

Figure 6.24: Conicity Repeatability for Altimax 89

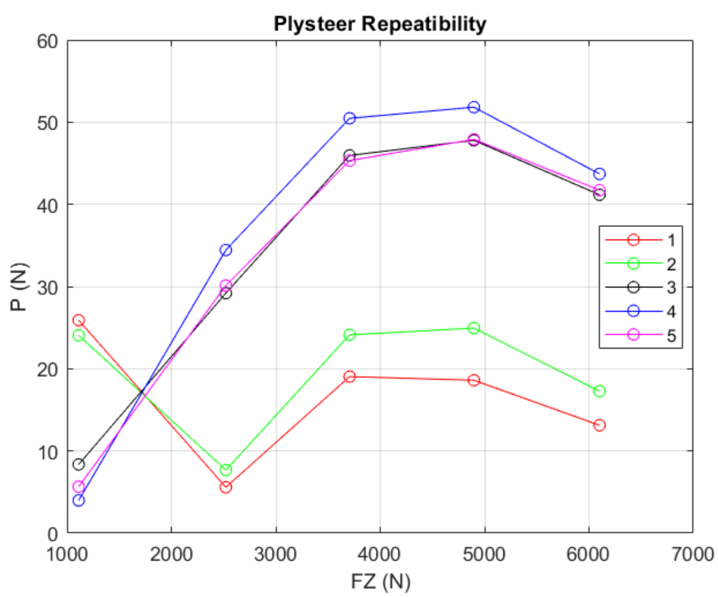

Figure 6.25: Ply Steer Repeatability for Altimax 89

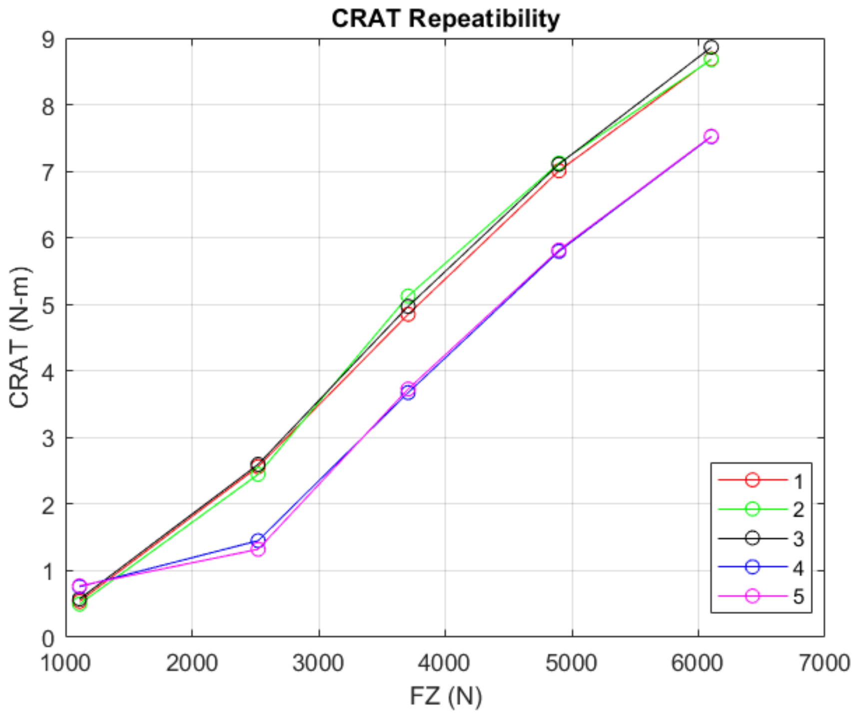

Figure 6.26: CRAT Repeatability for Altimax 89

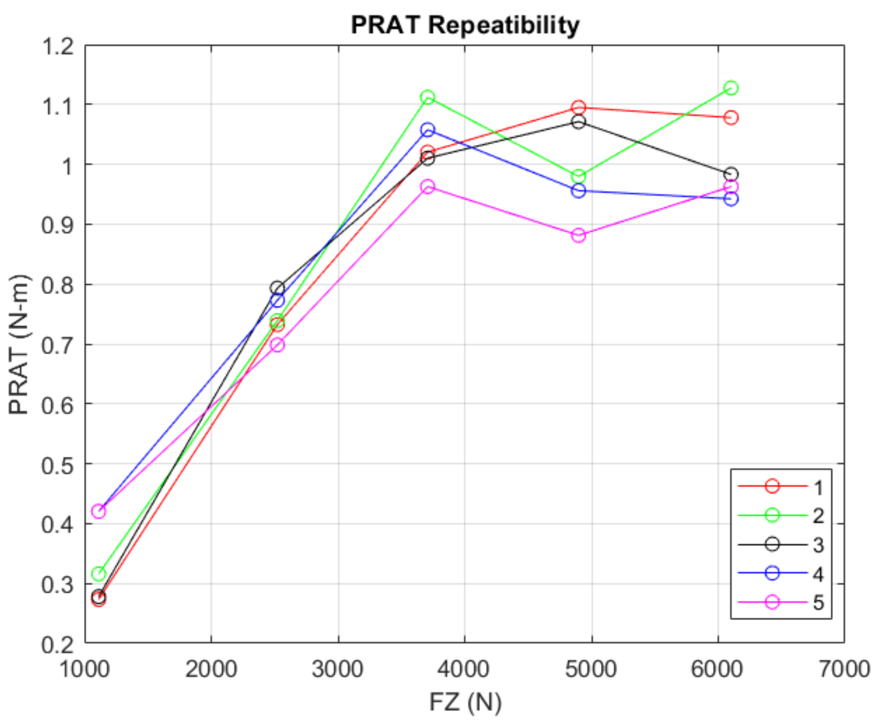

Figure 6.27: PRAT Repeatability for Altimax 89

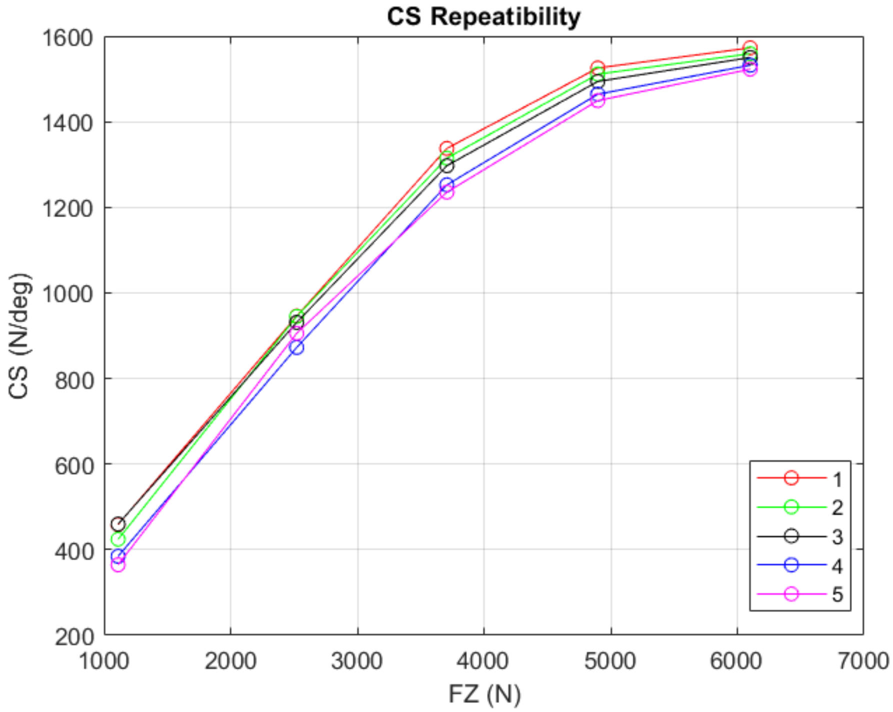

Figure 6.28: Cornering Stiffness Repeatability for Altimax 89

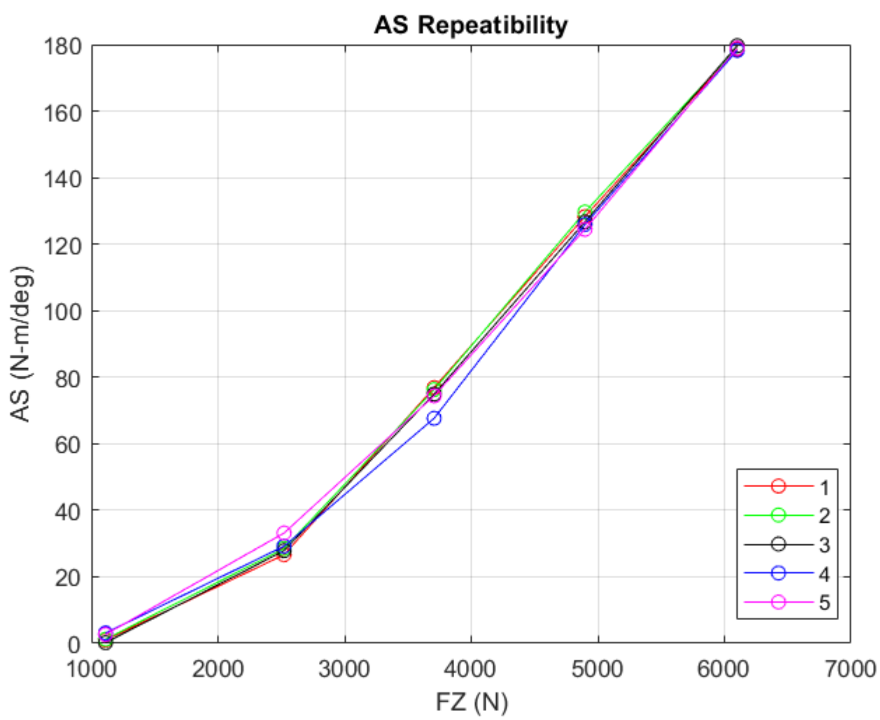

Figure 6.29: Aligning Stiffness Repeatability for Altimax 89

It is evident from plots that, values for conicity and plysteer for first two tests do not match with remaining tests. Reasons are different linear actuator speeds as tests were run on different days. Test conditions were not same on these days. However, these effects wear out for CRAT and PRAT and eventually cornering stiffness and aligning stiffness are identical.

CHAPTER 7: CONCLUSIONS

It can be established from Bridgestone's tire data on steel and sand paper (ran on the M-15) that, tire behavior changes significantly with the road surface material. Tire inflation pressures are unknown for the Altimax's data, it could be a major factor affecting tire curves. As mentioned before, shape of the tire contact patch, shape of road wheel, temperature, humidity, etcetera can all contribute to anomalies in data. Data anomalies is a trend with all Altimax tires which is backed with experimental proof from multiple tire tests. The tests ran on the M-15 are fairly repeatable as cornering and aligning stiffness are identical for all tests. With a MATLAB program developed and the Report Generator tool, the M-15 can provide tire engineers the required F&M data and various tire parameters like conicity, plysteer, etcetera in a 'quick to read' format.

7.1 Future Scope

By installing the entire tire data modelling and report generator setup on the M-15 computer, which is connected to PLC and has LabVIEW installed, test operator will be able to generate all files on the same machine. Full automation is to be expected in near future with the already installed automatic steer control. Modification and optimization of LabVIEW and MATLAB programs is however needed for the same.

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