STUDY OF SOURCES OF VARIABILITY IN TIRE FORCE AND MOMENT TESTING

by

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ABSTRACT

AJINKYA KHARE. Study of Sources of Variability in Tire Force and Moment Testing. (Under the Direction of DR. PETER T. TKACIK)

Tire Force and Moment Testing is the most important aspect of data-driven tire modeling and characterization. Conventionally, huge tire force and moment testing machines are being used for testing and more recently advanced technologies such as wheel force transducers are gaining popularity. The ability of on-track testing to replicate the actual operating conditions of the tire is a great advantage over indoor testing. Even though, on-track testing seems promising, controlling numerous environmental factors to get repeatable and reliable data is a great challenge for on-track testing. Considering the high cost and lack of reliability in the data, the inclination of tire the manufacturers and OEMs towards indoor testing can be justified. Though indoor testing provides more reliable data, it is very crucial to identify and keep track of the factors responsible for causing variability in the data and these factors are highly dependent on the capabilities of the machine and service provider. This study focuses on identifying the sources of variability in the data and methods to either eliminate or compensate for the variability. The document also illustrates the potential effect of calibration and data acquisition on the variability. This study describes findings from the tests conducted on 10 tires (from two manufacturers), under testing conditions designed to induce variability in the data in order to address the above-mentioned aspects and estimate the contribution of each factor in total variability.

DEDICATION

“Dream is not what you see in sleep. It is the thing that doesn’t let you sleep.”
- Dr. A. P. J. Abdul Kalam

“I couldn’t find the sports car of my dreams, so I built it myself.”
- Ferdinand Porsche

“I build engines and attach wheels to them”
- Enzo Ferrari

I would like to dedicate this to my parents and grandparents, and I am truly grateful to them for their unyielding support. Also, this work is for every single mechanical engineer who still believes in blocks.

ACKNOWLEDGMENT

I would like to acknowledge my thesis advisor Dr. Peter Tkacik for letting me explore the research opportunities in the tire testing and supporting me to throughout the thesis and allowing me to use his Mini Cooper while testing the wheel force transducer and M-15 for this study presented here. I really appreciate the time and work he has put in this study helping me out to solve problems and documenting the calibration protocols with minute details of the process. I am also grateful to Dr. Charles Jenckes for suggesting this topic, his guidance, and his valuable technical insights. I am thankful to Yokohama Rubber Company for providing the tires and Continental AG for the flat track data of the Altimax tires. I would also like to thank fellow PhD student Amin for helping me in tire testing, calibration of the machine, and Mr. Franklin Green for helping me with the LabView programs. Further, I would like to thank UNC Charlotte and Motorsports Research for this opportunity to conduct research in the field I am passionate about.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

SAE: Society of Automotive Engineers

SA: Slip Angle

CS: Cornering Stiffness

AS: Aligning Stiffness

PLF: Plysteer Lateral Force (Plysteer)

CLF: Conicity Lateral Force (Conicity)

CRAT: Conicity Residual Aiming Torque

PRAT: Plysteer Residual Aligning Torque

F_z: Normal Load

M_z: Aligning Moment

F_y: Lateral Force

γ: Inclination angle

α: Level of Significance

CHAPTER 1: INTRODUCTION

1.1 M-15 Tire Testing Machine

The Cornering Force and Moment Tire Test Machine at the university's Motorsports Research lab was donated by Michelin Research USA in 2015. The machine was manufactured at Clermont, France in 1973 and was in service at Michelin's research facility at Greenville, USA. The road wheel machine was reconstructed and put into service by Dr. Peter Tkacik at the university. Currently, it is controlled by modern electronics and uses modern data acquisition module to collect the data. Following tables show the specifications of the force and moment testing machine.

Table 1: M-15 Specifications

Road Wheel Diameter	2.7 m
Normal Load Capacity	4150 lb. (1880 kg)
Slip Angle	± 15 degrees
Maximum speed	67.3 mph (107.8 kph)

Table 2: Drive system specifications

Gearbox Reduction	4.73
Timing Belt Reduction	5

The maximum speed is limited by two factors. One is maximum RPM that the timing pulley on the road wheel can sustain (650 RPM) and the other is the maximum RPM of the motor (5000 RPM). In this case, the limiting factor is motor RPM and the road wheel speed is calculated accordingly. Currently, the machine has the ability to go through the automated sequence of normal loads at a fixed slip angle and acquire data.

Work is in progress to automate the slip angle as well. Automation of slip and load would provide the ability to construct fully automated test modules either according to SAE protocols or depending on the requirements for the research study. This would eliminate the possibility of manual errors and provide more repeatable and reliable data. The tire tests in the presented study are conducted with manual control of the slip angle.

1.2 Purpose of the study

The validity and reliability of any experimental result is the matter of credibility of the experimental data. For any experiment or well documented and well-practiced tests on tires, the results are countable only if the tire data acquired is dependable. Tires are the most complex and unpredictable yet the most important components of every road or track vehicle. At 200 mph on the track, the stability of the vehicle and safety of the driver depends solely on the four contact patches approximately 210 × 280 mm (8.5” × 11”) in size. The importance of having accurate tire analysis and consequently the importance of accurate tire data could not be stressed enough. Tires are susceptible to change due to various factors whose exact nature might be unknown. This can induce variability in the tire data which might not be practical and affordable to control or compensate, but there are some factors those can be controlled easily with proper knowledge and experimental study. Hence it is crucial to have knowledge about the potential sources of variability for the given testing facility in order to either control the source of variability or compensate it in the final data.

Every tire manufacturer or the testing facility across the globe has a history of the control tire as well as every tire which has been tested on the machine. This generates a huge pool of data over the period, which can be used to detect any considerable change in the data and keep track of the calibration of the machine. Further, most of the testing facilities have precisely controlled environments that reduce the possibility of the effect of any unwanted environmental factor either on machine components or on the tires themselves.

As the force and moment machine at the university is recently installed and put into operation and as it is not a commercial testing facility it is not possible to already have history of the data for the reference. Also, even though the motorsport research building is temperature-controlled, due to continuous activities in the building, the environment is subject to change which could have an effect on the machine and result in increased variability in the data. Hence it is very important to have knowledge of possible variability sources and repeatability of the machine. Depending on the analysis it is possible to set protocols for the testing and predict compensations for the uncontrollable factors. This study aims at designing the experiments and collecting data for multiple testing conditions and analyzing it to detect sources of variability and predicting the solution accordingly. It also aims at producing the data set for reference and future use.

1.3 Experimental Approach

As the goal of this study is to determine the repeatability of the machine and estimate variability and corresponding factor responsible for it, having experimental data with properly designed operating conditions is the key element. Statistical analysis is involved in this study and hence it is equally important to have enough amount of data for the accurate results of statistical analysis. Another important aspect was to have tires with the test data from the manufacturer which can be put as a reference. The research lab at the university has 10 tires from two different manufacturers. Following Table 3 shows the details of the tires used for this study.

Table 3: Tire Specifications

Make	**Quantity**	**Size**
Continental	6	P205/55R16
Michelin	4	P245/40ZR18

As mentioned earlier, for statistical analysis, a large amount of data is required and consequently, the tires had to be tested multiple times thought the same loading cycles which range from 20% to 100% of the rated load. Testing tires through these high load conditions at high slip angles would cause tires to wear out very quickly giving rise to an additional source of variability due to tread wear and permanent changes in the tire materials which means tires could not be tested any further after a couple of tests. Hence to generate a sufficient amount of data without considerably damaging the tires, low slip angle tests were selected for the study. Also, Continental provided test data of their tires which contains parameters such as Aligning and Cornering Stiffness, Plysteer, Conicity, and residual torques corresponding to tire pull phenomena (CRAT & PRAT). As mentioned earlier the manufacturer data will be used for comparing and validating the M-15 data, tests according to SAE J1988 were selected. Analysis of the data will be done according to the mentioned protocol to estimate the tire pull and stiffness parameters for every test. Adapting the low slip angle test not only reduced the tire wear but considerably reduced the time required for one test on the tire. This allowed acquiring more data in a comparatively lesser amount of time.

Now, another aspect to be considered here is making rims to mount the tires. Standard rims used on the road vehicles could not be mounted directly on the machine due to different hub, bolt pattern, and offset. Rim was available for the Continental tires, but the rim for the Michelin tires was to be manufactured. The feasible solution was to make a modular rim out of the three-piece rim, which can be used for other tire sizes as well. If the section width of 245 mm is considered, the ideal rim widths are 8” and 8.5”. Accordingly, a rim center to fit the machine hub was designed. Following Table 4 shows the rim halves selected.

Table 4: Rim Half Specification

Diameter	**Outer half**	**Inner half**	**Flange thickness**
18”	2.5”	6”	5.5 mm

The rim center(spider) was designed so that it can fit the hub dimension as mentioned below.

Table 5: Rim Center Specifications

Bore Diameter	**Bolt Pattern**	**Offset**
155 mm	M18×205×6	70 mm

The 70 mm of offset mentioned in the above Table 5 should be the final offset on the assembled rim. The offset is the distance between the point where the hub is pivoted on the ball joint and the point where the load cells are located. If the offset on the rim is matched with the offset on the machine, the tire can also be considered to be pivoted at the same point as the machine hub and the forces recorded by the load cells will be the forces acting on the tire itself. If the offset is not maintained correctly some transformations are required to derive the actual forces on the tire. To simplify the data analysis the offset on the rim is kept 70 mm. Getting the offset right was crucial in the design of the center. It can be easily imagined that there will be some offset already present due to two unequal rim halves and the center should have the offset such that when these three parts are assembled, the resultant offset is 70 mm. The simple mathematics gives the offset required on the rime centerpiece or spider. The figure below shows a sectional view of the three-piece rim assembly which helps to understand calculations clearly.

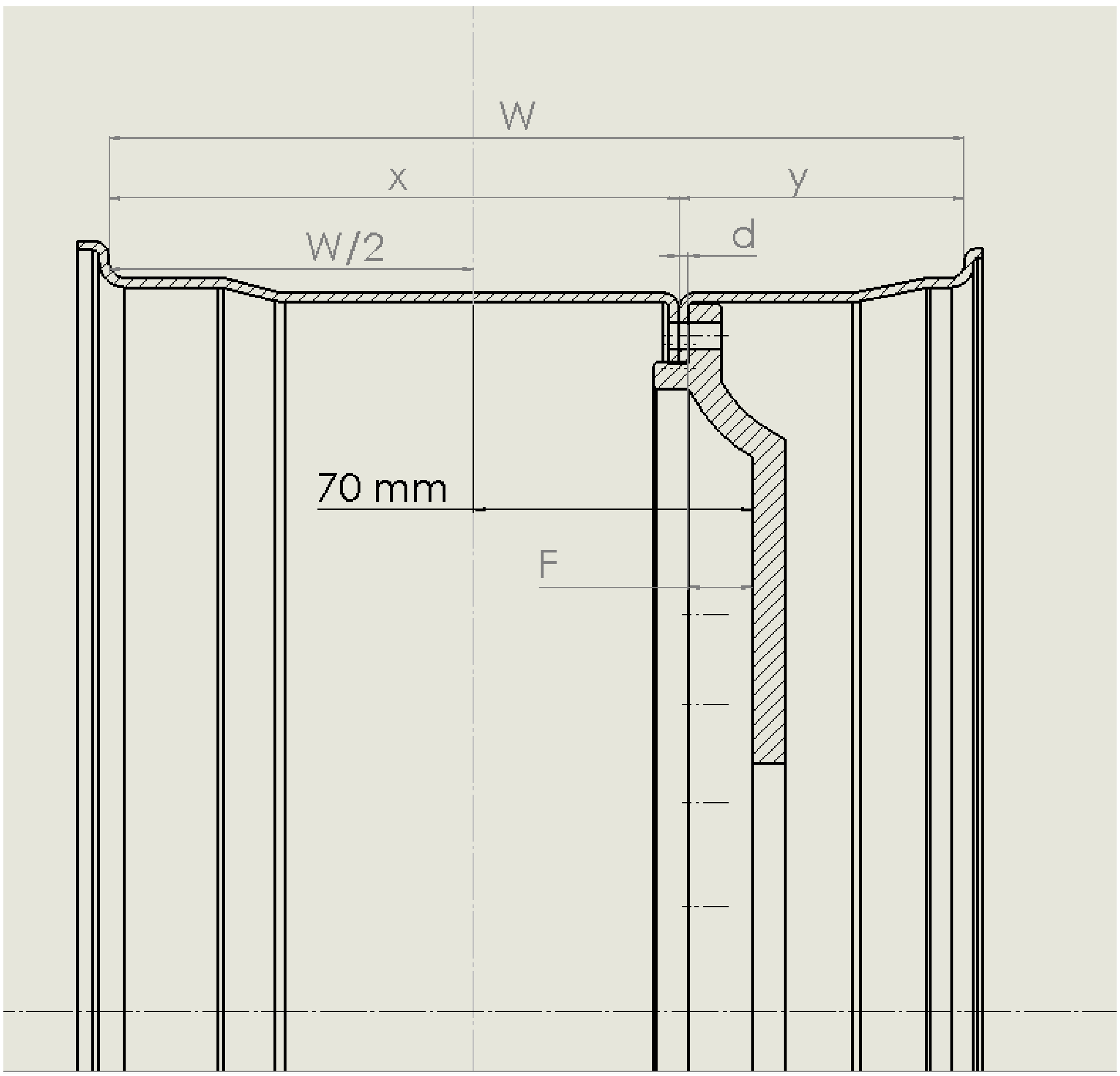

Figure 1: Calculation of offset on spider

W: Total Rim width

x: Inner half's width

y: Outer half's width

F: Offset on the spider

d: Outer half's flange thickness

Before going through the calculation, it is to be made clear that the offset on the spider is the distance between the face where rim rests on the M-15's hub and the face of the spider where it attaches to the rim halves. In the above drawing 'F' is the parameter that has to be calculated and incorporated in the design. From observation, the following equation for 'F' can easily be derived.

$$F = 70 - \left[\frac{W}{2} - (y) + (d)\right]\ mm$$

Note: Keep all the dimensions in either millimeters or inches.

According to the rim halves selected for the Michelin tires, the offset on the spider comes out to be 20.05 mm. The CAD of the spider designed with this offset is shown below.

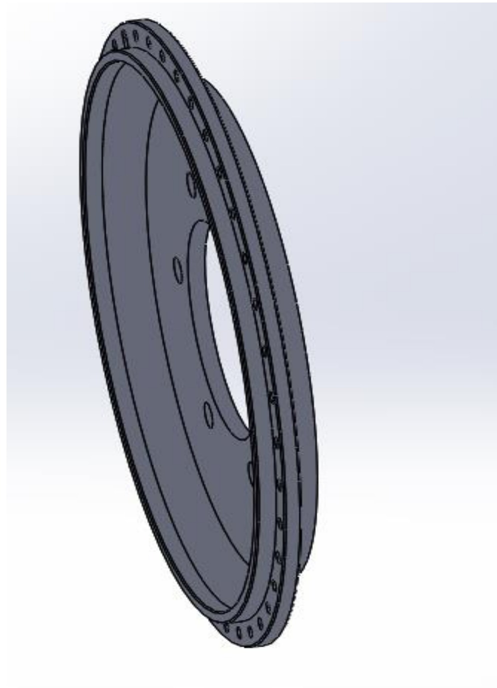

Figure 2: Spider for the Michelin Tire

This part was manufactured from the aluminum and clamped to the rim halves with 40 M8 bolts. An important aspect of the assembly of the rim halves is to maintain the run out on the rim to the minimal possible value. Having a larger runout can cause the normal load on the tire to fluctuate depending on the amount of runout, which causes a change in lateral force and aligning moment as well, and this could result in higher variability in the data. The effect of runout is analyzed further in the study. During the tests conducted on each tire, the distance through which each tire has been tested is recorded to generate the log of tire testing. The LabView program displays the cycle time after every test is finished. So, the time for which tire is being worked is available easily. In the further sections, the working of the program is explained in detail and it can be noted that, once the program gathers data through all specified loads, the operator manually needs to unload the tire and prepare it for the next test. Even though the loading cycle is finished, during unloading, the tire is going through continuously decreasing load and that unloading time is not recorded in the program. To be precise, this unloading time can also affect the tire even though very slightly, it is important to record this time as well, to get the exact distance tire has been on the machine. Unloading time for Continental and Michelin tires are noted manually and are 19 sec and 20 sec respectively. Unloading time is added to cycle time to calculate the distance traveled in one test.

CHAPTER 2: GENERATION OF TEST MATRIX

Referring to Table 3, there are 5 continental and 4 Michelin high-performance tires along with a control tire from Continental available for this study. Michelin tires are run for at most 5 miles before the university acquired them and the Continental tires are not tested or run on the car at all. Hence the tires are considered to be new and there have not been any scrubbing done previously except whatever loads would have been applied on the Michelin tires for 5 miles. Tires are very sensitive to numerous factors and for designing the experiments for such a huge array of the factors and possible levels of each factor, having a well-defined test matrix plays an important role. For the experimental design, potential factors for tire testing could be slip angle, normal load, pressure, camber, temperature, speed but this array considerably reduced and boiled down to few testing conditions due to two reasons. First, the effects of the above-specified factors have been well researched and documented and secondly, as SAE specifies the protocol for testing tires to study tire pull phenomenon which implies that the sequence of slip, normal load, speed, pressure and camber (should be zero for this test) levels cannot be varied. Following Table 6 shows the selected testing conditions for this study which are in compliance with SAE J1988 in most cases. Due to some mechanical constraints of the machine, some of the conditions are not possible to replicate on the machine.

Table 6: Test Conditions

Parameter	Values
Slip Angle	-1°, 0° and +1°
Load	20% to 100% of T&RA load in increments of 20% each
Pressure	34 psi
Inclination	0 degrees
Direction of rotation	Left and Right
Speed	12.93 kmph (8.03 mph)

Continental and Michelin tires have different T&RA load ratings and hence the normal loads for the test in case of these two makes are as follows:

Michelin: 1423 N (320 lb.), 2868 N (645 lb.), 4292 N (965 lb.), 5724 N (1287 lb.), 7156 N (1609 lb.)

Continental: 1112 N (250 lb.), 2522 N (567 lb.), 3705 N (833 lb.), 4897 N (1101 lb.), 6098 N (1371 lb.)

These operating conditions are the same for each test in this study. This, in fact, serves as a favorable condition, as not changing the test parameters results in the simplification of problem and analysis of data becomes easier due to reduction in the number of factors and the variability in the data can be assumed to be induced only due to the source of variability for which the experiment is designed. The following section shows the details of the tests conducted on tires. All the tests are divided into 6 sets depending on the potential source of variability estimated.

2.1 Randomized Order Tests

For the initial three tests on each tire (collectively for first 27 tests) the order in which the tires were tested, was randomized to reduce any possibilities of variability to be concentrated in any particular test. Randomization is a very basic and efficient principle of the design of experiments. The order was generated with MATLAB code made for randomizing the tires. By randomizing the order of the tests, no tire was tested consecutively for more than two tests. This means, after every test on the tire, it was kept unmounted from the rim until the next test. The order generated and the other data like date of the test, the distance for which the tire was on the road wheel, can be found in the excel file named '**Random Order.xlsx**' in the folder 'Repeatability M15'. Successively, all the data including test files, MATLAB codes, and analysis results along with the required graphs were stored in this folder. 5 Continental and 4 Michelin tires were used to complete this set of tests excluding the control tire. The intension behind conducting these initial tests was to get an idea about how the results compare for the same tire tested multiple times when plotted together. The results helped to figure out the conditions for designing further tests and identify the potential sources contributing to the variability. MATLAB codes were developed to analyze the results according to SAE J1988 and plot the results together to observe variability and produce the arrays of analysis parameters such as AS, CS, PLF, CLF, PRAT, and CRAT so that these can be imported into Minitab for its statistical analysis. The guidelines for using these MATLAB codes are given in Appendix A. The summary of this set is given in the table below.

Table 7: Set 1 Summary

Make	Number of Tires	Tests on each tire	Distance (miles)	Description
Continental	5	3	29.44	Tire unmounted from the rim after every test
Michelin	4	3	23.51	

Serial numbers	Run time (Cycle Time sec)	Speed (kmph)	Unloading time (sec)	distance travelled (miles)	Date
78608	768.62	13	120	1.994347766	20-Nov-19
91	760.244	13	114	1.96208342	21-Nov-19
78602	766.48	13	120	1.989544921	22-Nov-19
77170	767.16	13	120	1.991071059	25-Nov-19
93	758.95	13	114	1.959179269	25-Nov-19
89	770.26	13	114	1.98456253	26-Nov-19
90	764.85	13	114	1.972420758	27-Nov-19
92	764.35	13	114	1.971298598	27-Nov-19
77171	756.3	13	120	1.966697742	5-Dec-19
78602	644.318	13	120	1.715374284	6-Dec-19
90	760.47	13	114	1.962590636	6-Dec-19
77170	757.38	13	120	1.969121608	7-Dec-19
93	756.85	13	114	1.954466197	7-Dec-19
78608	756.79	13	120	1.967797459	11-Dec-19
77171	766.13	13	120	1.988759409	11-Dec-19
92	763.62	13	114	1.969660244	11-Dec-19
89	755.43	13	114	1.951279262	12-Dec-19
91	763.06	13	114	1.968403425	13-Dec-19
92	759.58	13	114	1.960593191	13-Dec-19
91	755.67	13	114	1.951817899	13-Dec-19
78602	754.31	13	120	1.962231545	13-Dec-19
77171	772.8	13	120	2.003729024	13-Dec-19
77170	761.36	13	120	1.978054002	16-Dec-19
89	759.4	13	114	1.960189213	16-Dec-19
93	757.62	13	114	1.956194324	16-Dec-19
78608	764.54	13	120	1.98519094	16-Dec-19
90	757.69	13	114	1.956351426	16-Dec-19

Figure 3: Random Order for Set 1

The figure above shows the details of the tests in set 1. Cycle time and Date are noted for every single test conducted for this study. For some of the tests, the temperatures before and after break-in and temperature after the test is also recorded. All this data can be found in the excel file mentioned above. Data acquired from this first set of tests was analyzed to determine the tire pull and stiffness parameters and the results of each test were plotted on the same graph to have an idea about the variability in the data. Depending on the results, conditions for further testing were determined.

2.2 Successive tests allowing the tire to cool down after certain tests

On analyzing the plots of the first three tests on each tire, variability in the data was observed to be higher. In this context, data refers to the parameters calculated from the force and moment data. An increase or decrease in these parameters was observed after the first test. This trend was found to be common for each tire. The first three tests cumulatively resulted in higher variability than expected. This holds true for the lateral forces and aligning moments as well. A general decrease in lateral force, aligning moment, cornering, and aligning stiffness and plysteer values was observed after the first test and these parameters fluctuate for the second and third the tests. On cautiously scrutinizing the conditions of tests for the first set, some conclusions could be drawn, which help to lay out the conditions for the successive sets of the test and justify the variability in the data.

- As stated earlier, most of the tires have either been tested for a very short distance or not tested at all. That is, these tires are almost new and have not been through the loading cycles what is called scrubbing. It is evident that tires change considerably as they are worked, and these changes might be permanent due to irreversible changes in rubber and other constituents. Also, mostly tires have protective wax coating as they roll out of the plant. Loading and steering the tire removes this coating and scrubs the tire. Every tire was kept idle after the first test until the next one. This allowed the tire to get scrubbed and gave enough time for rubber and plies to settle to a stable state. This created variability in the data of the first few tests.

- Even though the above point covered the largest source of variability for the first few tests, there could be other factors contributing to variability not in the very large cut compared to the first one, still, these factors are important when cumulative variability is considered. One of those factors could be mounting and unmounting the tire from the rim after every test. It is almost impossible to ensure that the tire is mounted exactly the same way every time. It is important to relax the tire on the rim so that the bead is seating perfectly on the rim.
- So, this set of tests focuses on eliminating variability due to frequent mounting and unmounting the tire if it exists. To achieve this, tires are required to be tested continuously for multiple tests which could also result in a rise in temperature. Changing temperatures can result in additional variability.

Considering these conditions above, tires were tested successively for 6 tests without unmounting them from the rim. Temperatures were recorded as described in the first set. From these temperature readings, the temperature rise per test was not significant to cause any considerable alterations in the tire properties. Though, the temperature readings recorded were only the surface temperatures which could be different from the bulk temperature of the tire and this holds true for the heat generation at the surface and bulk of the tire also. Generally, it takes more time to raise the bulk temperature and build up heat. Due to this difference in heat buildup, later into the tests, that is towards the end of tests (towards test 6) temperatures may change considerably and produce yet another source of variability. The instrumental setup on the machine currently doesn’t allow to acquire temperature readings continuously, hence whatever the temperature readings are to be recorded are taken after the test. Hence there is no way to detect any temperature changes while the machine is running. To avoid any undetectable variability due to temperature buildup, tires were kept idle after three tests (out of six) for at least an hour to allow them to settle to thermal equilibrium. After this idle period, tires were again tested for another three tests in succession.

Out of 9 tires, 5 tires were tested under this set of conditions. Appendix B specifies the serial numbers of tires selected for each set of tests. The remaining 4 tires were kept for the next set of conditions. The only difference in the current set and the next one is that, in the next set, tires are tested for 6 tests in quick succession without any idle time to cool it down to room temperature. This reduced the number of tests on each tire and to some extent reduced the tread wear as well. Table 8 gives a summary of the above discussion.

Table 8: Set 2 Summary

Make	**Number of Tires**	**Tests on each tire**	**Distance (miles)**	**Description**
Continental	3	6	35.09	Tire allowed to cooldown after 3 tests
Michelin	2	6	23.68	

2.3 Successive tests without allowing the tire to cool down during tests

Until this point in the testing, no tire has been tested continuously for more than three tests. Every tire was allowed to settle down after a maximum of three tests. As this study also aims at providing recommendations for conducting tire tests, it was important to know, how the variability looks like if the tire is tested for multiple tests in quick succession. This set of tests collects data for six successive tests on a total of four tires without any break in between. But there was a time gap between any two tires. Two

Continental and two Michelin tires were used for this set which were excluded from the previous set. The surface temperatures of the tires were recorded before and after the break-in and also at the end of the 6^{th} test. This set allowed to have the data of temperature buildup after six tests in a row, which also gave an idea about the contribution of temperature into total variability. Table 9 shows a summary of this set.

Table 9: Set 3 Summary

Make	Number of Tires	Tests on each tire	Distance (miles)	Description
Continental	2	6	23.33	Successive tests without cooldown
Michelin	2	6	23.88	

2.4 Control tire tests

Control tire is the slick tire provided by Continental having the same size as other Continental tires. SAE specifies the requirements for the control tire, those can be found in [3]. A control tire is an indivisible element of all sorts of tire testing. Tire engineers rely on the control tire data to a large extent. As explained in chapter 9 of [1], control tire data serves as a benchmark for tire development and could be a deciding factor whether the test driver would continue to work for the company. Having a control tire data also provides a reference for the indoor force and moment testing machines. Any deviation larger than allowable range from the control tire data represents a problem in the machine. Control tire data is also used for keeping track of machine calibration. As the machine at the university has recently put into service, it is important to have data of control tire to benchmark the calibration and other parameters of the machine. Hence, the control tire available was tested for 11 successive tests with initial break-in before the first test. Temperatures before and after the break-in and after the 11th test were recorded. The control tire was tested for a total distance of 21.51 miles. Control tire data on analysis shows a similar trend as seen for other Continental tires, though the deviation values were comparatively lower. Apparently, the only difference in other tires and the control tire is that the control tire does not have treads. This can explain the rescued variability. Treads on tire undergo phenomena called squirm, which means treads deflect when the tire is being worked and this can induce permanent changes in tread material giving rise to higher variability with tests. Absence of tread eliminated squirm and hence additional variability.

2.5 Tests Without Break-in

Break-in refers to the process of warming up the tire before the test. There happen to be different forms of the break-in at different periods of tire testing. For example, the commonly accepted break-in procedure in the 1970s [5] was completely different than what is described by SAE (SAE J1987) these days. Even though SAE has a protocol for break-in, testing facilities may use different versions or customers can also specify break-in procedures for their tires. There are some studies conducted to verify, whether there is any effect of break-in on force and moment data as there is one in [5]. The study in [5] is similar to this study where authors are investigating tires tested at low slip angles. The break-in procedure adapted in [5] is very rigorous where tires are rolled through 768 ft with 10 degrees of slip angle at 85% of the T&RA rated load. The paper concludes stating, there is no significant effect of break-in on variability in F&M data especially at low slip angles (1 & 2 degrees). Rather excluding the break-in will eliminate the break-in variable. Similar recommendations can be observed by SAE in J1988 [4], where SAE does not explicitly specify the break-in procedure though, it specifies that the tire should be warmed up to equilibrium operating temperature at a given pressure. All these references point towards not having a speculated break-in procedure for low slip angle tests. Though these documents are considerably old, one published in 1978 ([5]) and the other one in 1994 ([4]). From then there have been enormous changes in tire constructions, materials, and performance. Further the results are related to the specific environment and settings at the time of study and these results may change if the conditions specified in the protocol are not strictly followed. For the testing facilities and tire manufacturers, it is possible to have dedicated chambers for testing machines, but it is not possible at the university. Hence, it was important to have knowledge about the effect of break-in on F&M data for the M-15. This led to the set, without breaking-in the tires before the test. Five Continental tires were tested for three tests on each tire giving data for a total of 15 tests in this set. Table 10 provides a summary of this set.

Table 10: Set 5 Summary

Make	**Number of Tires**	**Tests on each tire**	**Distance (miles)**	**Description**
Continental	5	3	29.22	Tests without Break-in

2.6 Tests to analyze the effect of data acquisitions parameters on variability

To automate the process of loading and acquiring the data, a LabView program is used which controls the PLC and data acquisition module from national instruments called SCXI. LabView program uses some states of the machine to complete one loading cycle. One of these states is ‘save’ during which data from the acquisition system is saved to a specified file format. For saving the data, LabView uses the ‘DAQ’ module which allows users to specify some acquisition parameters such as sampling rate, number of samples to be saved, and other various factors related to sensor scales, excitation voltage, etc. While conducting the tests, it was observed that run out on the rims was causing cyclic variations in the normal load every rotation. As a consequence, lateral force and aligning moments are supposed to vary but the data recorded was contradicting this statement. The normal load seemed to be approximate sin wave unlike the lateral force and aligning moment. On careful observation of the LabView program, the cause was found to be a signal filter implied in the program. What program does is, it saves unfiltered values of F_z and filtered values of F_y and M_z. That is why when these parameters are plotted, the normal load seems to be sinusoidal (as it should be due to run out), unlike the other two parameters. So, this raises a question, whether the filter is affecting the actual values of lateral force and aligning moment by averaging the data. If this is true, to what extent the data is altered?

Along with the filter, another possible factor for variability in the data was identified to be the time for which the program is saving the data. Users can specify the time for which program stays in a particular state. In the LabView program, the 'save' state was being executed for 250 milliseconds. This was allowing the machine to save 100 data points in 0.25 sec. Considering the speed of the road wheel along with the maximum radius of the tire, the tire approximately completes one rotation per second and 0.25 seconds correspond to the quarter rotation. The program saves 100 data points in this period when the sampling rate is set to 1000 Hz. This predicts that data is saved only for approximately 36 degrees of rotation of tire which is less than even a quarter rotation of the tire. Now, consider the lateral force is fluctuating between some maximum and minimum every rotation, and user has no control over the part of the tire from which data is saved. Suppose that in one test the data is recorded from the part where lateral force is maximum and for the next test from the part where it is minimum. This would definitely cause some variability in the data. Hence a separate set of tests was focused on addressing this problem. In this set, the data is gathered with different sampling rates and saving times so that the acquired data is at least for one revolution of the tire. Similarly, some tests were conducted without implementing the moving average filter. One Continental tire was selected for this set. Details about selecting the sampling rate and save time will be discussed in the later chapters when all the results are explained. Figure 4 elaborates on the scenario explained above.

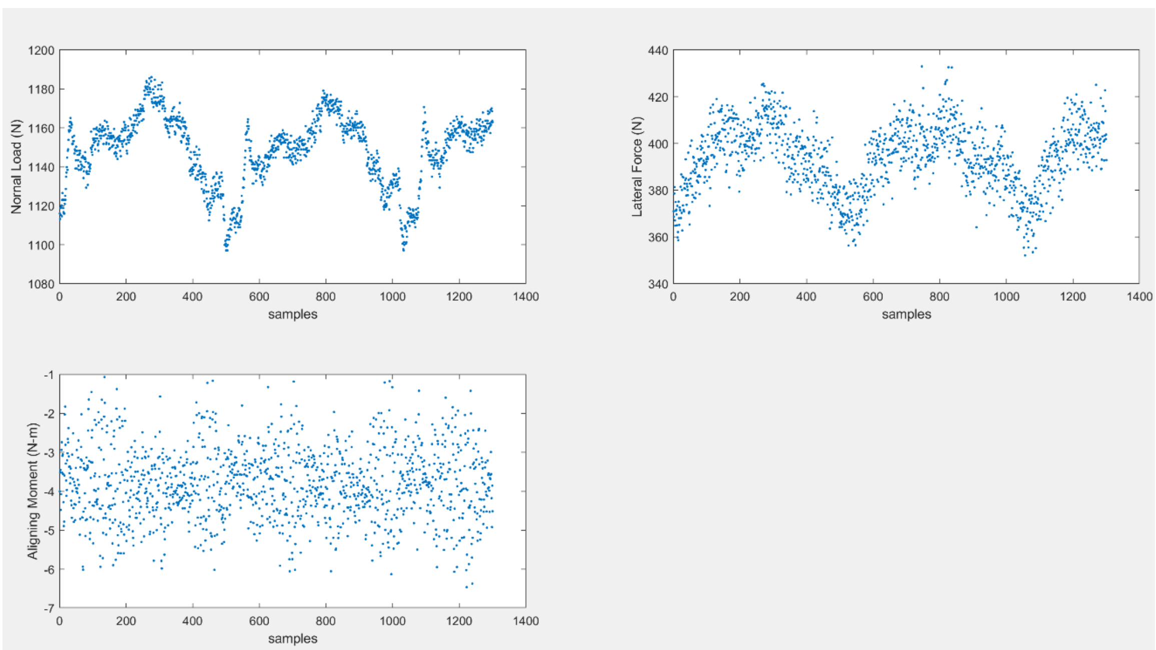

Figure 4:Unfiltered Data recorded for 2 revolutions of tire

The plot in the above Figure 4 shows the data recorded for Altimax 91, left rotation, negative one degrees of slip angle, and at 1112 N of the normal load. Due to runout on the rim, the sinusoidal nature of normal and lateral force is evident. Aligning moment seems less affected by the fluctuations but the scatter can be observed about some mean value. If the data is filtered and saved for around 100 points it looks like Figure 5 below. It is hard to identify exactly what part of the tire the data has been acquired. If the complete rotation of tire is considered, as shown above, it could be anywhere, either in the maximum part or in the minimum part giving different values which could be statistically significantly different. These fluctuations and no control over the part of the tire data being recorded, cause variability in the data which contributes to machine variability. Hence it is important to estimate this variability and make modifications in the LabView program accordingly so that it records the data at least for one complete revolution of the tire.

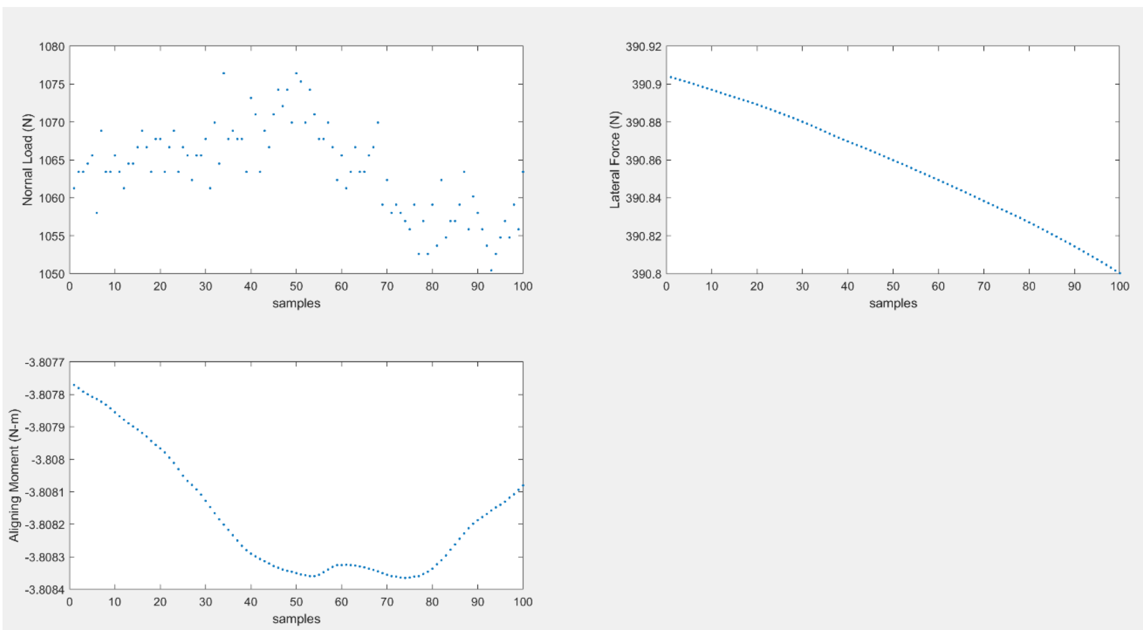

Figure 5: Filtered data, approx. 36 deg of rotation (100 data points)

CHAPTER 3: TEST PROCEDURE AND OPERATING LABVIEW PROGRAM

The LabView program being run on the M-15 testing machine is specifically designed for the machine. There are some details of this program that are critical to be aware of so that the test can be monitored carefully, and the machine can be set properly before the test. During the testing done in this study, it was observed that sometimes the computer loses connection with PLC and this makes the PLC to continue in the state in which it was before the connection was lost. For example, if LabView is loading the tire while going from one load to another and the computer loses communication with PLC. This causes the PLC to continue loading the tire without monitoring what the actual load is. This could be dangerous if the operator is not observing the test carefully and unaware of the steps to be conducted in this case. This chapter describes the preparatory and actual test procedures implemented for all the tests conducted in this study.

3.1 Breaking-in the tire before the test

Every tire tested on the machine was taken through the break-in process except for the set of tests without break-in explained in section 2.5. SAE J1988 [4] (which is used as a protocol for all the tests conducted in this study) does not explicitly specify the break-in procedure to be followed for the residual aligning moment testing. Though it specifies that tire should be in thermal equilibrium before the actual test and its responsibility of test engineer to assure this. Hence, a fixed break-in procedure is not available for this low slip angle tests. But SAE specifies the break-in process in J1887 [3] which is used as a reference for the break-in procedure adapted here. Although, due to some limitations of the machine, there were some changes to be made in the standard protocol of Break-in.

Before moving further, knowing the rotation sense of the road wheel according to the desired rotation sense of the tire is important. The tire rotation sense is explained in section 3.3 of J1988 [4] which depends on the way the tire is mounted on the rim. Assuming the tire is mounted correctly on the rim, if the left rotation of the tire is desired, clockwise rotation of the road wheel is required. Considering this, the red knob on the control panel of the machine is set on 'Reverse' and vice versa for the right rotation of the tire.

Figure 6 shows the knob on the control panel.

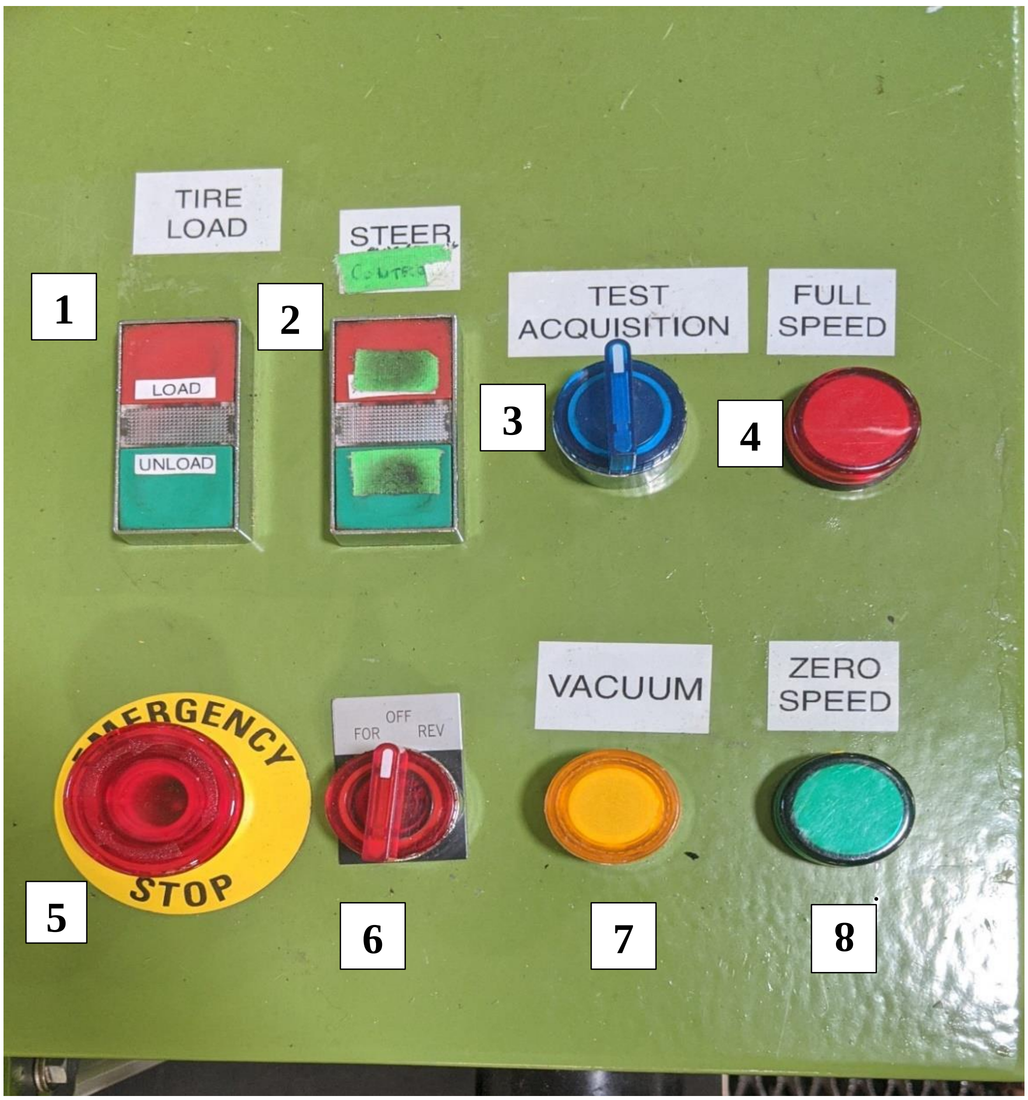

Figure 6: Control Panel

Table 11: Control Panel Terminology

Button	Description
1	Load/ Unload
2	Steer angle
3	Test Acquisition
4	Full Speed indicator
5	Emergency stop
6	Road wheel knob
7	Vacuum and brush
8	Zero Speed indicator

The following points explain the procedure for breaking-in the tire.

1. Set the tire to the specified pressure of the test and isolate the tire from the main pressure line. A ‘Stop’ button can be seen on the front panel of the program which is used to stop the program. A stop button is supposed to be a push-button that retracts automatically once pressed. But in the case of the LabView program, the feature for auto retract is not included. So, when the stop is pressed the button turns dark grey in color indicating the program was stopped. The program is stuck in that ‘stop’ state until the stop button is pressed again. Pressing the stop again probably changes its value to ‘false’ allowing the program to run again. Hence, make sure that the stop button on the front panel is light grey in color. Make sure the tire is not touching the sandpaper.
2. Run the program by clicking a small white arrow in the top left corner of the window. Now start the road wheel in the reverse direction (Clockwise rotation) so that the tire will rotate in left rotation. Turn on the vacuum and brush by the orange press button on the panel. Make sure the slip angle is zero otherwise set it to zero.

3. Observe the tares on 'F_z' and set the tare so that the normal load value is close enough to zero. Generally, due to noise, the normal load has a scatter of around ±3 lb. So, zero being an approximate average would be enough for the tests.
4. On the right side of the front panel, there are plots for load cells 'D51', 'D52', and 'E5' which contribute to the lateral force and aligning moment calculations. Observe the small displays at the right bottom corner, these represent lateral force and aligning moment. Adjust the tares of the three load cells so that the 'F_y' and 'M_z' are close to zero. Adjusting the tares with minute increments or decrements, it is possible to get a stable value of 'F_y' between ±2 lb. and 'M_z' between ±0.05 ft-lb.
5. Start loading the tire and take it to 50% of the T&RA load and hold it for 15 sec. After 15 sec, load tire to approximately 80% of the T&RA load and hold for 30 sec. This rolls the tire for more than 55 m at that load satisfying the SAE recommendation.
6. Unload the tire back to zero load and adjust the F_z load tare to zero if necessary.
7. Steer the tire to -1^o and successively to +1^o of slip repeating the step 5 and 6 for each slip.
8. If necessary, the same procedure can be repeated for the right rotation of the tire, but generally, breaking-in with either rotation should be sufficient. Bring tire back to zero slip after the break-in. Switch off the vacuum and brush along with the road wheel.

3.2 Conducting the Test

After the tire is properly broken-in, inspect the pressure, and connect the tire to the main pressure line again. SAE protocol requires the tire to be capped during break-in and at regulated pressure during the test. As specified in earlier sections, every test in this study has been conducted at 34 psi cold inflation pressure. Following Figure 7 shows the front panel of the LabView program.

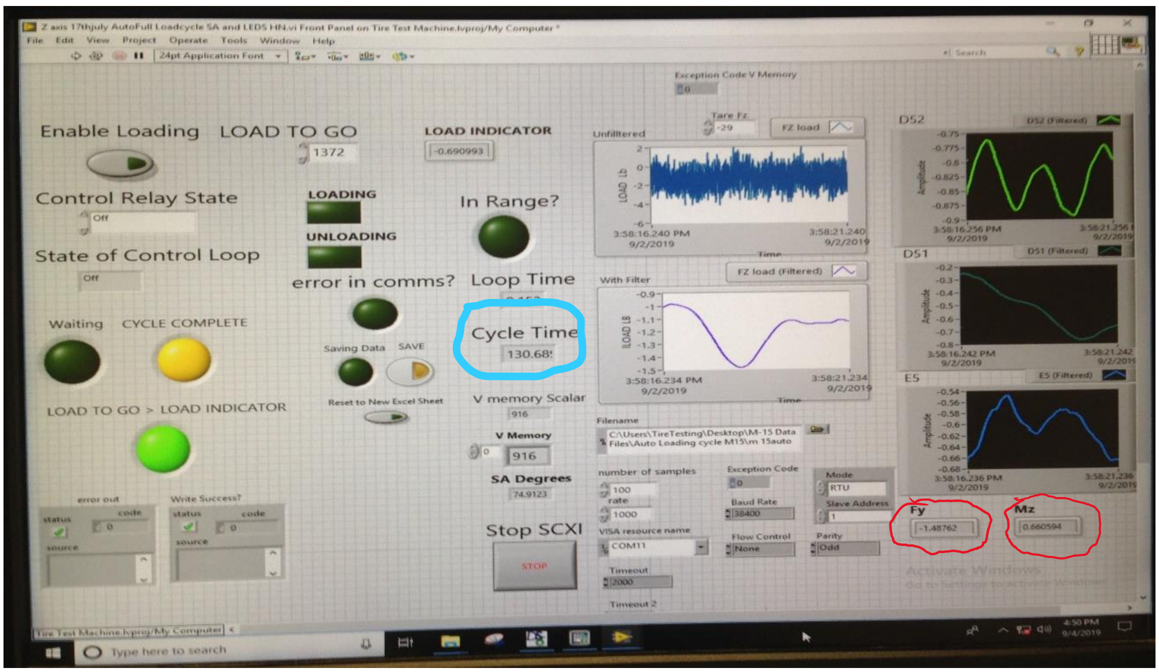

Figure 7: Front Panel of LabView Program

If the program was stopped after the break-in, first start the road wheel in the reverse direction (left rotation sense for tire), turn the vacuum on, and run the program.

1. Confirm the slip angle to be zero. It is to be noted that the least count of slip angle on the machine is 0.01735°. Getting an exact zero slip might take a few tries due to the sensitivity of the encoder and linear actuator. Type in the file name and location.
2. Check the tares for the normal load, lateral force, and aligning moment. Tares of the normal load were observed to change slightly when the tire is unloaded back

to zero. If needed, adjust the tares. For adjusting the lateral force and aligning moment observe the sections highlighted in the picture above. The value can be adjusted to the accuracy mentioned in the break-in process section. More specifically it is very important to get the aligning moment in the range of ±0.05 ft-lb because, aligning moment values at zero slip and lower loads are really small and if the tares are not adjusted properly, the noise in the data would be greater than the actual aligning moment and it will induce unwanted variability.

3. Now press the ‘Enable Loading’ button in the left top corner of the program window. The tire will start loading and acquiring the data. After saving the data for the last load a message will pop up sating ‘Test is complete, unload the tire’. Hit ‘OK’ and click on the small window below ‘Control Relay State’ and select ‘Unload’ to unload tire to the zero load. Once the tire is detached from the road wheel select ‘Off’ from the same dropdown list.
4. Steer the tire to -1° of slip and click the stop button. On clicking the ‘Stop’, program stops the SCXI system and it might take some time. When the program is completely stopped one can see the grid appearing on the screen as it can be observed in the Figure 7 above. Click on the ‘Stop’ button again to retract it.
5. The program has to be stopped after every test is complete to reset the loops in the program. Now the program can be rerun to conduct the next test. Repeat the procedure from 3 to 5 for -1° and +1° of slip.
6. After the test at +1° is complete and tire is unloaded, steer the tire to zero slip again and stop the road wheel and vacuum. The operator has to wait for the road wheel to stop completely before proceeding further on changing the direction

rotation. There is a resistor in the motor which facilitates braking the road wheel. This resistor might be damaged if the motor is reversed before it stops completely.

7. Change the direction of the road wheel by switching it in the forward direction (counterclockwise) and switch on the vacuum.
8. Repeat the procedures from step 2 to 7.

To keep the track of distance through which tire has been tested, the operator can note down the cycle time displayed in the area circled in blue in Figure 7 after every loading cycle is complete. To set out a terminology here, if the way program works is considered, the machine loads the tire through a range of loads at one slip angle and stops. That is, there are supposed to be 6 loading cycles (three for left and three for right rotation) to get the data sufficient to analyze with SAE J1988 and these 6 loading cycles make one test. As far as this study is considered every file saved is named according to the protocol, ‘Make_Serial Number_slip_direction.xlsx’, for example, for Altimax 89 tested at 0° slip in left rotation the file will be named as ‘Altimax_89_0_left.xlsx’. It is important to name the files strictly using this pattern to analyze data in MATLAB using the codes which are explained in Appendix A.

The default load values in the program are set according to the rated load of Continental tires. These load values can be changed depending on the rated load of the tire being tested. Load values can be edited in the block diagram of the program, accessed from the ‘Window’ tab in the title bar. The block diagram has relay states defined by the while loops. Load values are present in the load relay state. For testing the Michelin tires a separate copy of the same program with normal loads according to Michelin tires’ rated load was used. Figure 8 shows the files generated for one test containing 6 loading cycles.

Figure 8: Data files for one test

3.3 Axis system and sign conventions

To analyze tire data according to SAE J1988, it is important to have knowledge about what sign conventions being considered and how the ideal data should look like to come up with valid answers. According to SAE, the fitted data should be like the Figure 9 below.

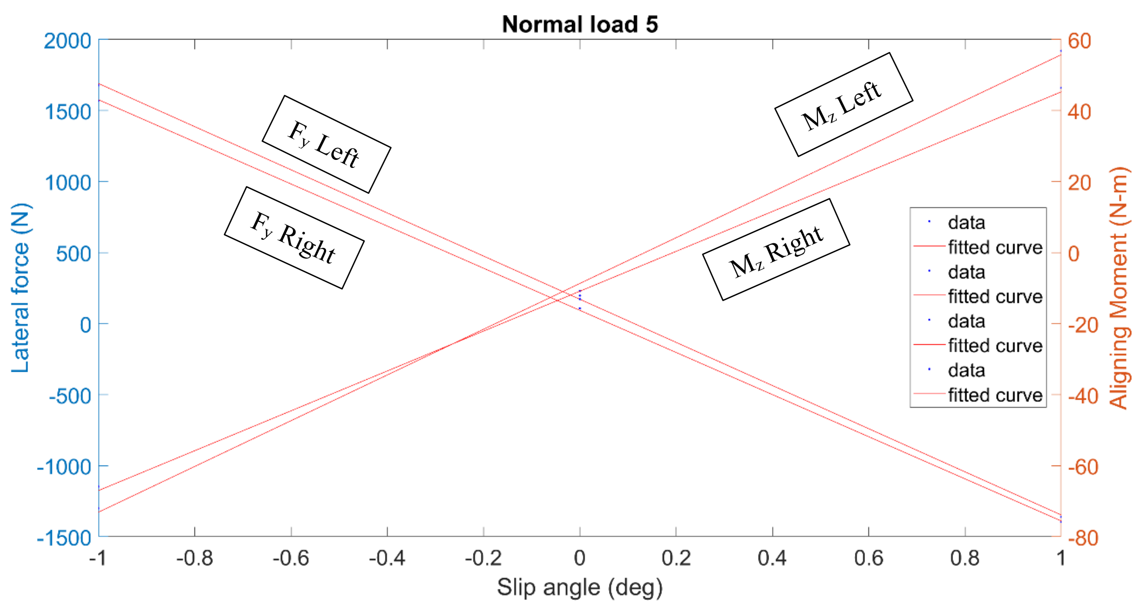

Figure 9: Reference Curve Fit

The M-15 tire testing machine has been calibrated according to the SAE Axis system. The detailed description of the SAE axis system can be found in [3] and also in [2]. The longitudinal and lateral axes lie in the ground plane, with a longitudinal axis (X-

Axis) pointing in the direction of the rolling of the tire and lateral axis (Y-Axis) along the rolling axis of tire. If this axis system is viewed from the top, the definition of the slip angle becomes easier to understand. Figure 10 represents the top view of the axis system as it is implemented on M-15 from the operator's perspective in the left rotation of the tire. The operator's perspective is when the operator is facing the hub of the machine. 'Positive slip' represents the direction of a positive slip angle according to the SAE system. So, when the tire is steered inwards (As shown in Figure 10), it is at the slip angle 'SA' which is considered as a negative slip. Hence, when the tire is steered inwards the lateral force is acting along the positive Y direction and F_y is negative when the tire is steered outwards (Positive Slip).

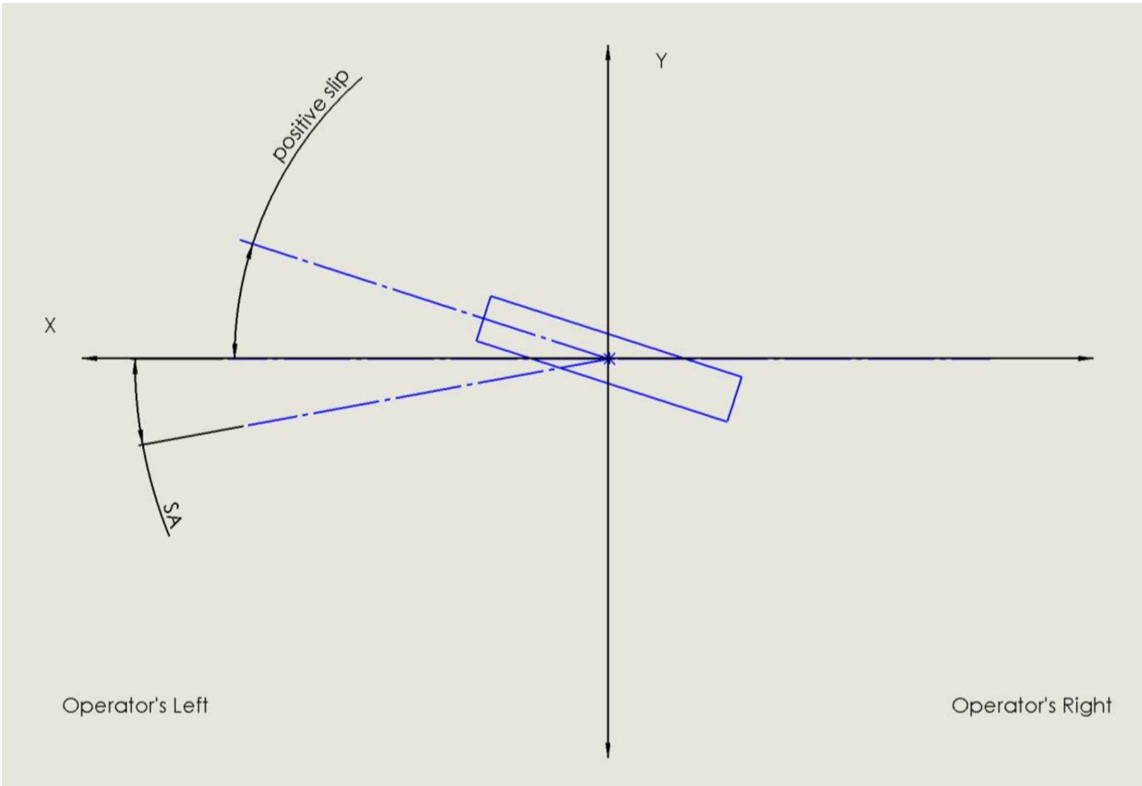

Figure 10: Axis System Left Rotation

Now suppose, keeping the tire in the same position as in the above diagram, the rotation sense of the tire is changed. That is, the tire is now rotating in the right rotation.

Hence the axis system will be a mirror image of the above Figure 10. The machine still reads slip angle to be negative as tire steer direction is not changed. But as noticed in the figure on the next page with the flipped axis system the slip angle induced actually is positive (‘SA’ represents induced slip angle and ‘Positive slip’ represents the direction of positive slip) and hence lateral force recorded should be negative in this case. This is what observed with the data recorded where, in left rotation, positive slip gives negative force and negative slip gives positive force (which agrees with the SAE axis system) but when the direction of rotation is changed it flips the direction of forces giving positive force for positive slip and negative force for the negative slip which is valid in general (Reversion of forces can be seen in FIGURE 4.20 in [2]). But SAE in its J1988 flips the axis system when the direction of rotation of tire is reversed which yields the forces as shown in Figure 9.

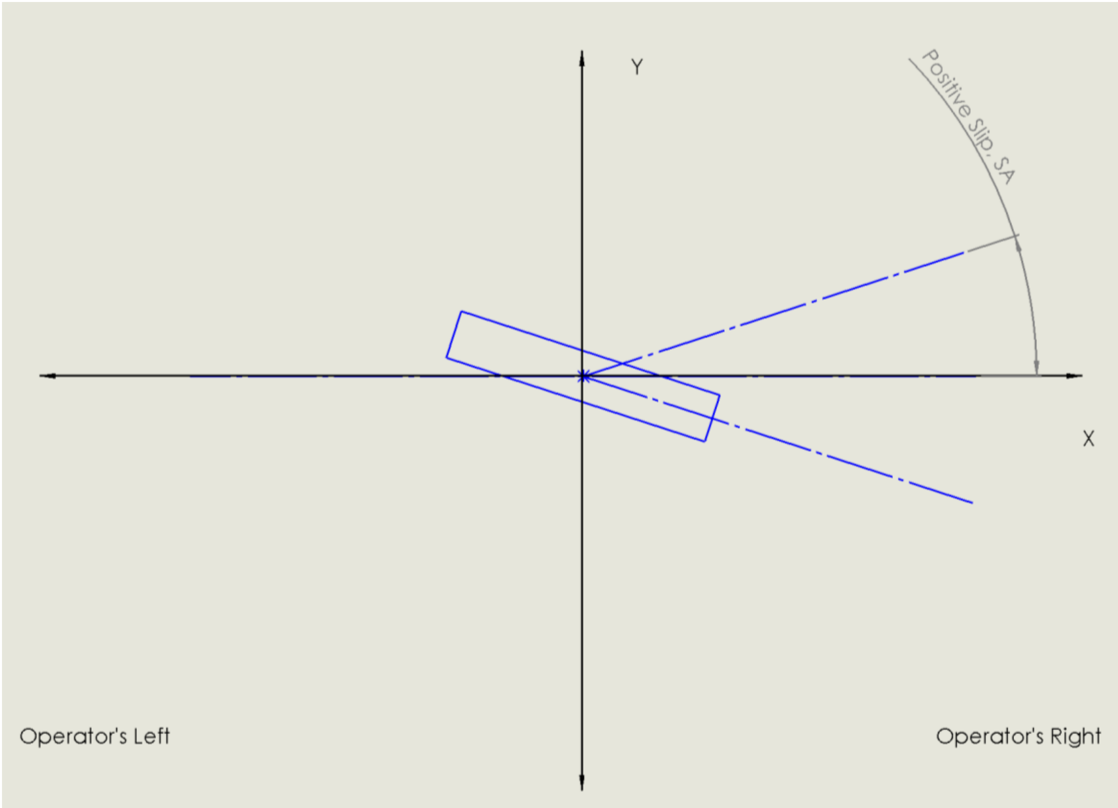

Figure 11: Axis System Right Rotation

To make the data compliant with the requirements of SAE the sign convention of the data is changed when importing it into the MATLAB code. The above issue doesn't mean that the machine is not recording correct data, it just has to be transformed before it is analyzed. For the data recorded before recalibration of the machine, signs of lateral forces for each slip angle in the left rotation are reversed while on the other hand, any data after recalibration of the machine, the same process is done for the right rotation.

CHAPTER 4: DATA ANALYSIS TO ESTIMATE TIRE PERFORMANCE PARAMETERS

Even though the nature of lateral force versus slip angle is not exactly linear over the range of slip angles, it can be assumed to be linear in low slip angle range particularly near the origin (Near zero slip). As the relationship between slip and lateral force is not linear, the cornering stiffness of the tire cannot be defined by a fixed value, rather it changes depending on the nature of the curve. Though in general, to characterize the tire the slope of the curve near the origin is commonly accepted as cornering stiffness of the tire at given normal load (F_z). Aligning stiffness is an analogy to the cornering stiffness. Aligning stiffness is the slope of the Aligning moment versus slip angle curve at the origin.

Similarly, Plysteer and Conicity are related to the residual lateral forces produced by the tire at zero slip as a consequence of construction and non-uniformity of the tire respectively. These parameters can be analyzed with the tire force and moment data between -1° and +1° of the slip in small increments. In this study, all the tests were conducted at -1°, 0°, and +1° slip angles giving three data points. Three data points are selected considering the time frame and wear of the tire and are sufficient to fit straight line. Tires are tested in left and rotation sense with the same values of slip angles and loads for the tire pull characteristics estimation. Plysteer and Conicity are distinguished from each other since plysteer lateral force changes the direction on changing the tire's rotation sense while the conicity lateral force acts in the same direction. As the behavior of tire is assumed to be linear in the range of slip considered here, the data can be fit through a simple equation.

$$y = mx + c$$

Considering the case for lateral force the dependent variable ‘y’ would be a lateral force with independent variable ‘x’ as slip angle and the y-intercept ‘c’ will represent the residual lateral force at zero slip. Slope ‘m’ represents the cornering stiffness. Similar terminology applies to the aligning moment as well. This process is done for both of the rotations of the tire giving stiffness and residual quantities. These are used to calculate the parameters as explained in SAE J1988 [3].

For the statistical analysis and estimating the variability in the data, ‘CS’, ‘AS’, ‘PLF’, ‘CLF’, ‘PRAT’ and ‘CRAT’ are calculated for every test and saved into MATLAB variables which can be further imported into scripts which process and plot the data. Details of the MATLAB scripts and guidelines to run the programs are given in Appendix A. ‘SAE_J1988_test_analysis.m’ file calculates these parameters for every test. Plots generated and results can be saved for further use. The program allows users to select the directory for saving the data.

Figures on the next page show the results of the analysis done in MATLAB. The data is for the Altimax 91 tire. As mentioned earlier Continental provided the data for Altimax tires, which is also plotted with M-15 test data. Validating the M-15 data with the flat track data provides verification that road wheel machines can generate data close to the actual operating conditions. Road wheel machines are being antiquated amid, what thought to be an inherent discrepancy of either underestimating or overestimating the forces and moments. The cost of tire testing can be considerably reduced if the compliance of road wheel data with a flat track can be proved. As it is observed, even though the trend is similar, there is a considerable difference in Plysteer, Aligning

Stiffness values and Cornering Stiffness looks close to the flat track data. The separation of the M-15 values could possibly be explained based on calibration errors. The method used for the analysis may also create a considerable difference. For example, the test procedures and analysis that Continental used is unknown. Having data for a wide range of slip angles and fitting Magic Formula gives considerably different values of the same parameters compared to the analysis performed in this study which complies with the SAE's protocol. Further study could be done to explain this anomaly and get the M-15 data closer to the flat track data.

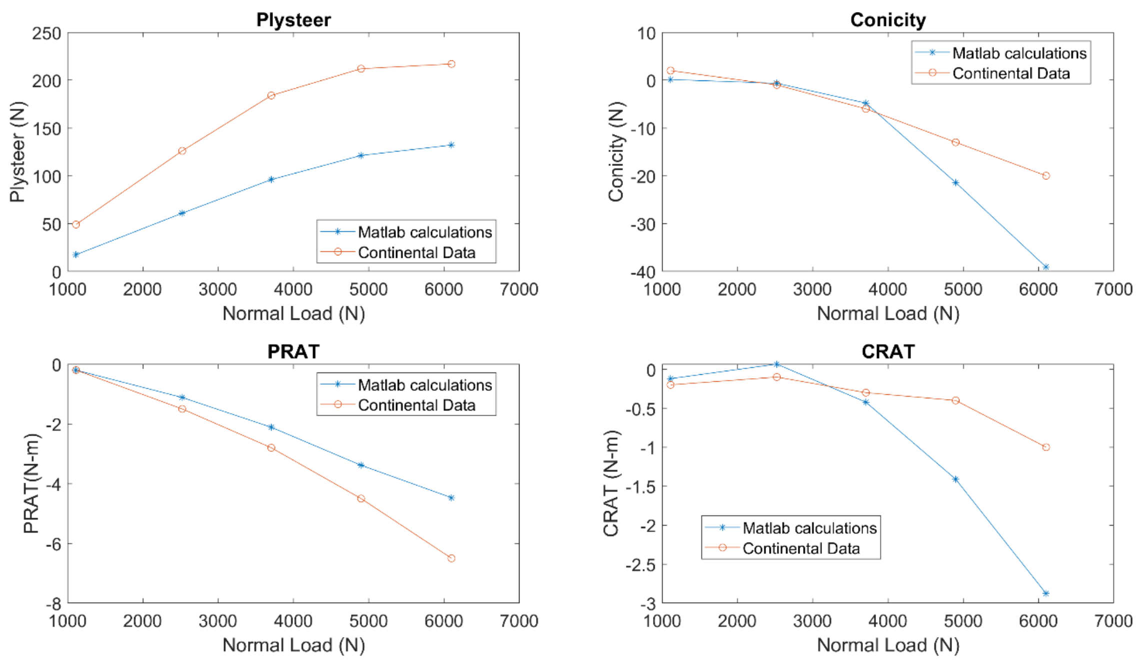

Figure 12: Altimax 91 Properties

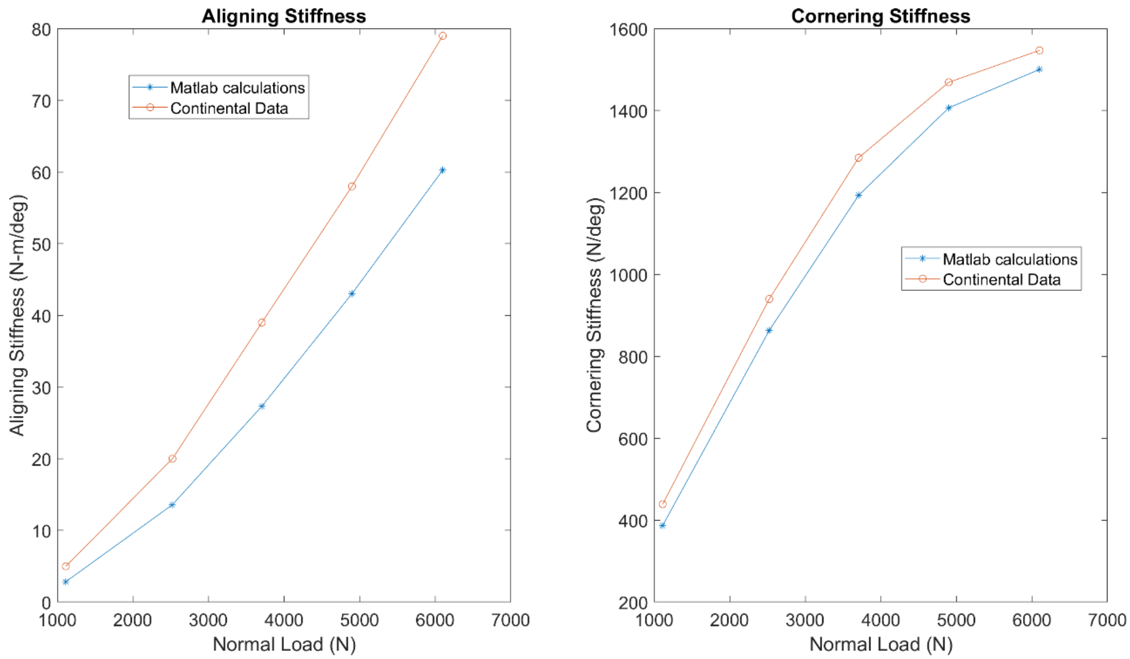

Figure 13: Altimax 91 Aligning & Cornering Stiffness

The above figures show the results of only one test done on one tire which does not provide a wider view of the condition of the machine, its ability to generate the same results in the specified tolerances every time the tire is tested. Repeatability is one of the important aspects of any instrument in general, and it becomes even more critical in case of tire testing as tires are sensitive to numerous factors some of which produce predictable effects and many other factors affect the tire whose effects are very hard to predict. Hence, it is important to have knowledge of how repeatable the machine is and what are the factors contributing to the variability in the data causing the significant change in the response variable and overall variability in the data.

In order to study the repeatability of the machine, data for multiple tests on multiple tires are required to be observed simultaneously. A MATLAB script was designed to import the test results (test results correspond to the results produced by SAE_J1988_test_analysis code.) either for the multiple tests on the same tire or for the multiple tires and plot them simultaneously. This code also produces MATLAB arrays for the variables required for the further statistical analysis of the data. The following graphs show the data plotted for all the tests conducted on the Altimax 91 tire. The graphs represent the means and standard deviation on 12 tests on the tire for every load. These 12 tests include all the sets of tests explained in Chapter 2; hence the standard deviation of these tests can be considered as a maximum variability induced on to force and moment data which includes the contribution of every potential source of variability collectively. A more detailed statistical analysis will be explained in the subsequent sections and chapters.

On running the code, named 'Combined.m', depending on the number of tests selected by the user, it produced a maximum of 26 graphs representing the 6 parameters from calculations, lateral force, and aligning moment at each load and rotation sense. All those graphs are not included in the document but can be found in the folder named 'Scatter Plots' in every tire's folder.

Table 12: Mean & Std. Deviation of Altimax 91 parameters

Load (N)	**CS (N/deg)**		**AS (N-m/deg)**		**PLF (N)**		**CLF (N)**	
	μ	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
1112	391.61	17.52	2.83	0.20	12.35	8.79	-3.1	4.41
2522	861.61	9.68	13.30	0.32	59.32	5.18	-5.62	7.73
3705	1202.9	17.13	27.57	0.75	100.93	5.63	-4.78	5.71
4897	1417.6	13.53	43.79	0.82	126.45	7.99	-19.7	6.29
6098	1502.1	14.57	60.10	0.53	136.20	8.17	-37.7	6.64

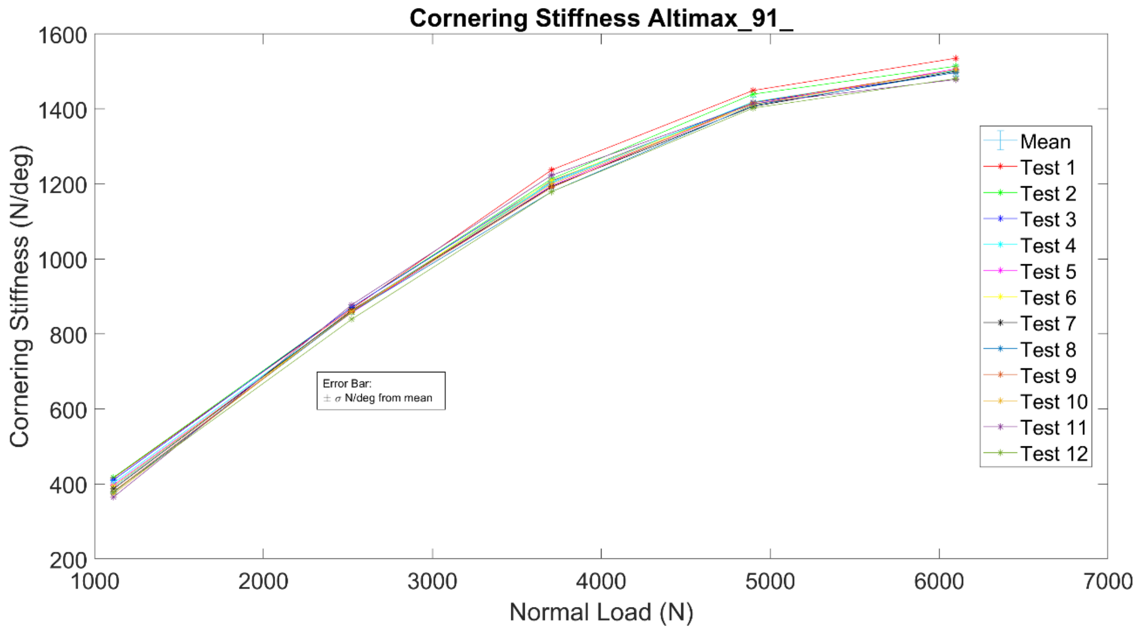

Figure 14: Cornering Stiffness Altimax 91

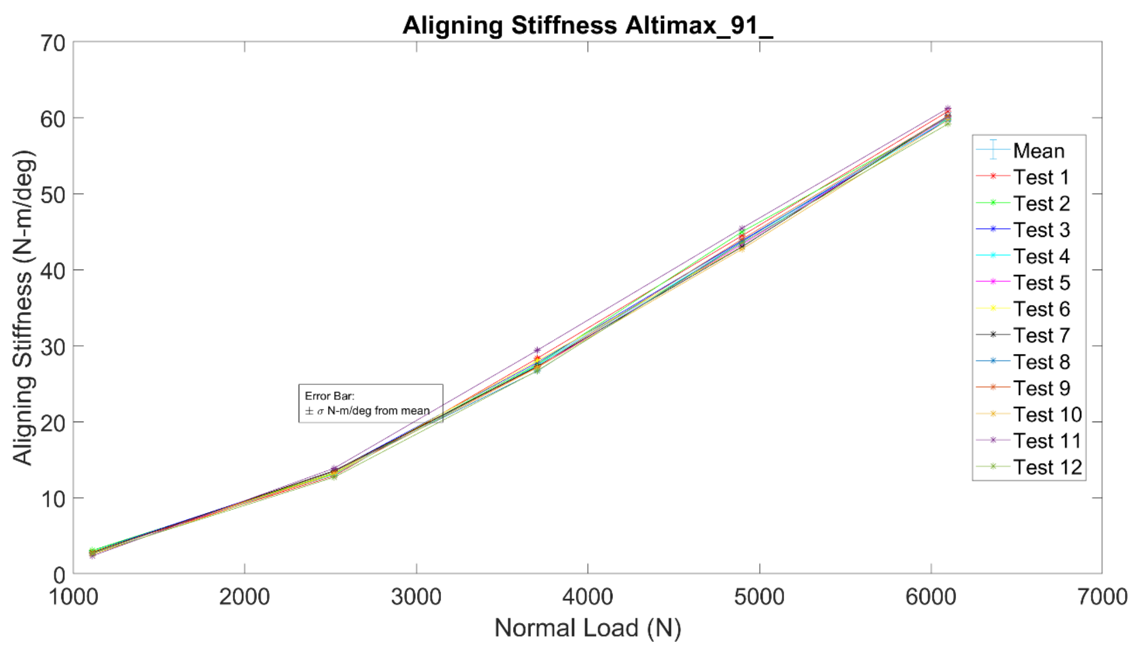

Figure 15: Aligning Stiffness Altimax 91

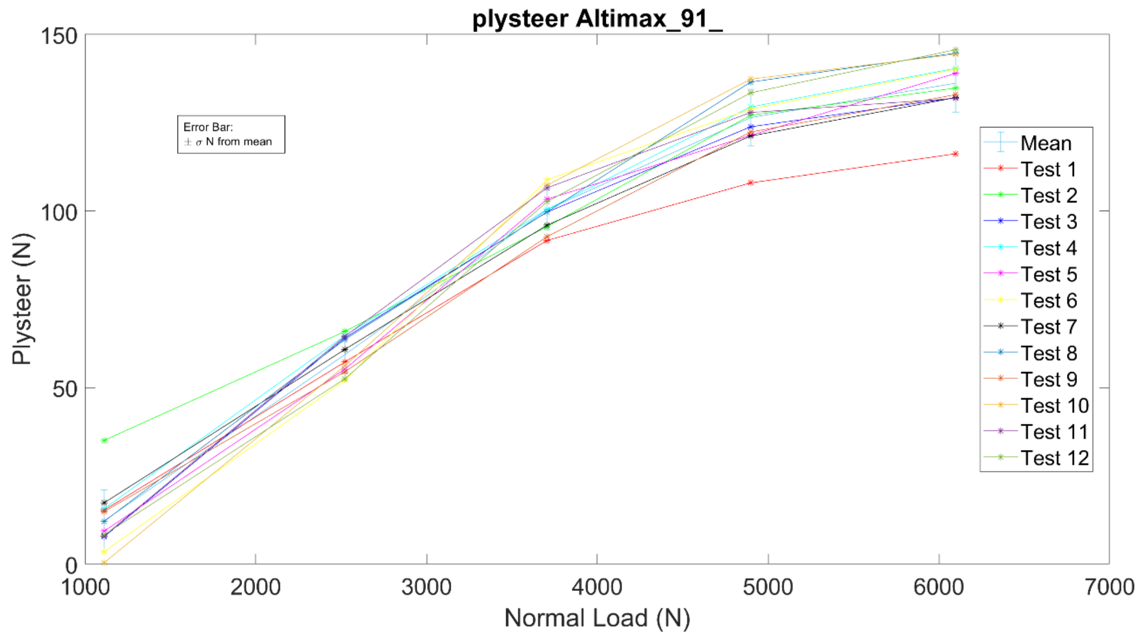

Figure 16: Plysteer Altimax 91

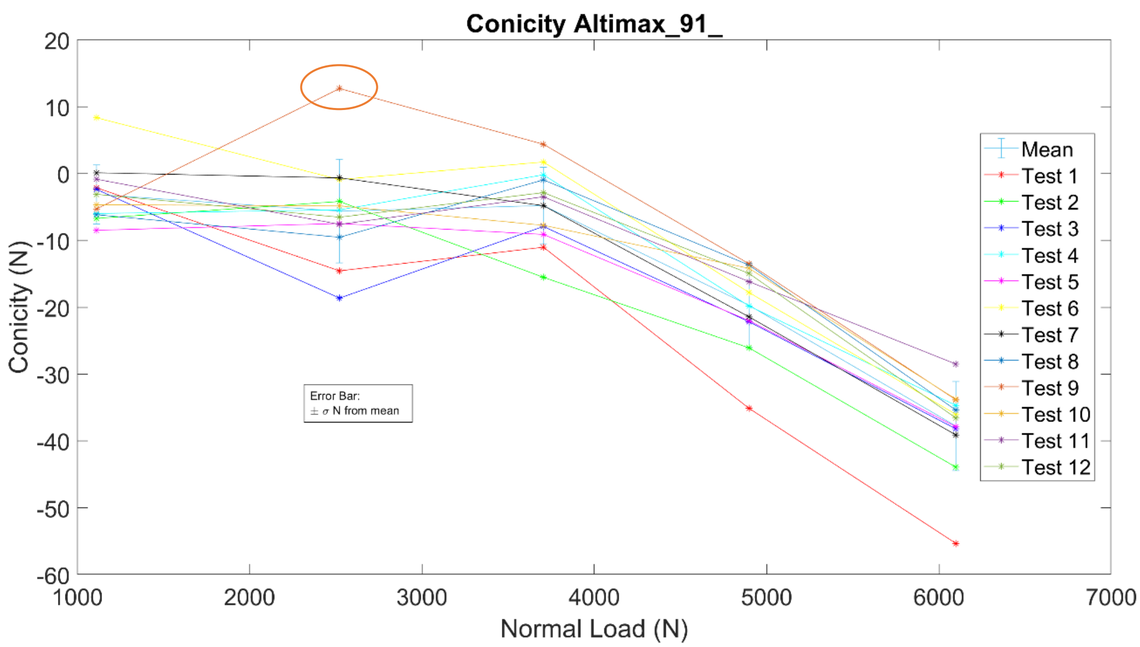

Figure 17: Conicity Altimax 91

Cornering and Aligning Stiffness values seem to be very close to one another based on which, standard deviation (variability) in these parameters can be said to be low, and hence the repeatability of the machine said to be good. Observing the values of deviation for cornering stiffness and aligning stiffness, one can speculate that these values seem to be changing with load and there could be a relation between load and variability. The more important question is whether the deviation is significantly different, producing a significant change in the response variable (CS & AS in this case). A more detailed statistical analysis is required to verify this, which is explained in the further sections. Also, the deviation for these parameters seems within a percent of the mean value for higher loads and it increases at lower loads.

Contrary to the CS and AS, deviations in plysteer and conicity seem independent of normal load but the scatter of these parameters is more compared to stiffness plots. There is inflation in percentages as well. Specifically, deviation in conicity is a considerably higher percentage of mean values for example, at the highest load, the deviation is 17.6% of the mean conicity at that load. The average value of deviations of plysteer is 7.15 N while for conicity it is 6.15 N, this indicates these two deviation values are not significantly different and can be considered the same even the percentages look very different.

This leads to the speculation that there are some sources of variability, which some factors are more sensitive to than others. Referring to the above discussion CS & AS are more sensitive to load while PLF & CLF don’t seem to be sensitive to the load rather these parameters are sensitive to some other factors. The possible explanation can be understood considering the definitions of these parameters. Stiffness parameters are the slopes of the fitted curves and the curve fitting process is robust against small changes in the forces and moments. Hence one could expect the same stiffness values (slopes) even though the data through which the curve is fitted has some variability. On the other hand, Plysteer and Conicity are calculated from the y-intercept, which is the forces at zero slip angle. Even though the y-intercept is taken from the coefficient of the fitted equation, this intercept is more sensitive to raw data than slope which can create variations in the final plysteer and conicity values.

Other than the noise in electronic systems, the variations mentioned in the above paragraph are possibly coming from the additional two factors. One of which is the accuracy of the slip angle and the other one is explained in section 2.6 of this document. The contribution of runout and data collection time will be explained in later sections. Now, consider the circled point in Figure 17. It points out the conicity of the tire calculated from the Test 10 data for a load of 2522 N. The mean of all the conicity value at that load is -5.62 N and the highlighted value of 12.72 N. Hence the difference in absolute values is 18.34 N. The cornering stiffness of tire at this load is on an average 861. 61 N/deg. Considering this cornering stiffness value, to create a lateral force of 18.34 N, a slip angle of approximately 0.02° is required which is very close to the least count of slip angle of the machine. That is, such a minute change in slip can cause variability in conicity and plysteer which may seem considerably high, but SAE specifies the required accuracy of 0.05° in slip angle which consequently can produce variations of around 43 N at 2522 N. Hence the relatively higher standard deviation numbers for plysteer and conicity are justified and can be reduced by even more accurately controlling the slip angle or having the tire swept through the range of slip angles and reducing the runout of the rim.

The total 12 tests are divided into groups of 3 as each set reported in chapter 2 has at least 3 tests on the same tire. Averaging the values for 3 tests yields mean values for each set and provides information about the tire evolution. As one can expect, the cornering stiffness seems to decrease with tests but the mean cornering stiffness for tests 10,11 and 12 is seemed to be higher than the second and third set. It is to be noted that these 10,11 and 12 tests are conducted without breaking-in the tire which points towards the occurrence of the process of restoration of the rubber properties due to viscoelastic nature. The same pattern is observed for the aligning stiffness. While conicity shows a shift towards the positive side of the graph. More interestingly plysteer values seem to increase as the tire worked progressively.

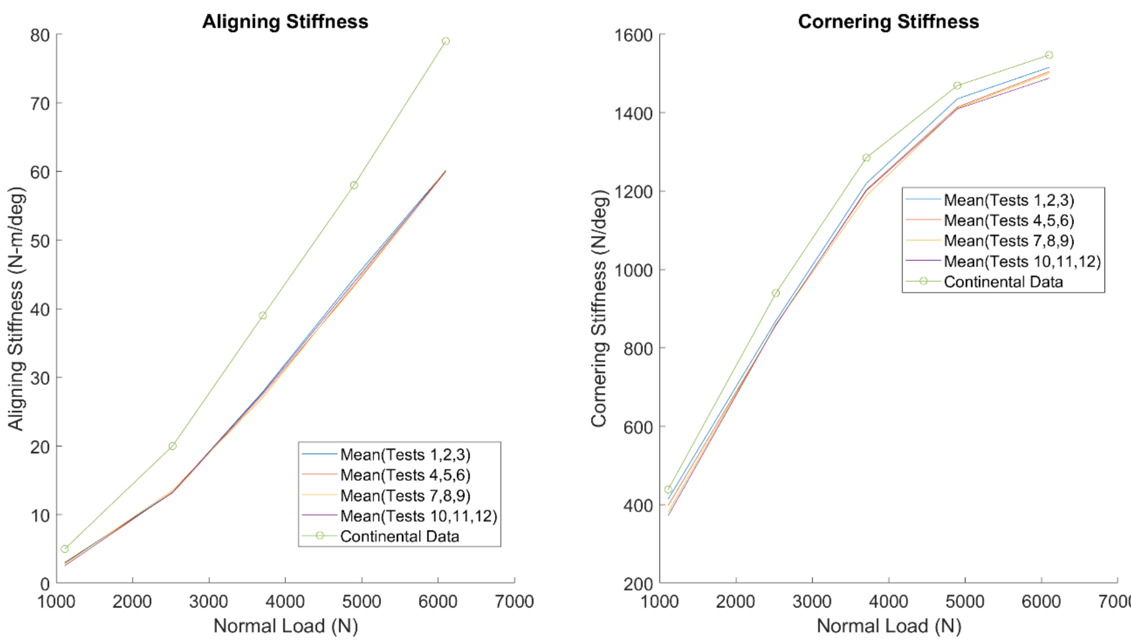

Figure 18: Evolution of Cornering and Aligning Stiffness

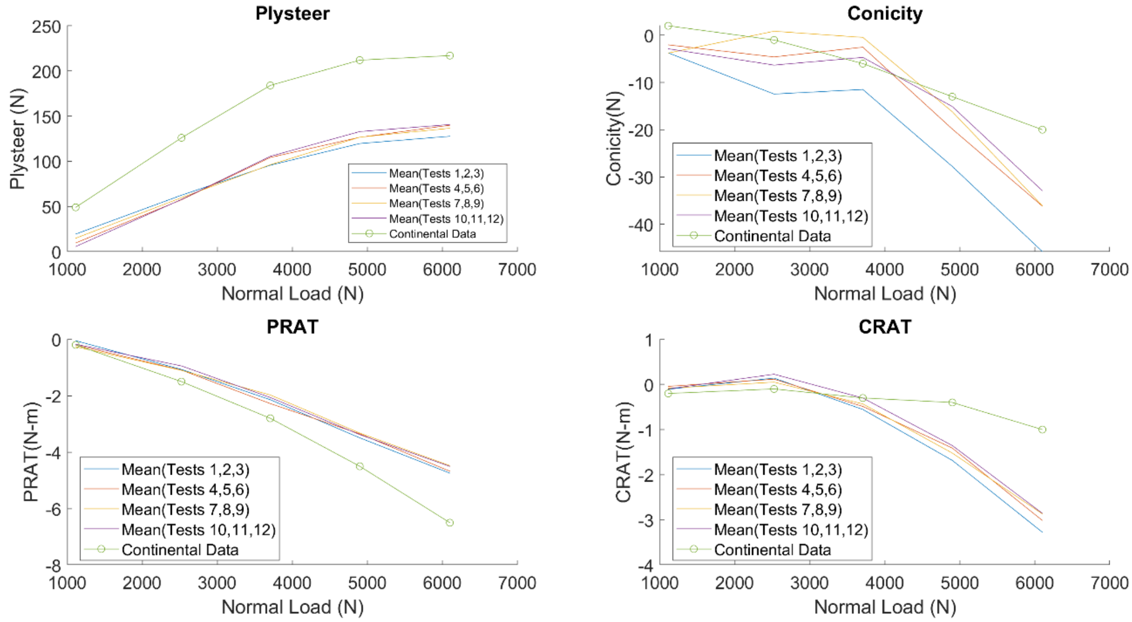

Figure 19: Evolution of Plysteer, Conicity, PRAT & CRAT

The MATLAB code also plots all the performance parameters, lateral force, and aligning moment against the test number for every load along with the error bars equal to the standard deviation of a group of three tests. Having standard deviation plotted for 3 tests provides an idea about the changes in mean values and the variability in the data. The following graphs make this point clear, as the shift in the data can be seen prominently.

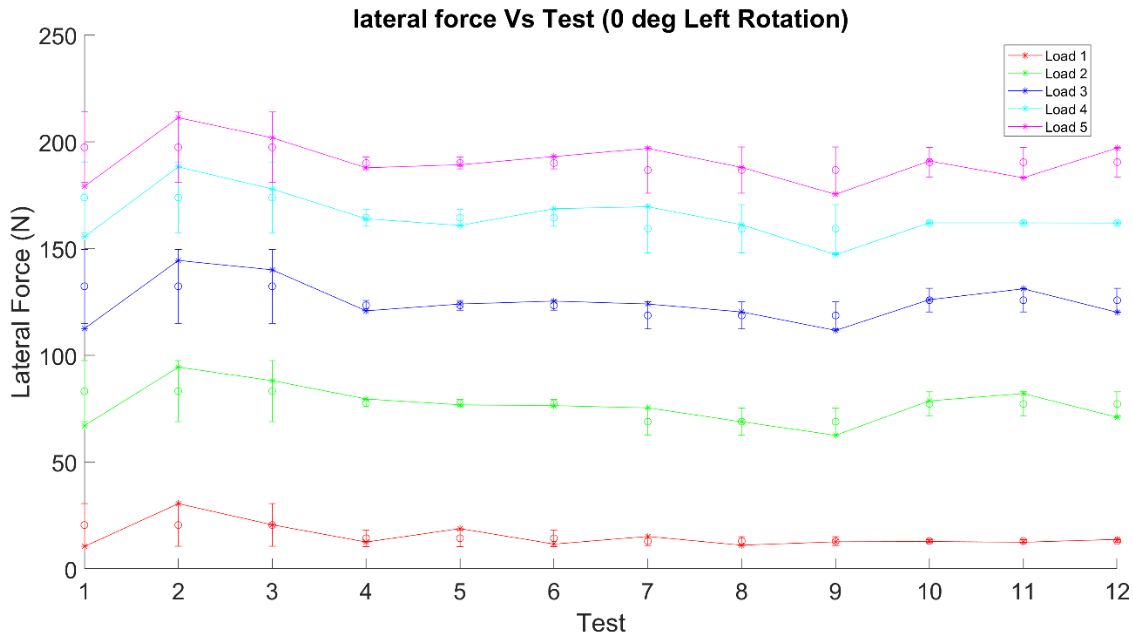

Figure 20: Lateral Force Vs Test at zero slip left rotation for Altimax 91

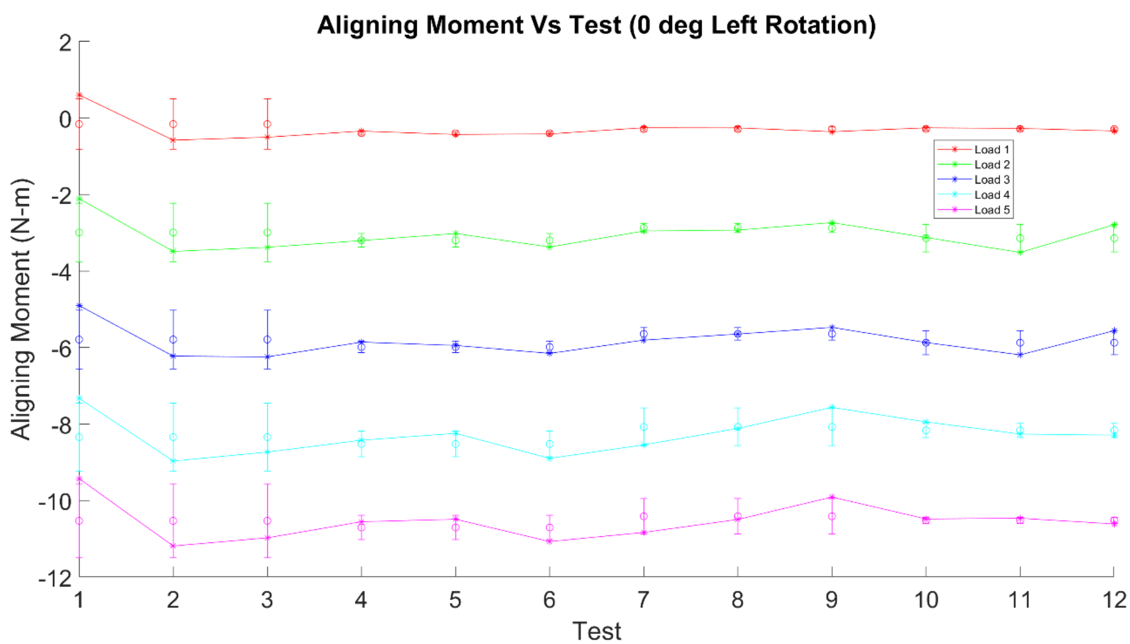

Figure 21: Aligning Moment Vs Test at zero slip and left rotation for Altimax 91

There are some variations observed for lateral force and the aligning moment when the tire is at zero slip. This explains the variations in the parameters derived using these forces and moments. There is a general trend of increase in lateral force from the first test to second and a similar decrease for the moment. This change is observed in other tires including Michelin and a Control tire. Another observation that leads to further investigation is the change in standard deviation over the tests. That is, the deviation for the group including the first 3 tests is the highest of all groups. This seems to decrease from tests 4 to 9 which are conducted in succession (for Altimax 91 it's without cooldown). Out of these continuous tests, deviation of Test 4,5 and 6 is comparatively lesser than the deviation of Test 7,8 and 9. This effect is more prominent for the lateral force at higher normal loads. On the other hand, if the same plots are observed for the Altimax 93 which was tested with a cooldown after three successive tests, deviation seems lesser for the tests 7,8 and 9. This leads to the thought that the deviation might be dependent on whether the tire was allowed to cooldown or not, but the collective deviation from tests 4 to 9 might result in the same values for both the cases. Statistical analysis was conducted to verify this and presented in further sections. The following figures show the same data as in the above two figures but for the Altimax 93. The trends observed in the tires presented here apply to the other tires including the control tire, eliminating the possibility of chance occurrence of these events in the tires.

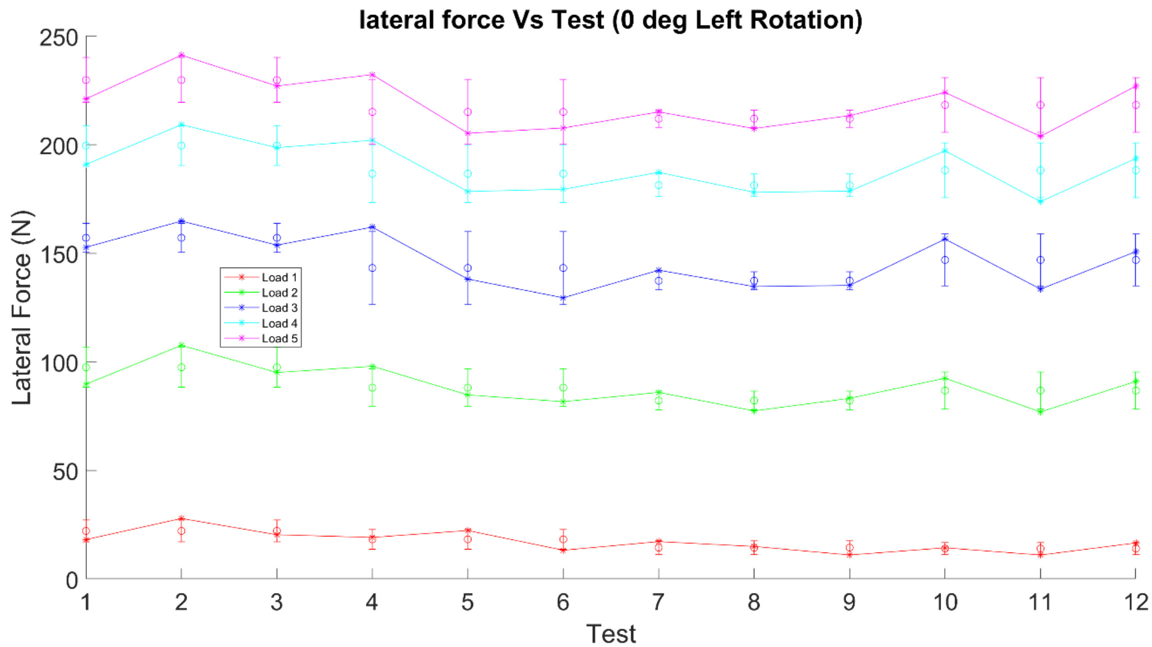

Figure 22: Lateral force Vs Test at zero slip left rotation for Altimax 93

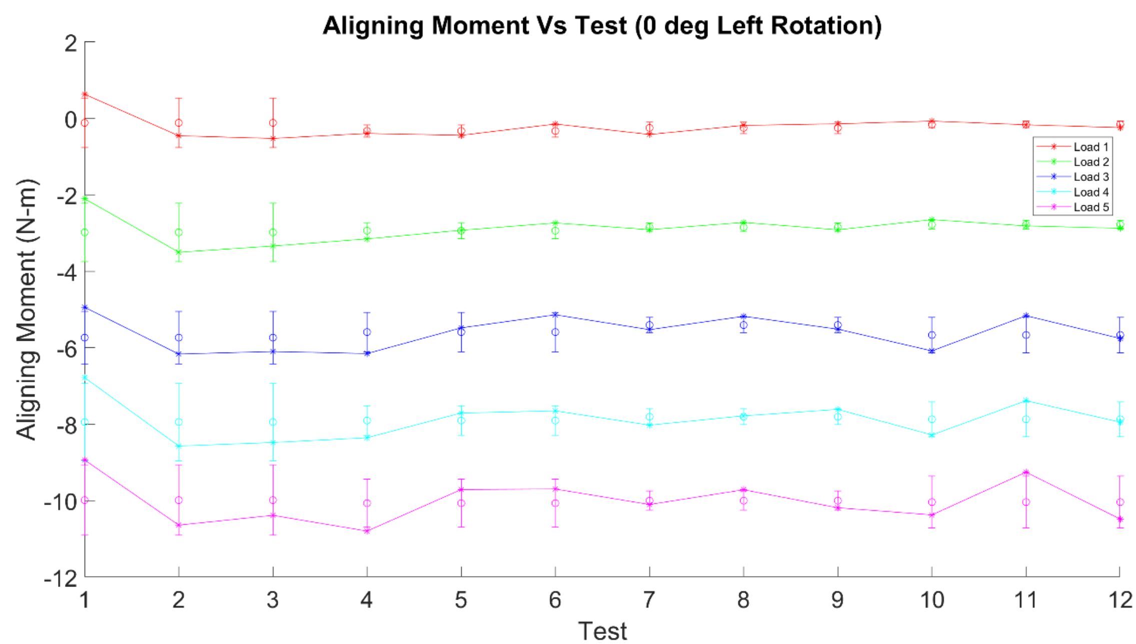

Figure 23: Aligning Moment Vs Test at zero slip left rotation for Altimax 93

CHAPTER 5: STATISTICAL ANALYSIS OF DATA

The data presented in the previous chapter is, particularly for one tire. Studying such data for multiple tires and for multiple tests can illustrate the trends in the variability of the data and what could be the factors affecting it. The data being plotted with MATLAB codes have the ability to generate means and standard deviations indicating some aspects of variability and a rough estimate of where the variability would have come from. The standard deviations or the variability in these plots is the collective variability observed in data under a particular set of conditions the tire has been tested. The total variability is the summation of parts contributed by the individual sources of variability. It is important to have knowledge of these factors and their individual contributions in order to design an experiment to achieve minimum variability. Further, as the tire test has to comply with the protocol, there are some factors that cause variability but cannot be controlled to reduce the effect; these factors can be referred to as uncontrollable factors. The complexity of the problem is further raised because of the nested nature of the factors. The interactions between these factors result in one source of variability linked to another and coexist and it is hard to separate these nested components to quantify individual contributions. It is equally important to know whether the factor causing variability affects the response significantly and whether the variability produced is significantly different than the other contributions.

Statistical analysis plays a critical role in quantifying the variability components and their significance in the total variability. There are some analysis models applied in this study depending upon the required results. Mainly, Analysis of Variance (ANOVA), the test of equal variances, and Mixed effect model are implemented to statistically study the pool of data simultaneously for all tires. The most important benefit of this kind of study is its ability to predict results that hold true for the whole population by analyzing a limited sample of data.

5.1 Tire Variability

It is said that every tire that rolls of the manufacturing plant is different, even though having the same design, construction, materials, and production batch. There are inherent differences in every tire due to variability induced in manufacturing instruments themselves. Generally, tire studies are done on a certain number of tires from the same batch to have enough volume of data. Especially in the studies where the effect of some factor on selected response variable is to be studied explicitly or the studies such as the one presented here or in [5], knowing tire variability plays a critical role. Continental tires used here are intentionally made different from one another and hence the tire variability for these tires is expected to be high and the properties are significantly different. This is confirmed from the results of ANOVA done on these 5 tires. Michelin tires are from the same production batch and expected to have the same properties which can be seen from the ANOVA results on these tires. To get required replicates for the mixed effect model, test data from two or more tires have been used. For the analysis to be valid, these tires have to be statistically the same. Hence ANOVA serves a medium to identify whether Michelin tires have the same properties and justify the Mixed Effect Model analysis.

As it is known, every test has been conducted at 5 loads and data analysis yields 6 performance characteristics, performing ANOVA for every load and every property was time-consuming and doesn’t seem practical. Referring to [5], the paper presents a statistical study done on multiple tires which focuses on cornering and aligning stiffness as these two properties are of more importance in the industry than others. Hence, for the ANOVA of these Michelin tires, cornering and aligning stiffness at the lowest and highest loads were considered. From Table 12, (though the table shows a summary of Continental tire, it applies to Michelin tire as well) it is observed that cornering stiffness has higher variability at low loads while aligning stiffness has the highest variability at highest load. So, considering the lowest and highest loads provides the most inclusive idea about the tire variability. CS & AS data from Test 4 to 9 of all 4 Michelin tires was considered in this analysis.

ANOVA is the technique to compare three or more means with hypotheses as follows,

$$H_0 = All\ means\ are\ equal$$

$$H_1 = At\ least\ one\ mean\ is\ diffenent$$

According to these hypotheses, ANOVA can only predict whether all means are equal or at least one mean is different. To identify the different mean, there are some additional tests to be carried out. In this study, Tuckey and Dunnett's tests are performed to identify significantly different mean. Details of these tests can be found in [15]. As one-way ANOVA was performed, only one factor can be analyzed at a time for specified levels. In this case, tire serial number can be considered as a factor with 4 different levels with response variables CS and AS. Snip of MINITAB worksheet with the data inserted is shown below.

C1	C2	C3	C4	C5	C6	C7	C8	C9
Mich 70 CS 320	Mich 71 CS 320	Mich 02 CS 320	Mich 08 CS 320		Mich 70 CS 1609	Mich 71 CS 1609	Mich 02 CS 1609	Mich 08 CS 1609
636.265	663.208	661.923	633.797		2636.33	2632.23	2547.34	2635.98
646.626	651.035	650.520	632.133		2614.41	2608.02	2553.46	2627.23
646.531	642.025	654.393	634.451		2638.83	2630.65	2565.58	2626.72
654.883	659.230	627.667	647.243		2641.59	2634.03	2537.59	2610.86
612.941	630.133	650.881	639.734		2623.61	2612.84	2553.35	2610.14
622.407	638.398	637.920	640.474		2624.28	2616.42	2551.10	2609.45

Figure 24: Data for Tire Variability

The 6 rows are considered as replicates on for each level of factor (each row is a test from 4 to 9). Columns from C1 to C4 are the levels of factors, that is 4 tires and entries are response variables (CS & AS). Each response can be seen at two loads, 1423 N (320 lb.) and 7156 N (1609 lb.). Similar data entries are done for aligning stiffness. The results of ANOVA are discussed below.

Before going to the results, it is important to be familiar with the significance level and P-value. P-value is the probability of ending up in a type 2 error. (Type two error refers to not rejecting the null hypothesis when it is not true). That is when the P-value is less than the specified significance level, the factor creates a significant change in the response. In this case, if the P-value of the ANOVA analysis is less than the significance level of 0.05, it indicates that the means are significantly different leading to the conclusion that tires are statistically different from one another.

Table 13: ANOVA of Michelin Tires for CS at 1423 N load

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	604.1	201.4	1.33	0.292
Error	20	3025.8	151.3		
Total	23	3629.9			

Table 13 shows the MINITAB output with statistical terms such as degree of freedom, the adjusted sum of squares, adjusted mean squares for factor and error. The factor represents the tire serial number having 4 levels. SS and MS are used to calculate the F-statistics value used for calculating the P-value and confidence intervals on means. Details about these calculations can be found in [15]. This study considers the P-value. The P-value for this analysis is 0.292 which is greater than the significance level of 0.05 which signifies that the means are not statistically different, and tires can be considered to be the same at the normal load of 1423 N. Tires can behave differently at other loads and this can be proved with ANOVA at highest load shown in Table 15.

Table 14: Mean values of CS at 1423 N load

Means				
Factor	**N**	**Mean**	**StDev**	**95% CI**
Mich 70 CS 320	6	636.61	16.09	(626.13, 647.08)
Mich 71 CS 320	6	647.34	12.74	(636.86, 657.81)
Mich 02 CS 320	6	647.22	12.33	(636.74, 657.69)
Mich 08 CS 320	6	637.97	5.64	(627.50, 648.45)
Pooled StDev = 12.2999 and Dev in means = 5.7964				

In the above Table 14 ‘N’ is the number of replicates available and the ‘StDev’ is the standard deviation of those N replicates. Simply it is the deviation of each column in Figure 24. There is a significance of these values which is explained in the next section. Now, the tire variability can be understood as a standard deviation in tire properties that is, from the above Table 14, tire variability in CS at 1423 N will be the standard deviation of those mean values in column 3 which comes out to be 5.796 N/deg. But tire variability cannot be defined solely from one analysis, it might be different at some other loads and it might be different for other properties such as aligning stiffness. The tire variability will be the average of the values of deviations at the lowest and highest loads.

Table 15: ANOVA of Michelin Tires for CS at 7156 N load

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Factor	3	24089	8029.5	70.94	0.000
Error	20	2264	113.2		
Total	23	26352			

Contrary to the results for 1423 N load, these results show that at least one mean is different out of four values, but this analysis does not identify that mean. Dunnett comparison test is conducted to identify it. The P-value is less than the significance level.

Table 16: Mean values of CS at 7156 N load

Means				
Factor	**N**	**Mean**	**StDev**	**95% CI**
Mich 70 CS 1609	6	2629.84	10.67	(2620.78, 2638.90)
Mich 71 CS 1609	6	2622.36	11.26	(2613.30, 2631.42)
Mich 02 CS 1609	6	2551.40	9.13	(2542.34, 2560.46)
Mich 08 CS 1609	6	2620.06	11.36	(2611.00, 2629.12)
Pooled StDev = 10.6390 and dev in means= 36.5824				

Table 17: Dunnett Comparison for CS at 7156 N load

Dunnett Multiple Comparisons with a Control Grouping Information Using the Dunnett Method and 95% Confidence			
Factor	**N**	**Mean**	**Grouping**
Mich 70 CS 1609 (control)	6	2629.84	A
Mich 71 CS 1609	6	2622.36	A
Mich 08 CS 1609	6	2620.06	A
Mich 02 CS 1609	6	2551.40	
Means not labeled with the letter A are significantly different from the control level mean.			

The Dunnett multiple comparison test identifies Michelin 78602 to have different cornering stiffness than other tires at 7156 N (1609 lb.) load. Due to this, the deviation in means is higher. Also, the pooled deviation value seems slightly lower than the value at 1423 N (320 lb.) load. The following tables show a similar analysis for aligning stiffness of the tires.

Table 18: ANOVA of Michelin Tires for AS at 1423 N load

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Factor	3	0.6205	0.20683	9.36	0.000
Error	20	0.4418	0.02209		
Total	23	1.0623			

Table 19: Mean values of AS at 1423 N load

Means				
Factor	**N**	**Mean**	**StDev**	**95% CI**
Mich 70 AS 320	6	4.5555	0.1921	(4.4289, 4.6820)
Mich 71 AS 320	6	4.8056	0.1286	(4.6791, 4.9322)
Mich 02 AS 320	6	4.7594	0.1590	(4.6328, 4.8859)
Mich 08 AS 320	6	4.4058	0.0981	(4.2792, 4.5323)
Pooled StDev = 0.148629 and Dev in means= 0.1857				

Table 20: Dunnett Comparison for AS at 1423 N load

Grouping Information Using the Dunnett Method and 95% Confidence			
Factor	**N**	**Mean**	**Grouping**
Mich 70 AS 320 (control)	6	4.5555	A
Mich 71 AS 320	6	4.8056	
Mich 02 AS 320	6	4.7594	A
Mich 08 AS 320	6	4.4058	A
Means not labeled with the letter A are significantly different from the control level mean.			

Table 21: ANOVA of Michelin Tires for AS at 7156 N load

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Factor	3	29.52	9.8400	17.75	0.000
Error	20	11.09	0.5543		
Total	23	40.61			

Table 22: Mean values of AS at 7156 N load

Means				
Factor	**N**	**Mean**	**StDev**	**95% CI**
Mich 70 AS 1609	6	104.374	1.097	(103.740, 105.008)
Mich 71 AS 1609	6	102.190	0.679	(101.556, 102.824)
Mich 02 AS 1609	6	103.004	0.621	(102.370, 103.638)
Mich 08 AS 1609	6	105.009	0.408	(104.375, 105.643)
Pooled StDev = 0.744492 and dev in means= 1.2806				

Table 23: Dunnett Comparison for AS at 7156 N load

Grouping Information Using the Dunnett Method and 95% Confidence			
Factor	**N**	**Mean**	**Grouping**
Mich 70 AS 1609 (control)	6	104.374	A
Mich 08 AS 1609	6	105.009	A
Mich 02 AS 1609	6	103.004	
Mich 71 AS 1609	6	102.190	
Means not labeled with the letter A are significantly different from the control level mean.			

Generally, the variabilities are defined in percentages calculated with respect to the total range of forces and moments that the machine can either record or sustain without failing. In the case of M-15, the exact maximum range was unknown. Also, the machine was calibrated at the university with limited resources. Even though the maximum forces were known, one could be confident about the behavior of load cells within the range for which it has been calibrated. The nature of load cells might be different at extremely high loads, and present calibration might not hold true in that range giving completely different values of variability. Considering this possibility, the percentages are calculated with respect to the calibrated range defined as follows.

Calibrated Range for Lateral Force: ± 5337.6 N (1200 lb.)

Calibrated range of Aligning Moment: ± 106.75 N-m (78.74 ft-lb)

As a conclusion of the above discussion and ANOVA results, Table 24 below summarizes the tire variability values as an average of values at both the loads.

Table 24: Summary of Tire Variability

Load (N)	**Variability in CS (N/deg)**	**Variability in AS (N-m/deg)**
1423	5.7964	0.1857
7156	36.5824	1.2806
Mean	21.189	0.733
% of calibrated range	**0.3969**	**0.6866**

5.2 Machine Variability

Machine variability is the variability produced in the data as a consequence of the electronic noise, calibration errors, and due to mechanical limitations of the moving parts. Every experimental setup has inherent machine variability in the produced data. In case of M-15, noise in the electronic system, accuracy of slip angle control and measurement system, control for the vertical loading actuator, any vibrations induced due to working of machine and drive system are the potential sources of machine variability. Another potential source identified is explained in section 2.6 and can be easily eliminated by acquiring the data for at least one complete revolution of the tire. Machine variability cannot be eliminated completely though it can be accounted for and reduced by improving the hardware system that is causing it. Improving the control system of actuators can be very expensive and time-consuming. Accounting for the machine variability can facilitate a method to compensate for it in the data if it is beyond the acceptable limits.

Estimating machine variability requires the data where the contribution from other variability sources is minimum. Considering this, the tire data where tests are conducted continuously without unmounting the tire would serve as a good basis to run the analysis for machine variability. Testing tires continuously for multiple tests may increase the temperatures and create unwanted variability in the data. But the tire surface temperature change from the recorded data was not significant to alter the tire properties and induce variability. According to [5], approximately 10 to 11° F of change does not create any significant change in properties and the maximum temperature rise observed during this study was 3° C (approx. 5° F) which indicates that temperature has no significant effect on tire properties during the continuous tests.

Using the data of CS and AS for tests 4 to 9 at 1423 N and 7156 N on all Michelin tires, initially, a test of equal variances was performed. The same data as shown in Table 24 can be used for this analysis. The test of equal variances indicates whether the variances of every set are equal. The logic behind checking for equal variances is to verify machine variability is the only source of variability in the data. It can be assumed that machine variability is the only variability source if the variance for each tire is equal. As expected, the variance values were not exactly the same, but those values were not significantly different either.

Test on equal variances showed that the variance of each group is statistically the same, and hence the results from Analysis of Variance can be used to estimate machine[1]

[1] **Note:** If the data used for analysis is not normal, MINITAB program gives P-values according to Levene's test as well as Multiple Comparisons test. Multiple Comparisons provide more reliable and accurate P-values.

variability. ANOVA gives out the term called ‘Pooled Standard deviation’ which is the average of standard deviations of each column in Figure 24 (applies to all other columns). Referring to the assumption made earlier, if the variability is only due to the machine, this pooled standard deviation can be considered as machine variability. Similar to the tire variability, machine variability can be different for different parameters but calculating it for CS gives an idea about plysteer and conicity while AS gives an idea about residual torques associated. Table 25 shows a summary of machine variability collected from ANOVA results in the previous section.

Table 25: Summary of Machine Variability

Load (N)	**Pooled StdDev of CS (N/deg)**	**Pooled StdDev of AS (N-m/deg)**
1423	12.299	0.1486
7156	10.639	0.7444
Mean	11.469	0.4465
% of calibrated range	**0.2148**	**0.4182**

5.3 Effect of Load on Variability

Looking at the ANOVA results and the standard deviations, one might argue that the variability is somehow dependent on the normal load. To elaborate this, consider the ‘n’ number of tire tests at some load say 1423 N (320 lb.) and the same number of tests under the same conditions at 7156 N (1609 lb.). Dependence of variability on load would lead to different values of the standard deviation of ‘n’ tests at 320 lb. and the deviation of ‘n’ tests at 1609 lb. Here, the deviation of tests refers to the deviation in values of calculated parameters (CS, AS, etc.) for ‘n’ tests.

On analyzing the data for equal variances this assertion was found to be valid. There are some parameters that show sensitivity to the load in terms of variability.

Results show a significant change in variability from lower loads to the higher specifically for the aligning stiffness. The equal variance test was done on Altimax 89 and 91 considering tests from 1 to 9 at each load. 4 parameters, CS, AS, PLF, and CLF were analyzed. The results are shown below. Equal variance test has the option to select whether the data are normal and depending on the normality it selects the appropriate test. A simple normality test was performed to check the normality of the data. This can be found in the 'Basic Statistics' tab in MINITAB.

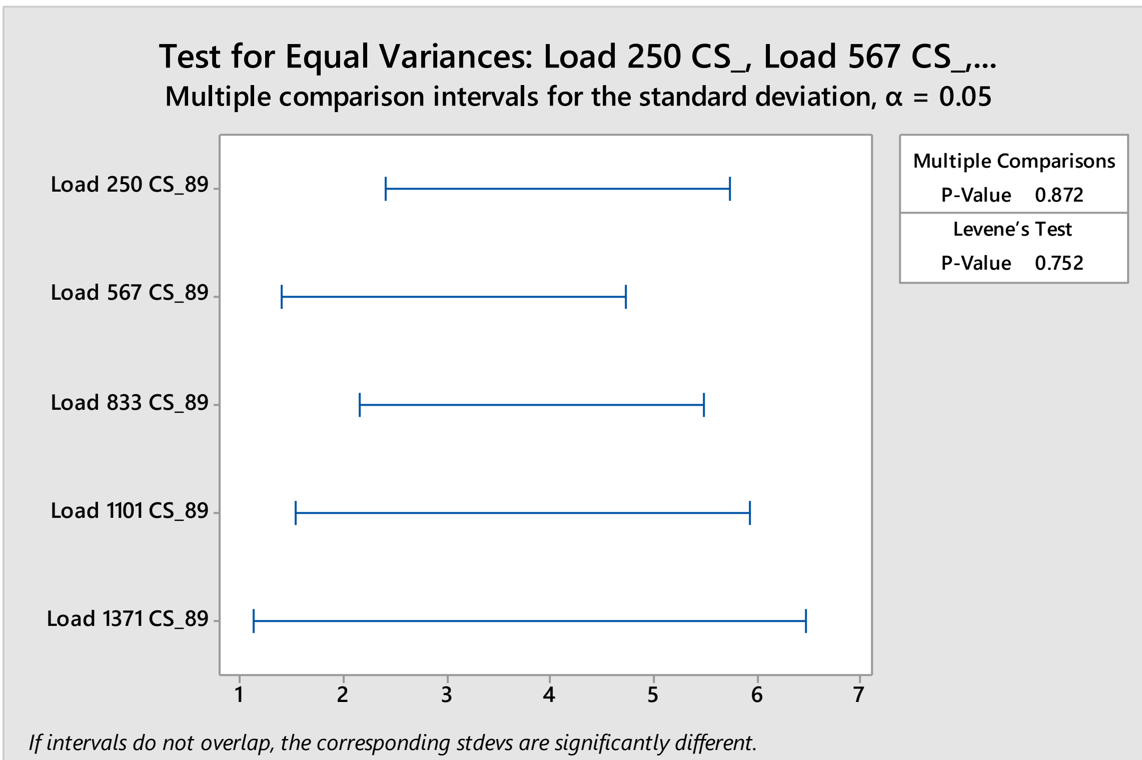

Figure 25: Equal Variance Test for all loads (CS, Altimax 89)

If the normality test is not satisfied by the data, Multiple Comparisons and Levene's tests are conducted and P-values are displayed in the graphs. It's to be noted that the significance level of 0.05 (95% confidence interval) was selected throughout the analysis. If the P-value is less than the α selected, at least one standard deviation is different. Hence, Figure 25 indicates that the variability in cornering stiffness is unaffected by the normal load. The results are different for the aligning stiffness. Variability of Aligning Stiffness seems to be dependent on load and this trend is seen in both the tires analyzed. Figure 26 shows confidence interval for AS at all loads and it can be observed that intervals for first and third loads are not overlapping showing significantly different standard deviations.

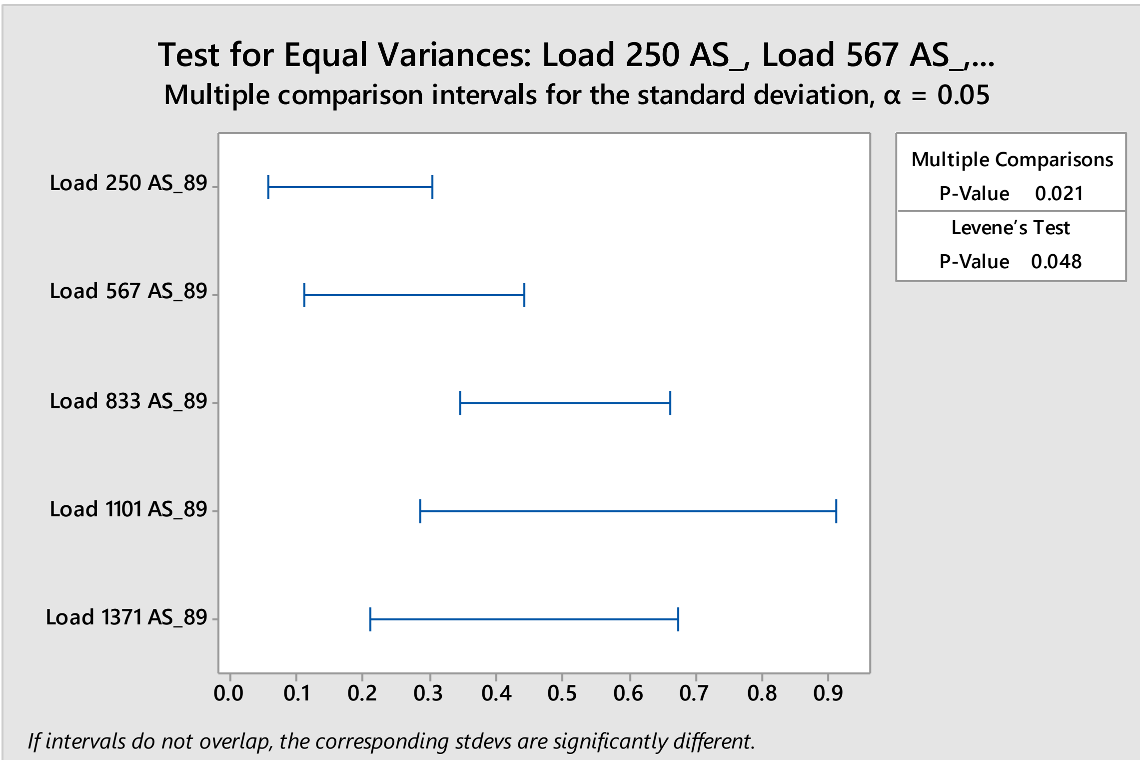

Figure 26: Test of Equal Variances for all loads (AS Altimax 89)

The exact reason behind this behavior is unknown and can be a subject of study independently. Another interesting observation is about the plysteer of these tires. Equal variance test on plysteer (same test done for CS and AS) for Altimax 89 shows a significant change in deviation with a load while results contradict for Altimax 91. This leads to the doubt that this change in deviation could be a tire specific phenomenon. Variability in conicity seems robust to the normal loads and does not show any significant change.

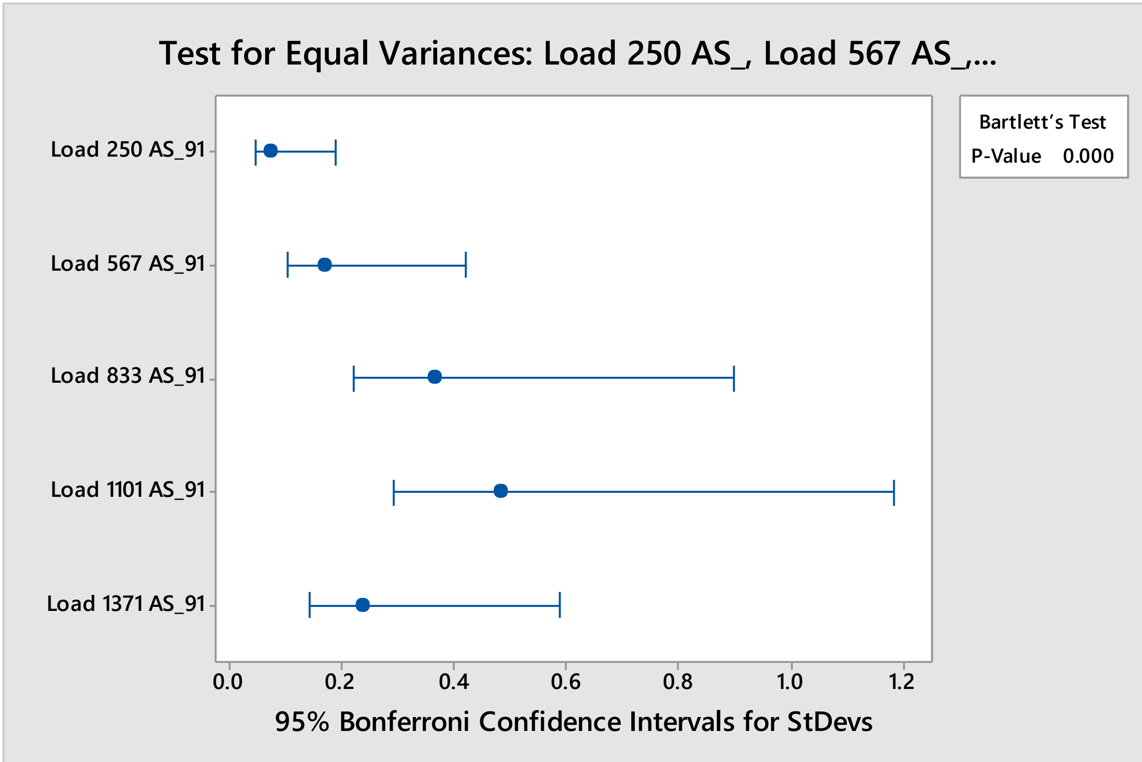

Figure 27: Test of Equal Variances for all loads (AS Altimax 91)

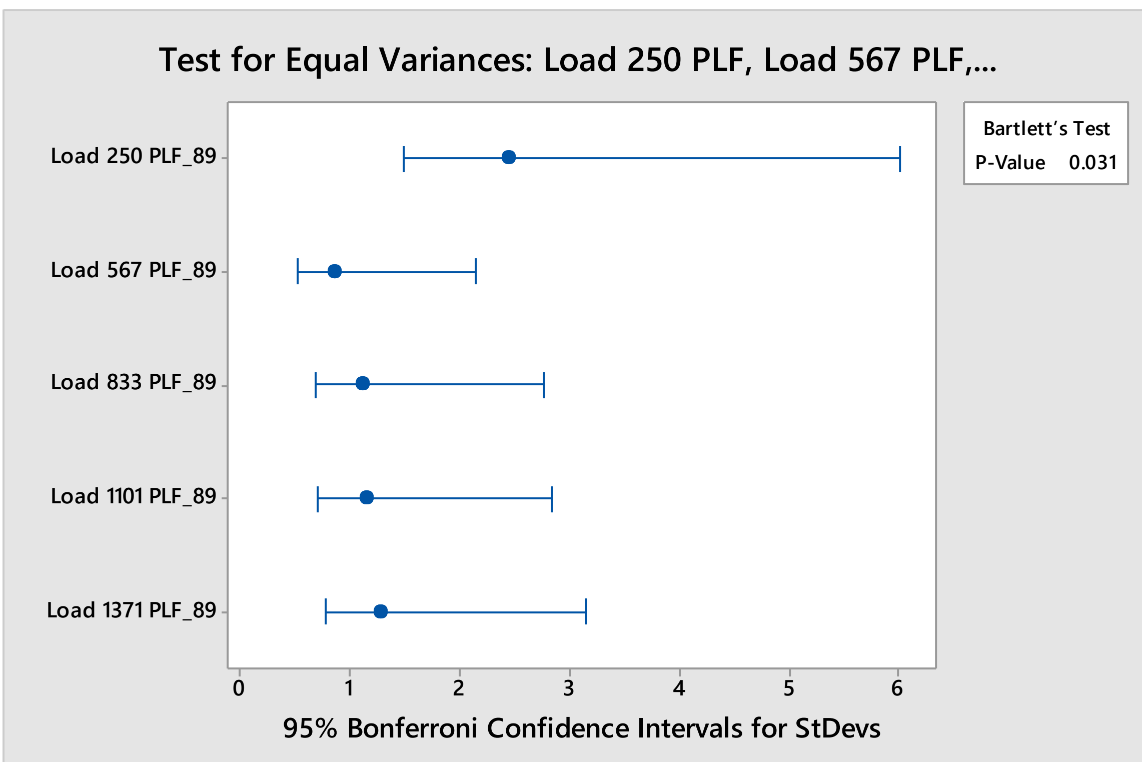

Figure 28: Test of Equal Variances at all loads (PLF Altimax 89)

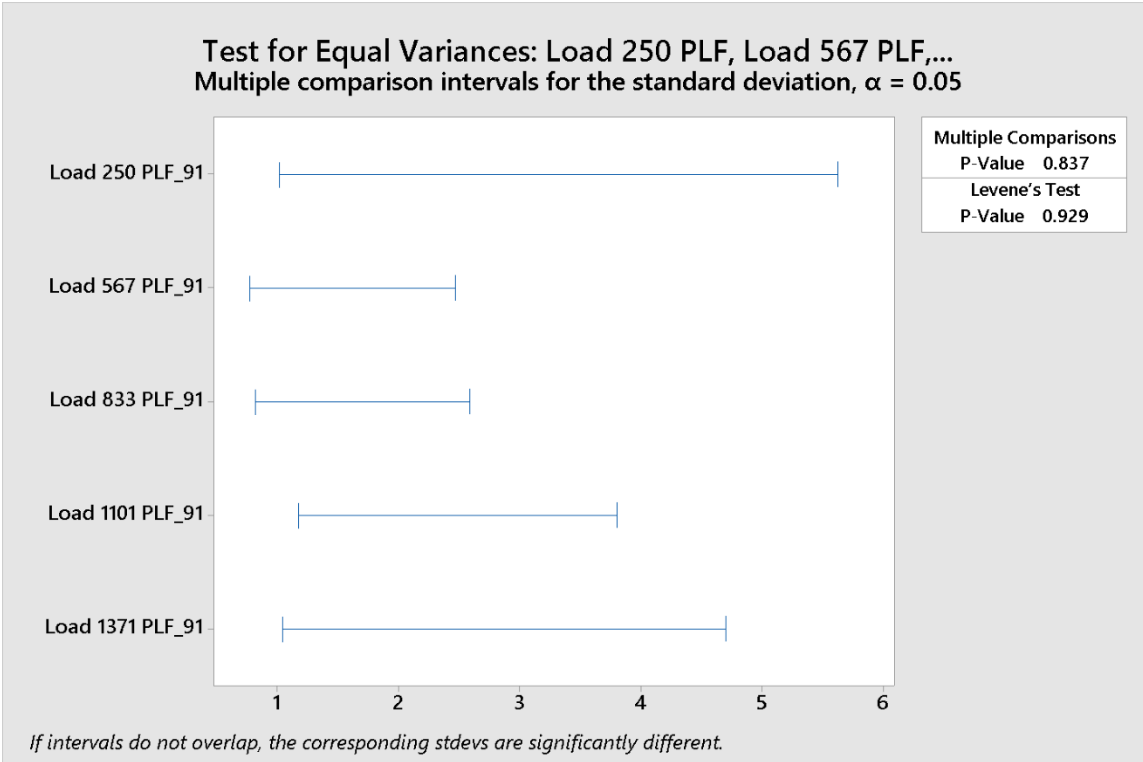

Figure 29: Test of Equal Variances at all loads (PLF Altimax 91)

The confidence interval indicates the range which the estimated value will fall within to satisfy the specified confidence level. That is if the confidence interval of 95% is specified, the span indicates the range in which the estimate could be, to have the estimate within 95% of the mean. That is, if the span of this confidence interval is greater, there is a higher probability of ending up on a higher standard deviation. The knowledge about the dependence of variability on normal load might be useful in justifying the higher total variability in mixed-effect model analysis explained in the successive section of the document.

5.4 Effect of Unmounting and Break-in on Variability

The contributions made by factors like unmounting and mounting, break-in process on the tire, and the cooldown will be discussed in sections later. This section explains the analysis conducted to have an estimate about how the variability is affected in general when testing conditions are changed. The analysis gives the estimate of the standard deviation and a 95% confidence interval for every testing condition. For example, for estimating condition which gives lesser variability between continuous tests and the tests with unmounting the tire, an equal variance test was performed on the respective data to get an estimate of variability. The important aspect is to identify the testing condition which produces lower variability. This can be done by observing the confidence intervals on the estimated value of the standard deviation. The conditions with a narrower confidence interval will have lower variability. Also, every analysis related to this section was carried out for the highest load of the test.

5.4.1 Effect of Unmounting the Tire from the Rim

The plots in Chapter 4 show deviations plotted along with the means against test the number. The observable reduction in error bar spans (deviations) from the first three tests to the continuous tests leads to the suspicion that unmounting the tire from rim might be responsible for any additional variability. Higher variability was expected in the first few tests as tires might be changing during those tests but there could be an additional contribution from the unmounting process which can be eliminated by simply keeping the tire on the rim for all the tests. Before going for any suggestions, the data was to be analyzed. To eliminate tire variability, this analysis was done on the data of the same tire. One of the data sets was formed with parameters from Tests 4 to 9 and another was from 10 to 12. One of the sets contains data where the tire was not unmounted, and another set is with unmounting the tire. Tests 10 to 12 are selected intentionally as these tests were taken when the tires have already been worked enough which reduces the probability of tire evolution and variability due to break-in as well. Altimax 89, 91,92, and 93 were analyzed for this section. Among these tires, Altimax 91 shows a significant difference in variabilities for the two testing conditions mentioned, while others don't. Though, a decrease in variability can be observed for the tests where the tire was kept on the rim and tested without unmounting it. It is to be noted that the primary concern here is variability or the standard deviations. There might be a significant change in mean values of the properties of the tire between these sets of data considered but, it is not that important while studying the variability.

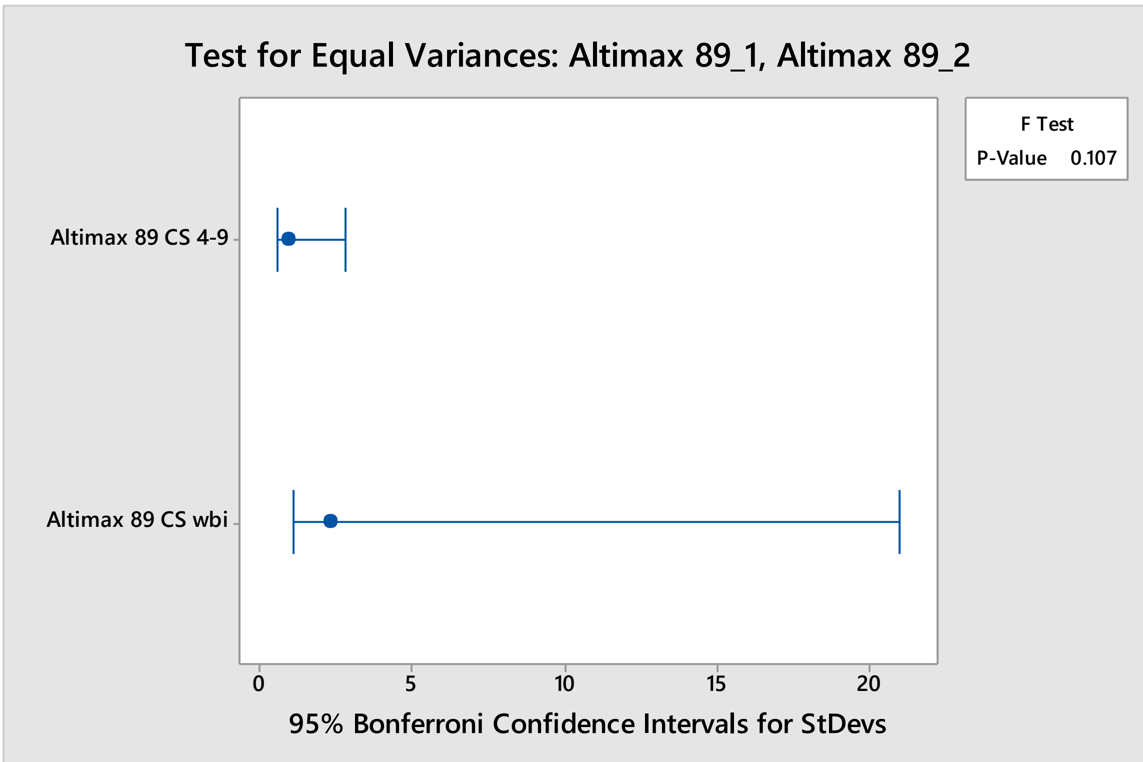

Figure 30: Test for equal Variances- Unmounting effect Altimax 89 CS

The Y-axis represents the conditions being tested along with the property and tire serial number. 'wbi' stands for without break-in. The difference in confidence intervals can be seen clearly along with the estimates of standard deviation (Points show this estimate). The data were tested for normality and the corresponding option was selected in Minitab. P-value is greater than the significance level which predicts no significant difference in standard deviations, but it seems reduced considerably when the tire was kept on the rim (interval on top in the graph). Similar results were obtained for Aligning Stiffness, Plysteer, and Conicity of Altimax 91, 92, and 93 as well. To keep this as concise as possible other plots are not included and can be found either in the Minitab project named 'STATISTICAL ANALYSIS_ALTIMAX(1).mpj' or in the word document 'Unmounting effect analysis'. Results for Altimax 91 are presented below as it shows some different trend than other tires.

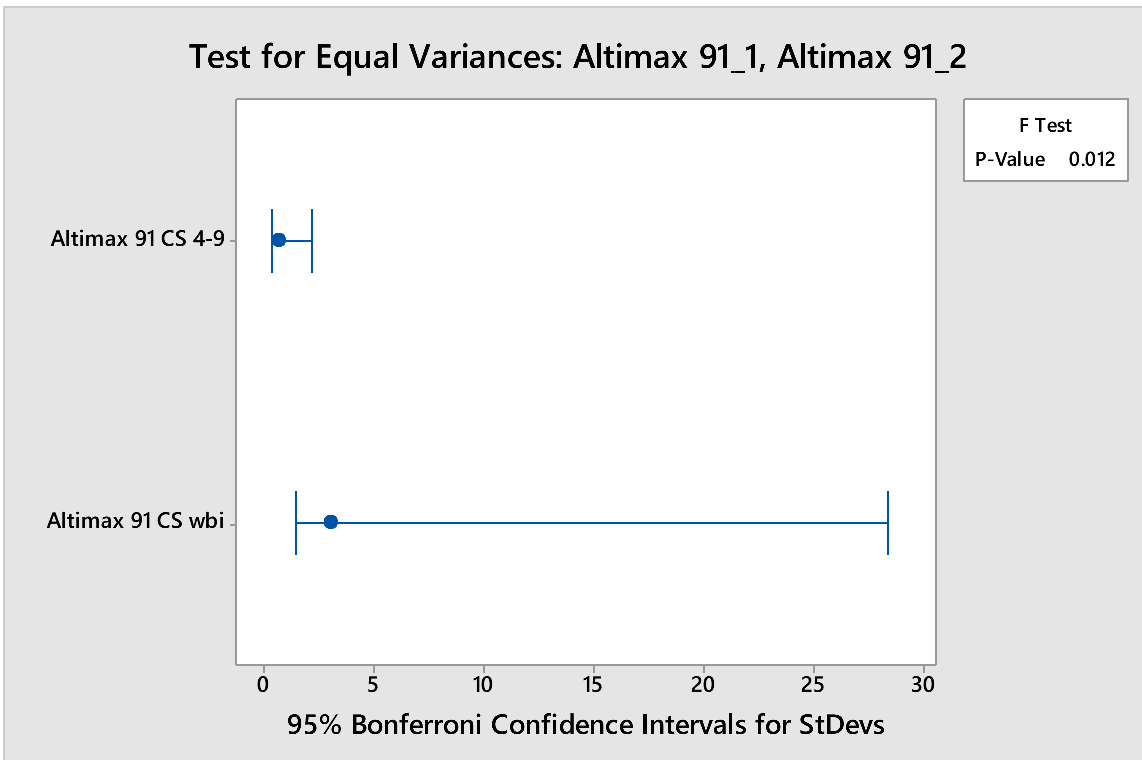

Figure 31: Test for equal Variances- Unmounting effect Altimax 91 CS

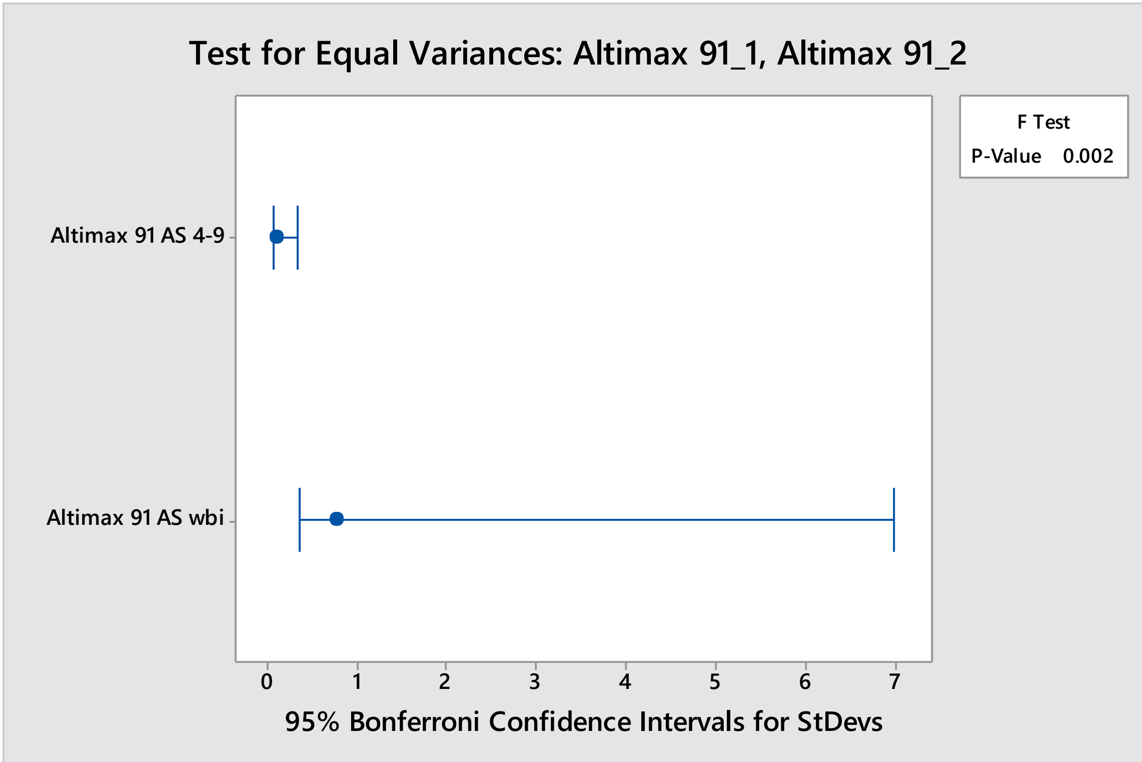

Figure 32: Test for equal Variances- Unmounting effect Altimax 91 AS

Standard deviations for Cornering and Aligning Stiffness are significantly different from two conditions. These results show, if the tire is tested without unmounting it for multiple tests, variability in the data can be reduced significantly. This significant change (P-value= 0.012 & 0.002) is observed only for Altimax 91 so, it might be a chance occurrence as other tires do not show the significant change. But it should be noticed that this might be the case with some tires.

5.4.2 Effect of Break-in on Variability

Tests in Set 5 are designed to analyze whether break-in has any significant effect on variability. The study in [5] does focus on the same phenomenon but implies considerably different break-in procedures and dated back in 1978. It is highly possible that tires being used today may behave quite differently. So, for this analysis, variability in Tests 1,2, and 3 is compared to the variability of Tests 10,11, and 12. These tests are conducted in exactly similar conditions except the break-in process. During Tests 10, 11 and 12 tires were not broke-in before the test. As the testing conditions were the same, it can be assumed that machine variability, variability due to unmounting, and any other possible sources of variability will cause the same effect in both cases. Hence if any difference is observed, it will be mostly due to the break-in process.

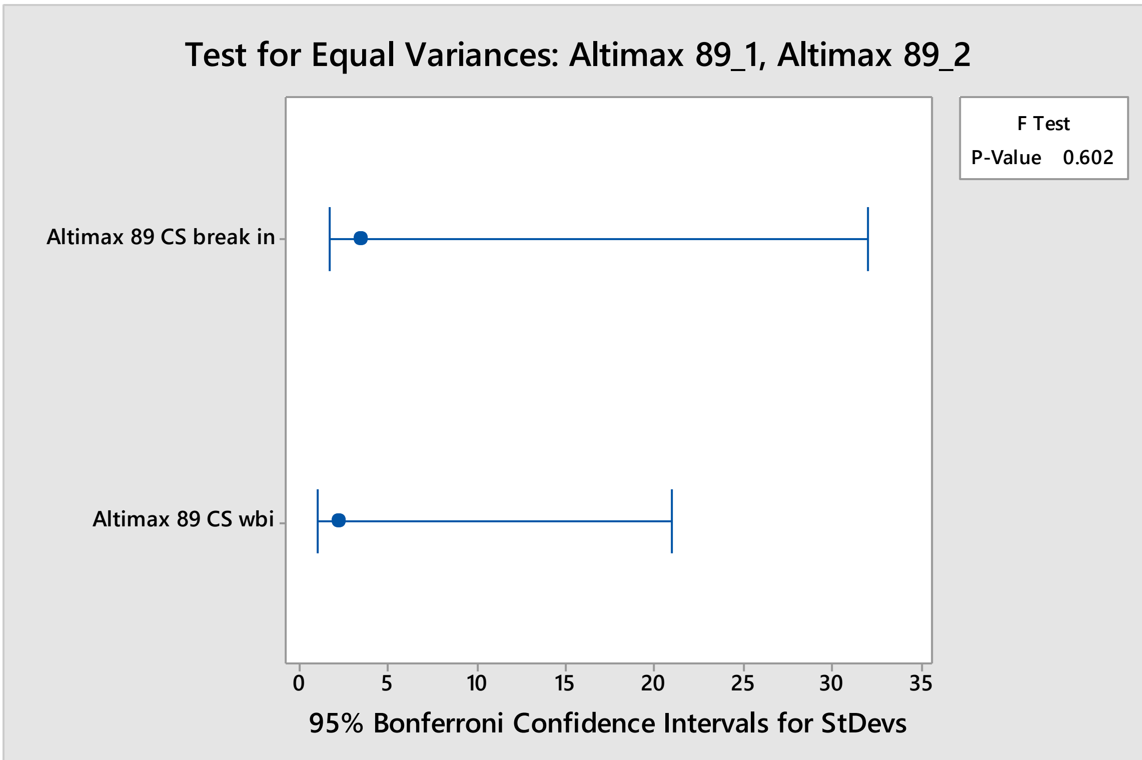

Figure 33: Test for Equal Variances- Break-in Effect Altimax 89 (CS)

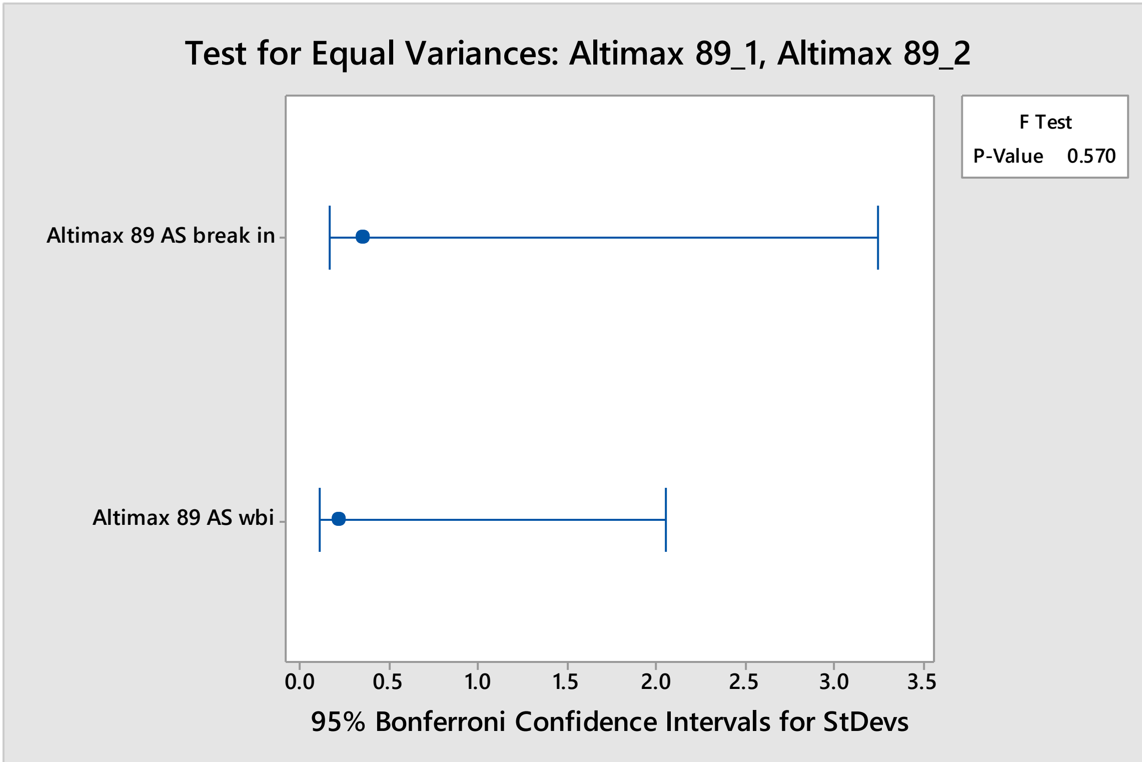

Figure 34: Test for Equal Variances- Break-in Effect Altimax 89 (AS)

The above analysis has been done at the highest load for Altimax tires which is 6098 N (1371 lb.). P-values values for the Cornering and Aligning Stiffness are greater than the significance level and hence the variances are equal for both the cases. Having equal variances corresponds to equal variability. This conclusion is similar to the one in [5]. Again, the mean values for stiffness parameters could be different for these two cases, but the quantity concerned here is the variability that seems to be equal no matter whether the tire was broken-in before the test. The same results can also be observed for other tires analyzed.

Even though the variabilities are not different for two cases, confidence intervals as well as the estimated standard deviations are observed to be different, rather estimate is slightly lower and confidence interval has shrunk when the tire was not broken-in. While this explanation holds true for stiffness parameters and conicity, plysteer shows opposite characteristics. That is the estimated deviation is lower and the interval is narrower with breaking-in the tire. This behavior is also seen in Altimax 92.

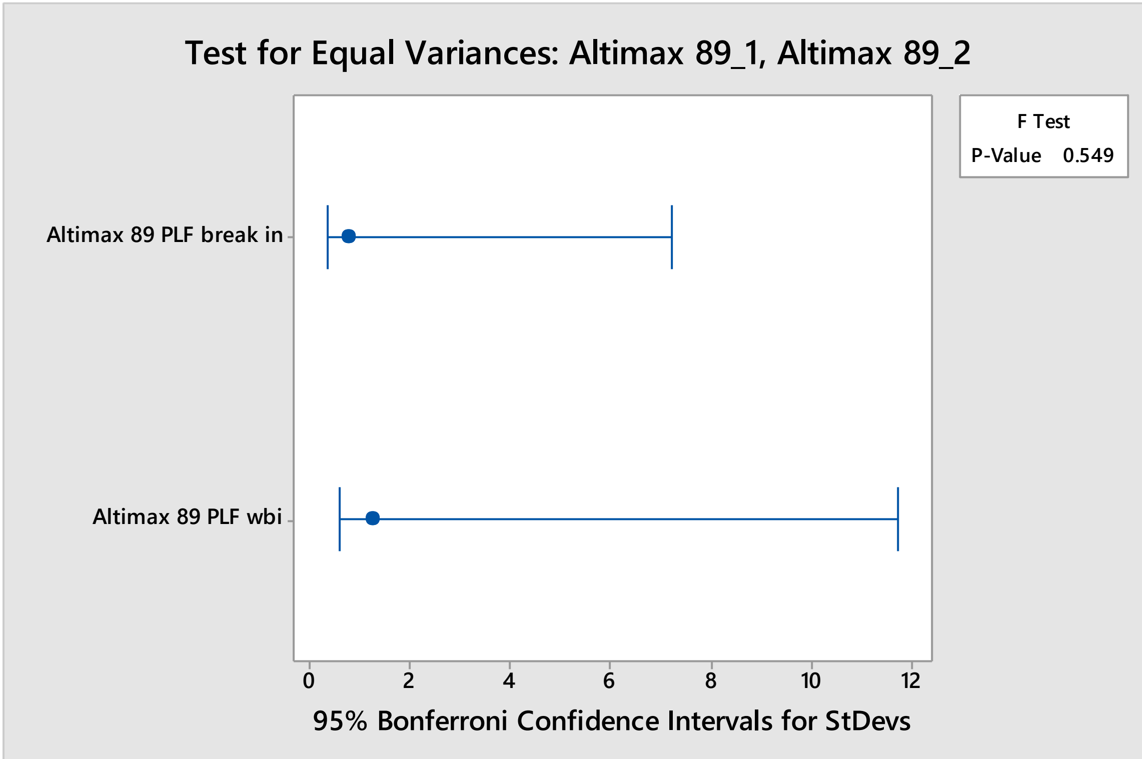

Figure 35: Test for Equal Variances- Break-in Effect Altimax 89 (PLF)

As P-value is greater than α= 0.05, the standard deviations are not significantly different but tests without break-in show higher variability in plysteer.

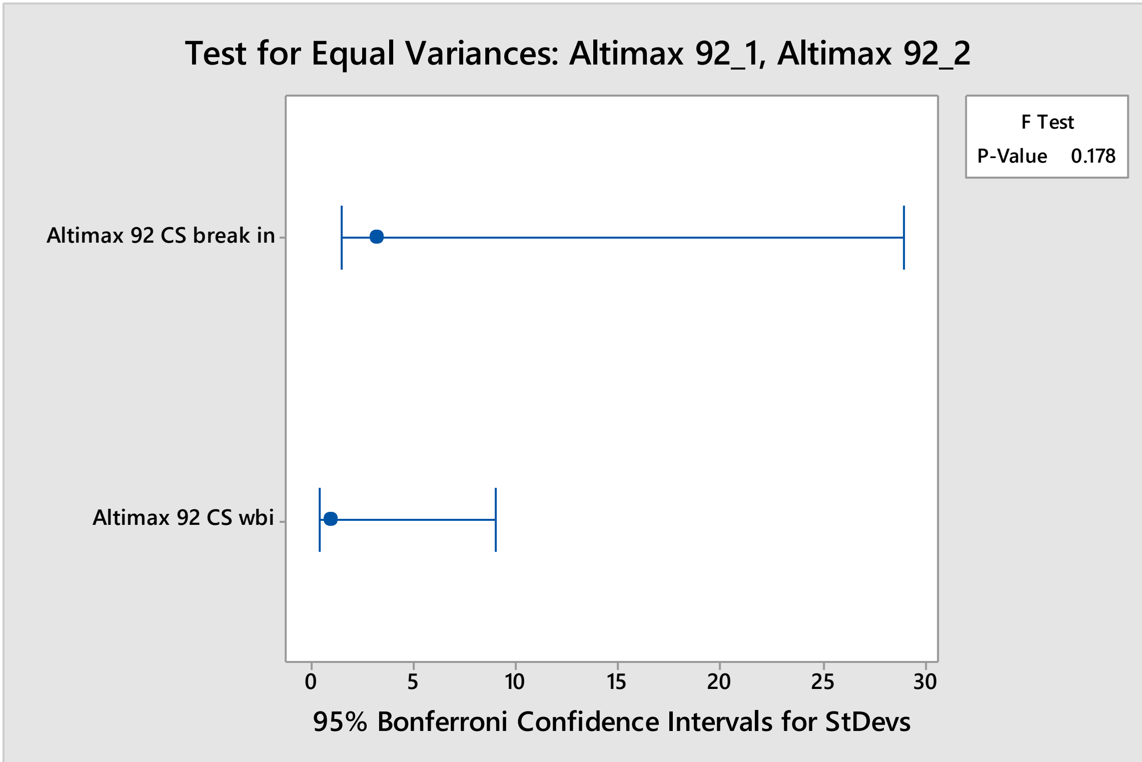

Figure 36: Test for Equal Variances- Break-in Effect Altimax 92 (CS)

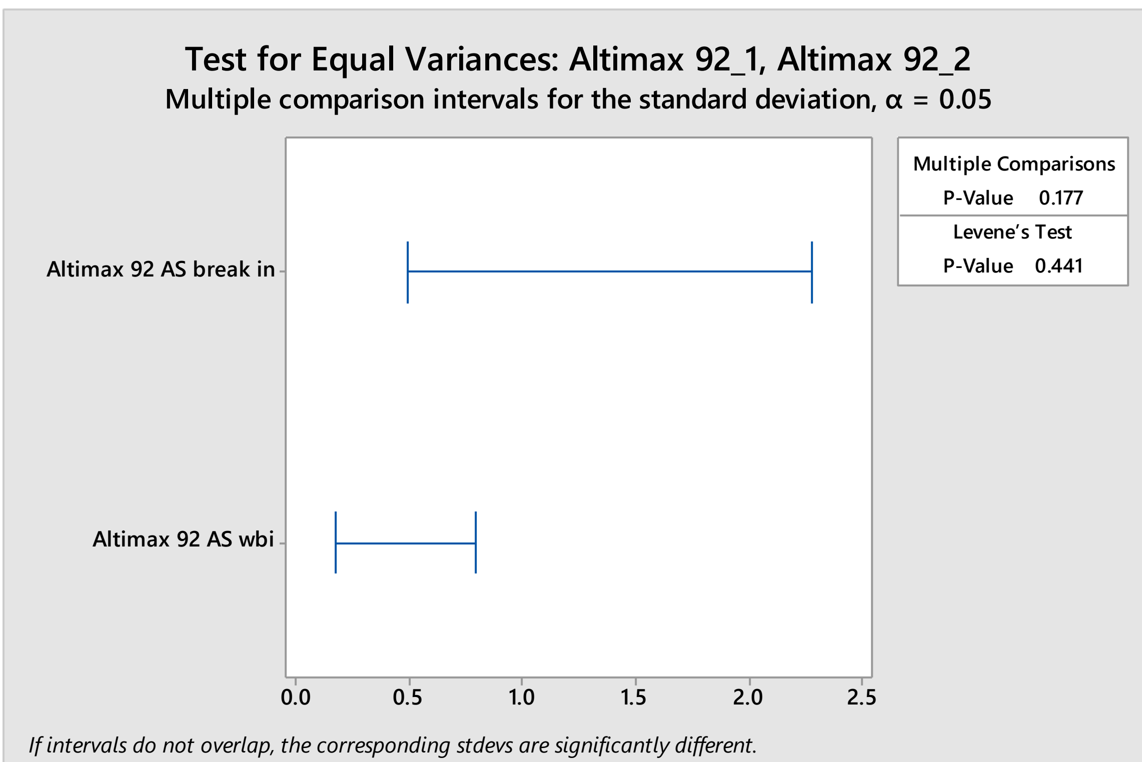

Figure 37: Test for Equal Variances- Break-in Effect Altimax 92 (AS)

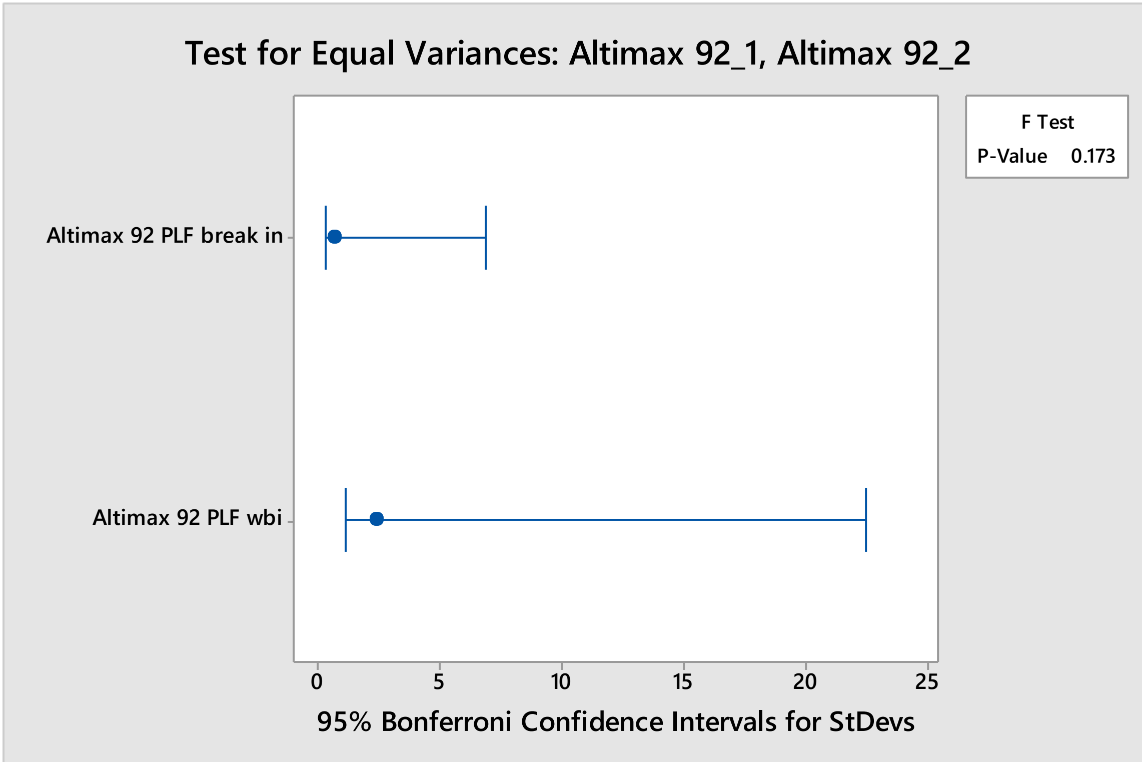

Figure 38: Test for Equal Variances- Break-in Effect Altimax 92 (PLF)

Figure 36 to Figure 38 shows the results of a test for equal variances for Cornering and Aligning Stiffness and plysteer of Altimax 92 at the highest load. A decrease in variability is observed for CS and AS while an increase is observed in plysteer when the tire was not broken-in before the test.

5.4.3 Effect of Cooldown on Variability

In set 2 and 3 of the testing, Continental and Michelin tires were divided into two groups, one tested with an idle time after 3 continuous tests, and the other group of tires was tested continuously for 6 tests without any idle time. This idle time is referred to as the cooldown process. Actually, it is more of a relaxing time for the tire after 3 continuous tests. There might be viscoelastic recoveries in the rubber compound and the belts of the tire during this idle time. Due to these possible changes, one can expect the tire to have changes in properties even so slightly, which may result in significant changes in variability if all the tests are being analyzed together without any distinction.

From the above explanation, an inference can be made that, some of the tires were tested with idle time and some are not. Hence, to compare the variability due to cooldown, at least two different tires are to be analyzed. One might argue that such analysis will add the other variability sources such as tire variability in the equation and results could be distorted. Also, if the total variability in one tire is significantly different than the other due to some unaccounted factors, it may cause problems. Hence before carrying out variance tests for the cooldown effect, equal variance tests were conducted collectively for all tires considering all tests. The result shows no significant difference in variability for every parameter. These plots can be found in the 'Minitab Graphs.doc' file.

Note: These analyses are conducted for data at the highest load of Altimax tires. (1371 lb. or 6098 N)

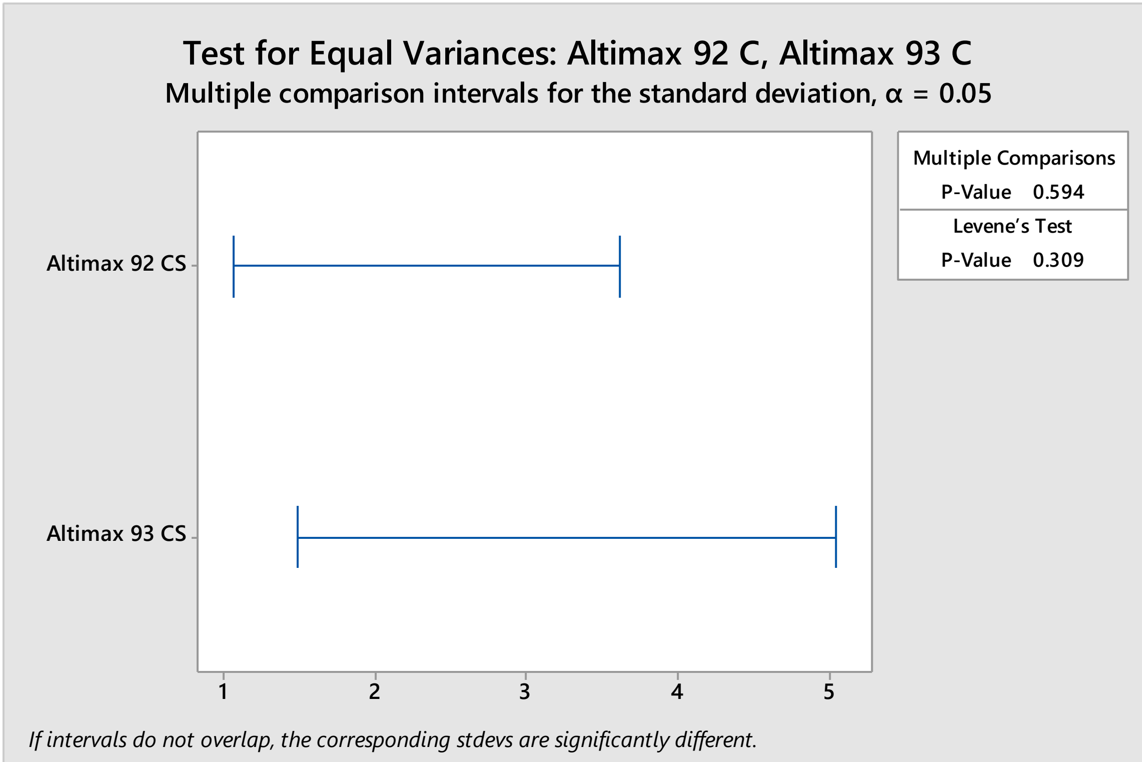

Figure 39: Test for Equal Variances- Cooldown effect (CS)

P-value is greater than the significance level, indicating no significant difference in standard deviations. Though the difference in confidence intervals and estimate of deviation is prominent. Out of those two tires in the above graph, Altimax 92 was tested without an idle period that is, it had no cooldown between the tests. The estimate of deviation is lesser for Altimax 92 than 93 and confidence interval seems shrinks as well. This verifies that the reduction in variability can be achieved if there is no idle time or else tire is tested in quick succession. Similar results are obtained for a pair of Altimax 91 and 90. The following graphs are for other parameters.

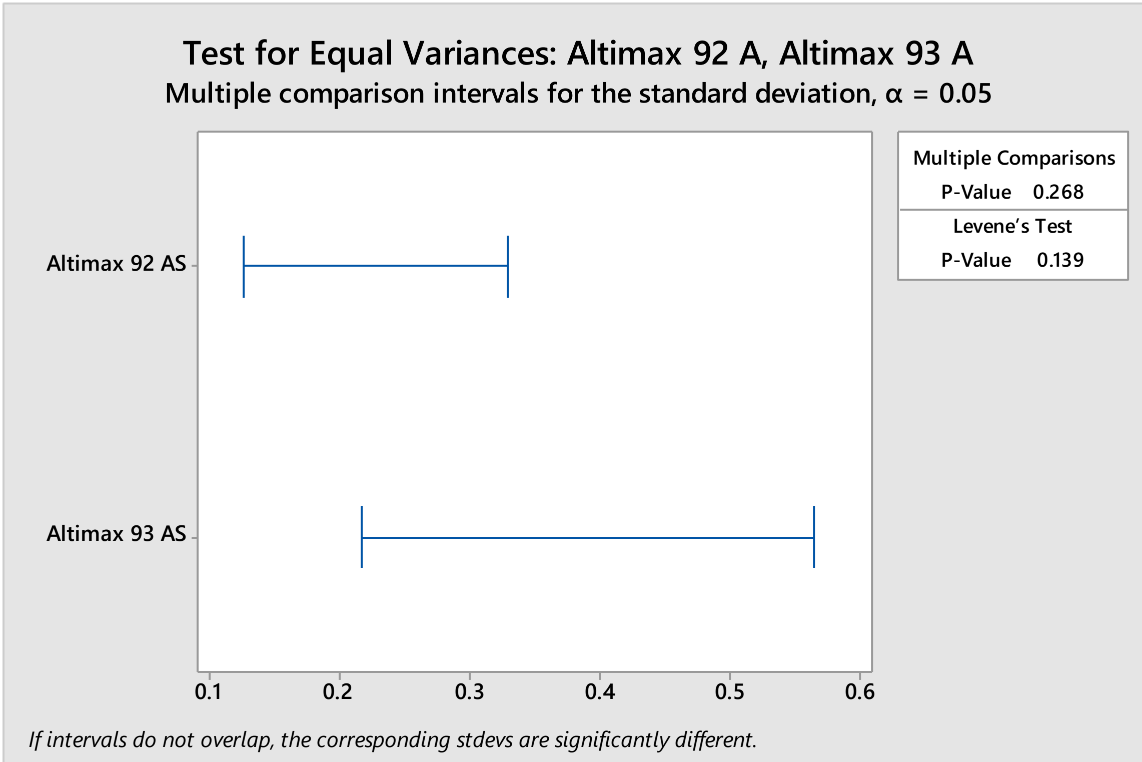

Figure 40: Test for Equal Variances- Cooldown Effect (AS)

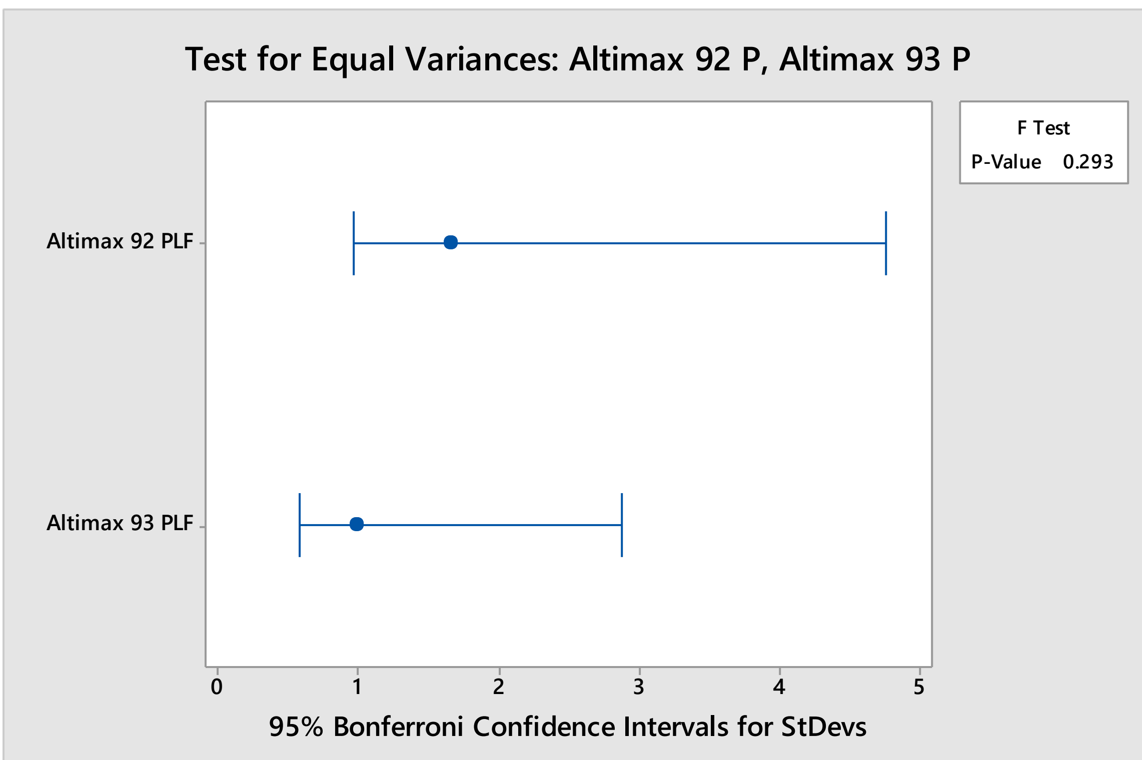

Figure 41: Test for Equal Variances- Cooldown Effect (PLF)

Figure 40 is the test for equal variance test for the plysteer of two tires. Unlike CS, AS and CLF, this shows inverted results. That is variability in plysteer is reduced when there is the idle time between tests. From the results of the current and previous sections, plysteer seems anomalous to the general trend. That is the variability in the parameters reduces if the tire doesn't undergo break-in and is tested continuously without cooldown, variability in plysteer would be expected to go higher on the other hand.

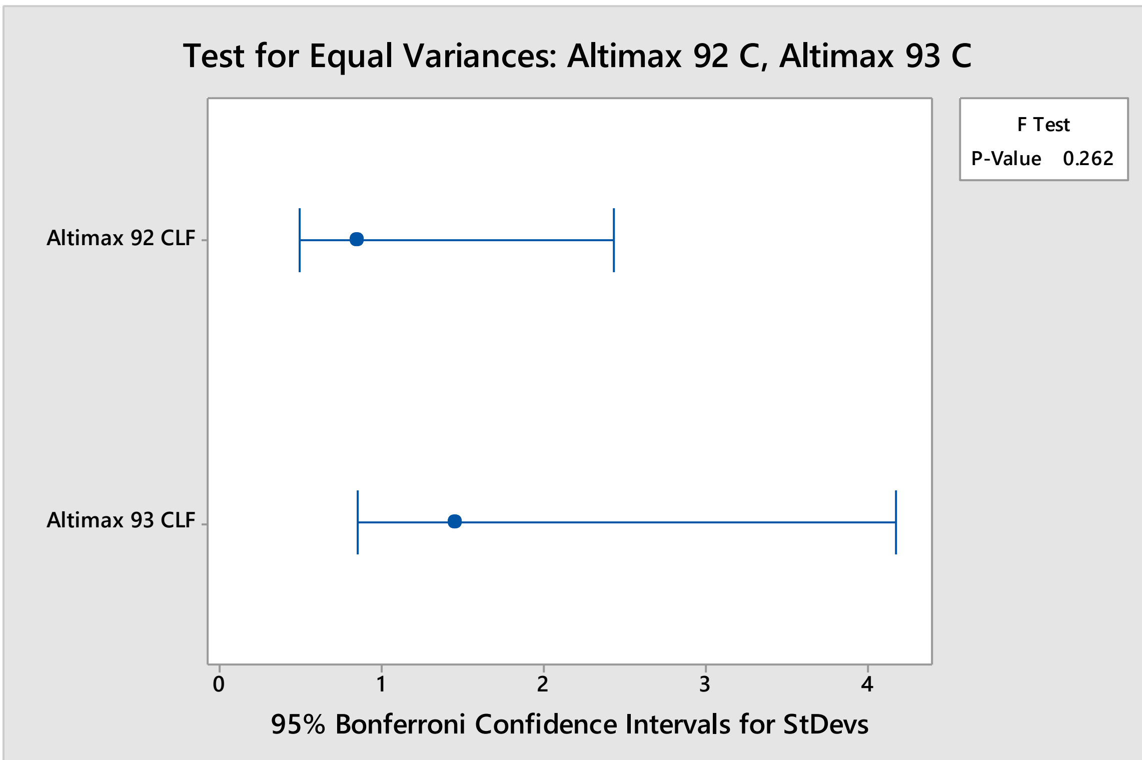

Figure 42: Test for Equal Variances- Cooldown Effect (CLF)

5.5 Effect of Data Acquisition Settings and Runout of Rim

The introduction of these two parameters and the reason for studying these variables have already been discussed in section 2.6. This section presents the results of the analysis. Tests on Altimax 91 were taken by removing the moving average filter from the LabView program. Mainly the saving time and sample rates are varied to get the data for different conditions. The analysis presented here corresponds to the test where data has been collected for 2 revolutions of the tire. The actual program saved data for 250 milliseconds which recorded approximately 100 filtered data points for each load. The user had no control over the part of the tire from which the data is saved. A MATLAB code, named 'sample_effect.m' is used to analyze the data. With a sample rate of 500 Hz and save the time of 4 sec. approximately 1000 data points are saved per load (corresponds to 2 revolutions of the tire). The MATLAB code divides the data for each load into groups of 100 points each. Hence, one group of points can be considered as the data equivalent to one tire test taken on a normal program. Further, for these groups (containing 100 points each) the code derives every parameter which 'SAE_J1988_test_analysis.m' derives and calculates the standard deviation of these parameters. The following Figure 43 and tables elaborate on this analysis.

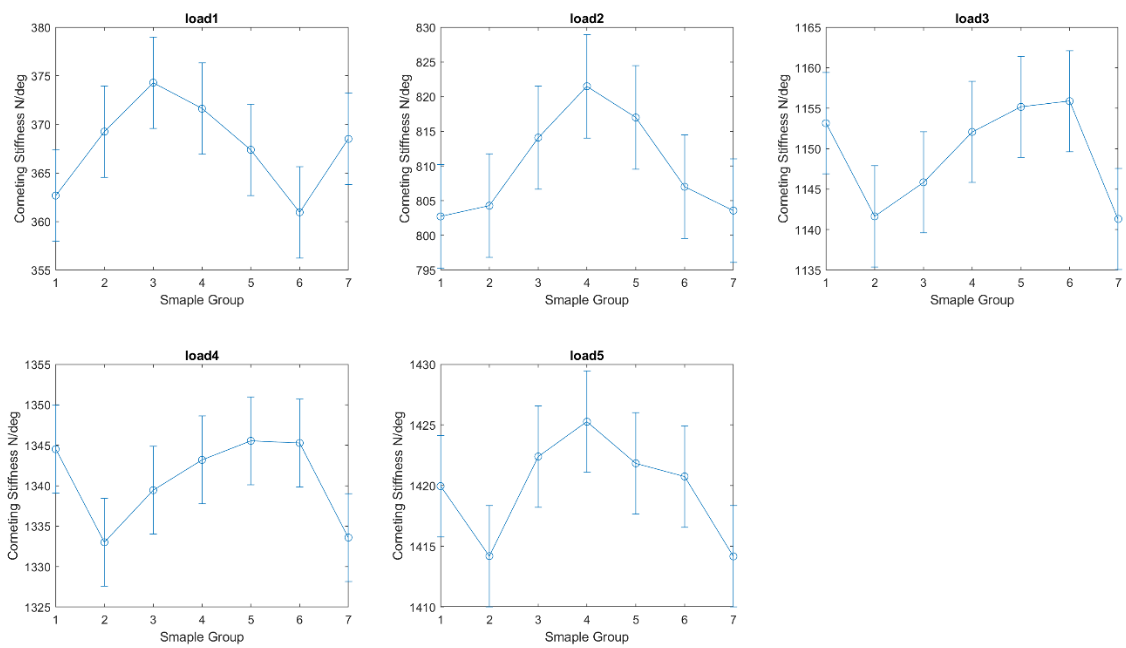

Figure 43: Cornering Stiffness Vs Sample Group

If the cornering stiffness and aligning stiffness are calculated for every 100 points for approximately 2 rotations of the tire, the values would look like as in Figure 43 and Figure 44 respectively. Error bars are the standard deviations of those 7 values at each load. There are some values in these two graphs which are significantly different than at least one other point. So, in some random test, if the program is recording data which corresponds to 1st group and in other test data from group 6 is recorded, definitively there will be higher variability observed in the data.

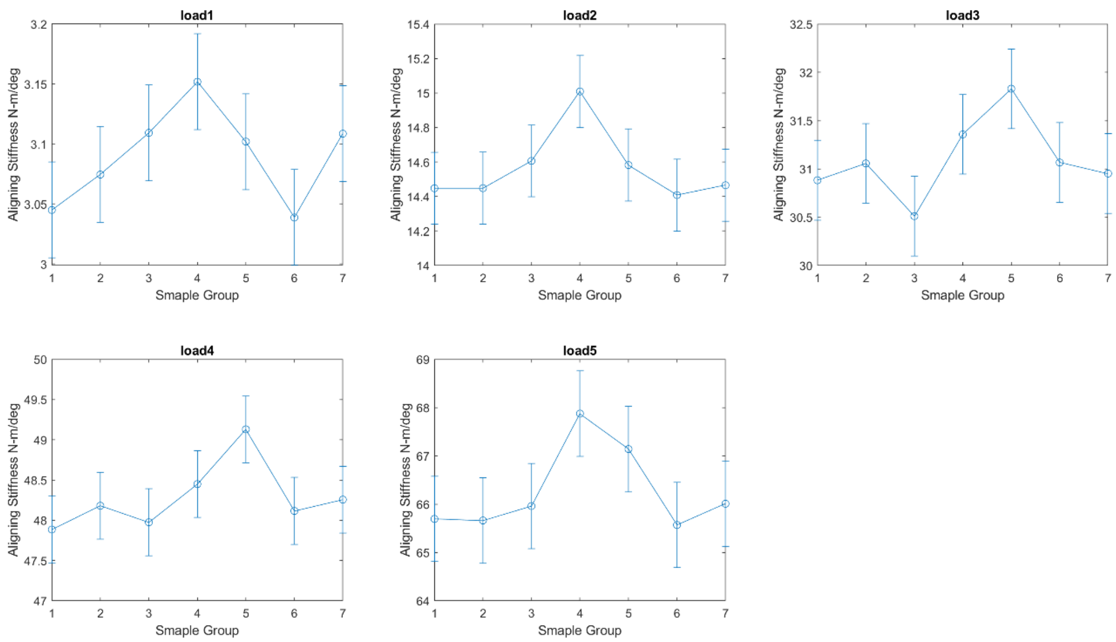

Figure 44: Aligning Stiffness Vs Sample Group

The standard deviations of the 7 points are presented in Table 26 below.

Table 26: Variability in Parameters due to Sampling Effect

Load (N)	**StdDev CS (N/deg)**	**StdDev AS (N-m/deg)**	**StdDev PLF (N)**	**StdDev CLF (N)**
1112	4.70	0.039	3.659	2.602
2522	7.45	0.208	2.264	3.693
3705	6.25	0.411	3.073	5.451
4897	5.42	0.415	3.399	5.654
6098	4.18	0.884	4.189	7.102

As these variations are produced due to data acquisition parameters, which can be considered as part of machine variability. The highest value of deviation for cornering stiffness is 7.45 N/deg which makes about 65% of the machine variability estimated in the earlier section. This can be interpreted as 65% of the machine variability is due to wheel runout and a short period of time for which the data is acquired. As a conclusion, the machine variability can be squeezed down by 65% only by changing the time for which the machine is saving the data. Another way to further reduce this is to make rims having a minimum possible runout. Similar to the above results, standard deviations for lateral force and aligning moment are also generated by MATLAB and displayed on the command window. One of the tables is shown below.

Table 27: Lateral Force Deviation for Left Rotation

Slip (deg)	**1112 N**	**2522 N**	**3705 N**	**4897 N**	**6098 N**
-1	11.359	15.979	15.451	16.14	14.43
0	2.508	4.944	6.9783	7.8976	9.8837
+1	9.515	9.551	7.8113	4.7946	5.1989

CHAPTER 6: INDIVIDUAL CONTRIBUTION OF FACTORS TO TOTAL VARIABILITY

In the previous chapter, the effect of potential sources on variability was observed but, the analysis didn't speculate any quantitative analysis regarding the contribution of each source to the total variability. Apart from the machine and tire variability the factors explained in the previous chapter contribute to the total variability. Previous sections can be considered as a recommendation to design the test with minimum variability. With the quantitative analysis, one can deduce the percentage change in variability by conducting tire tests with underlying conditions. This chapter attempts to produce quantitative results with the help of the 'Mixed Effect Model'.

Mixed Effect analysis is the type of ANOVA which allows the calculation of variance components of random variables. Random variables are the factors that can vary during the experiment and do not carry any well-defined levels which are the same for every experiment. For example, an experimenter aims to analyze the quality of grapes depending on the level of micronutrient supplied. The factor micronutrient has 4 different levels. Now suppose that the samples were collected from 'n' different fields which the experimenter does not have control over and were selected at random. In this case, the micronutrient can take only 4 levels as specified, but the filed can be any random field, hence the factor 'field' is the random factor whose contribution to the variability is to be studied along with the fixed factor, which is a micronutrient. MINITAB has an option to perform the analysis with the 'Mixed Effect Model'. The details for this model can be found in [18] and [19]. The dedicated option for the mixed effect model has been introduced in MINITAB versions from 2018 onwards. A similar analysis can also be done with a general linear model. The only difference between these methods is that the general effect model does not produce results for variance components as displayed in the mixed effect model. Observing the P-values for the random variables defined, the significance of these factors can be estimated. If the P-value for the random variable seems to lesser than the specified significance level, the factors are considered to have a significant effect on the response variable.

The way this model works is, the user has to specify the fixed and random factors along with their levels and corresponding response variable of interest. In case of the tire data analysis, goal is to estimate contribution due to break-in, unmounting the tire, and cooldown in the total variability. These factors are considered random variables as these factors' levels are not specified explicitly in the design of experiment and the data can be selected randomly from these testing conditions. Further, the parameters that are being calculated from force and moment data are dependent on the normal load which is specifically defined by the experimenter and cannot have levels other than specified by the test maker. Hence, the normal load is the fixed factor in this analysis with levels determined by the rated load of the tire and test protocol under consideration. Considering the load as a fixed factor has a basis of the analysis presented in section 5.3 which shows, the normal load has a significant effect on the standard deviation of some parameters. Incorporating load into this model takes care of possible variability caused by it.

In statistical analyses, it is common to use coded variables for factor levels. The term coded variable refers to specifying a certain value to the numeric factor level. For example, in the experiment of quality of grapes stated above consider 2 mg and 4 mg are two levels of micronutrient. These levels can be coded as 0 and 1, 0 representing 2 mg and 1 representing 4 mg. These levels are generally called ‘Low’ and ‘High’ respectively.

The only possible levels for the random variables selected for the tire data analysis are whether the process is done on the tire or not. That is for ‘break-in’ as a variable, possible levels would be 0 if the tire was not broken-in before the test and 1 if it was broken-in. Similar logic applies to the ‘Unmounting’ and ‘Cooldown’ as well. Though, ‘load’ and ‘Tire’ are not coded as these factors have specific values and it is easier not to code these variables. Factor ‘Tire’ corresponds to the serial number.

B	C	D	E	F	G	H	I	J
load	cooldown	unmounting	break-in	Tire	CS	AS	PLF	CLF
250	1	1	1	89	420.3531	2.98217	15.7349	17.37908
250	1	1	1	89	434.4366	3.196582	20.43122	13.48898
250	1	1	1	89	440.6412	3.288642	19.60939	14.35624
250	1	0	1	89	421.8255	2.989795	-10.3988	24.92296
250	1	0	1	89	412.15	2.973544	10.31296	20.03407
250	1	0	1	89	414.1124	2.996154	24.56017	16.84
250	1	0	1	89	404.1536	2.87058	4.740125	21.63093
250	1	0	1	89	398.7973	2.792211	16.45967	25.90622
250	1	0	1	89	406.9239	2.951017	2.693719	23.35741
250	1	1	0	89	402.8282	2.807327	12.2718	5.738371
250	1	1	0	89	396.226	2.652276	10.31833	12.73562
250	1	1	0	89	398.0967	2.792167	8.715245	12.56025
567	1	1	1	89	940.6874	14.68605	71.74788	13.78483
567	1	1	1	89	935.6457	14.26781	65.44184	26.28104
567	1	1	1	89	907.9129	13.70777	70.99442	33.14058
567	1	0	1	89	923.6951	14.1509	68.60153	27.18176
567	1	0	1	89	921.7668	14.23183	66.12234	30.31254
567	1	0	1	89	923.1743	14.31593	68.69359	28.00011
567	1	0	1	89	924.5351	14.35953	71.51773	30.55017
567	1	0	1	89	917.124	14.22555	78.50704	36.26636
567	1	0	1	89	921.2096	14.25202	67.97943	38.34
567	1	1	0	89	910.2013	13.73721	65.11424	26.02948
567	1	1	0	89	918.2705	13.98739	72.4824	30.18468
567	1	1	0	89	910.3734	14.06759	63.981	23.48519
833	1	1	1	89	1289.337	29.97614	104.3366	20.14146
833	1	1	1	89	1312.709	30.65888	108.3486	35.77329
833	1	1	1	89	1281.235	29.72222	102.6191	32.76355
833	1	0	1	89	1302.478	30.74098	106.9119	30.55785

Figure 45: Data for Mixed Effect Model

Figure 45 shows the data prepared for the analysis. According to the testing conditions, 1s and 0s are specified in the respective column along with the response variable recorded. Altimax tire data was used for estimating the effect of unmounting, break-in, and tire, while Michelin tire data was used for the effect cooldown. The following tables show the results of this analysis.

Table 28: Variance components CS

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
unmounting	58.833734	3.28%	89.649383	0.656265	0.256
break-in	205.717265	11.47%	299.648884	0.686528	0.246
Tire	1077.297581	60.08%	767.081189	1.404411	0.080
Error	451.119622	25.16%	37.535420	12.018505	0.000
Total	1792.968202				
-2 Log likelihood = 2690.320445					

The MINITAB output gives the contribution of every random variable to the total variance in the data along with the P-value for each. P-value represents whether that random factor creates a significant change in response. The factor is not significant if the P-value is greater than the significance level. The predictions of the equal variance tests in earlier sections are confirmed and it can be concluded that break-in and unmounting the tire don't have a significant effect on variability. Also, P-value for 'Tire' confirms the higher tire variability for Altimax tires and significantly different properties.

In addition to the random factors defined, Table 28 shows the variance contribution of the error. This error corresponds to the variability induced in the data but not accounted for by the random variables. In this case, this comes primarily from machine variability and cooldown. Reason for not considering the cooldown as a random variable lies in the fact that no same tire was tested under both the conditions; with cooldown and without cooldown (Altimax 89,90 & 93 were tested with cooldown while Altimax 91 & 92 were tested without cooldown) hence, to analyze the effect of this factors, data for at least two different tires had to be grouped together. As a result, there was a high probability that tire variability will be nested with the concerning effect. Option to eliminate this was to analyze tires having least tire variability which means analyzing data for Michelin tires.

Further, it seems that these random factors have a different effect on different parameters, and their contribution to total variability changes depending on the parameter. To elaborate on this, the same analysis was performed on AS, PLF, and CLF, and results are given below.

Table 29: Variance components AS

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Unmounting	0.002365	0.13%	0.015194	0.155632	0.438
Break-in	0.095145	5.40%	0.155424	0.612163	0.270
Tire	0.870649	49.37%	0.625015	1.393005	0.082
Error	0.795248	45.10%	0.066278	11.998714	0.000
Total	1.763406				
-2 Log likelihood = 813.019058					

Table 30: Variance components PLF

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Unmounting	9.721024	11.15%	14.430999	0.673621	0.250
Break-in	22.195231	25.47%	32.305957	0.687032	0.246
Tire	7.390432	8.48%	5.790048	1.276402	0.101
Error	47.843724	54.90%	3.980681	12.018981	0.000
Total	87.150410				
-2 Log likelihood = 2018.265183					

Table 31: Variance components CLF

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
unmounting	12.545616	4.08%	18.667257	0.672065	0.251
break-in	12.166447	3.96%	18.432075	0.660069	0.255
Tire	218.780602	71.18%	155.454220	1.407364	0.080
Error	63.889693	20.79%	5.316223	12.017872	0.000
Total	307.382358				
-2 Log likelihood = 2114.704553					

Even though the break-in and unmounting have a different effect on parameters, the percentage-wise contribution can be considered to be constant. That is, suppose that the above analysis is done on the data of the same tire (rather than using data from different tires) to eliminate the tire variability from the equation, it will remove the part of tire variability from the total variance but the contribution of other two factors will remain the same. The percentage contributed by an error that is machine variability will be higher as machine variability is solely dependent on machine hardware and it is constant. In any test, the machine variability is around 0.21% of the calibrated range (for CS, PLF, and CLF). So, for example, if the total variance is 300 the part contributed by machine variability is approximately 121 which makes 40% of the total. Hence, if all the sources of variability are removed, the minimum possible variability would be machine variability which will be 100% in that case. From this discussion, it is clear that the **percentage of total variance** contributed by machine variability my change but the contribution by random variables remains the same for that particular parameter under consideration.

Effect of cooldown can also be incorporated in the same analysis with slightly different design of experiment in which every tire is tested with and without a cooldown.

For this study that aspect is studied with Michelin tires' data. Response variables CS, AS, PLF, and CLF for every tire and at each load are recorded for 9 tests. This creates a pool of 180 data points. The results of the mixed effect model analysis on this data are as shown below.

Table 32: Variance Component of Cooldown in CS

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Cooldown	45.024468	4.78%	77.789897	0.578796	0.281
Error	897.848637	95.22%	96.259478	9.327379	0.000
Total	942.873105				
-2 Log likelihood = 1709.472371					

Table 33: Variance Component of Cooldown in AS

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Cooldown	0.115052	13.90%	0.173911	0.661555	0.254
Error	0.712840	86.10%	0.076424	9.327379	0.000
Total	0.827892				
-2 Log likelihood = 461.270216					

Table 34: Variance Component of Cooldown in PLF

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Cooldown	0.435620	0.13%	5.830466	0.074714	0.470
Error	330.993355	99.87%	35.486213	9.327379	0.000
Total	331.428976				
-2 Log likelihood = 1533.244103					

Table 35: Variance Component of Cooldown in CLF

Variance Components					
Source	**Var**	**% of Total**	**SE Var**	**Z-Value**	**P-Value**
Cooldown	30.846360	5.08%	52.693720	0.585390	0.279
Error	576.950167	94.92%	61.855551	9.327379	0.000
Total	607.796527				
-2 Log likelihood = 1632.132131					

To validate these results, now consider Table 28. The 'Error' contributes 25.16% of the total variance and as explained, it contains the machine variability and the variability due to the cooldown effect. Also, from Table 32, the variance component due to cooldown is 4.78% of the total variance for CS. Now, considering this contribution remains the same, one can argue that the same contribution is made by the cooldown effect in Table 28 which goes into the error part. Again, consider Table 28, 4.78% of total variability is 85.66 and the corresponding standard deviation is 9.255 (square root of variance). Similarly, the standard deviation of Error is 21.239, hence by subtracting the deviation of cooldown effect from the deviation of the error, machine variability can be derived which comes out to be 11.984. This value is very close to the machine variability 11.46 from Table 25. This validates that the analysis holds true for the tires under consideration.

CHAPTER 7: CONCLUSION

During this study, a total of 10 tires were tested with the specified testing conditions to record data to be analyzed. Collectively the machine was run for approximately 200 miles with tire against the road wheel being loaded and unloaded. The numerous plots presented in this document provide a broader view of how the data looks like when viewed collectively. The statistical analysis assisted in estimating the variability produced by potential sources and their significance in the response variables. Tires can behave very differently under a certain set of conditions than they would do under another set of conditions. From the analysis, it is clear that the way a source of variability affects certain tire property doesn't affect the other properties the same way. Hence, it is difficult to make generalized conclusions about tires. Probably tires are the most unpredictable components in a very predictable way. This makes tires very interesting entities to study. The study conducted in this document is a small attempt to possibly reduce the uncertainties in the experimental data and a trivial contribution in understanding the complexities of these multibody components. The following are some conclusions and recommendations which can be drawn from the analysis presented in previous chapters.

- Machine variability is the noise produced in the data due to the limitations of electronic and mechanical components of the machine. Estimated machine variability for Cornering stiffness is 0.2148% of the calibrated range of lateral force and for Aligning stiffness 0.4182% of the calibrated range of aligning moment. Other parameters such as Conicity, Plysteer are residual lateral forces, and machine variability for these can be considered to be the same as cornering stiffness. Similarly, for CRAT and PRAT which are residual moments in the tire.

- Tire variability is also an important aspect of any statistical study on tires and is an uncontrollable factor. It depends completely on the capabilities of the manufacturer. Michelin tires used in this study were from the same batch of production and as expected, have very low tire variability, while Continental tires were constructed differently and as a result, comparatively have higher variability. The scenario where multiple tires are to be tested and analyzed collectively, the group of tires is supposed to have the least possible tire variability. Potentially it can be accounted for by implementing blocking principles while designing the experiment. In some cases, observing tire variability can provide insights into the manufacturing process and possible issues.
- No significant change in variability was observed due to the break-in process of the tires. Though, some decrease in variability was observed in the cornering stiffness, aligning stiffness and conicity when tires were not broke-in before the test. On the other hand, variability in plysteer seems to increase without the break-in process. This supports the findings from reference [5] and additionally presents the case for plysteer. Further, from the results of the mixed effect model, it can be concluded that 11.47%, 5.40% and 3.96% reduction on total variability can be achieved in case of CS, AS and CLF while 25.47% increase in case of plysteer can be expected by not breaking-in the tire before the test.
- A logical explanation is possible for the slight differences occurring in the way the tire sits on the rim every time it is mounted and its possible effect on

variability. It can be inferred that variability could increase due to frequent mounting and unmounting the tire. The analysis done in this study quantifies that variability. A general trend of decrease in variability of every parameter is observed if the tire is kept on the rim without unmounting it. Decrease of 3.28%, 0.13%, 11.5% and 4.08% of total variability can be achieved in cornering stiffness, aligning stiffness, plysteer, and conicity respectively by simply not unmounting the tire.

- As explained previously some tires were tested for 3 continuous tests succeeded by around 1 hour of the idle period and again 3 continuous tests. The primary motive was to allow the tire to achieve equilibrium with the environment and study temperature rise. But the temperatures noted did not show any significant change which can cause tire properties to alter. Though the statistical analysis of this case showed changes in the variability of the data. Decrease of 4.78%, 13.90%, and 5.08% was observed in the variability of cornering stiffness, aligning stiffness, conicity while plysteer shows a 0.13% increase when tires were tested continuously without any idle period. This phenomenon seems to be linked to the structure of the tire itself rather than temperature effects. This behavior might be associated with the viscoelastic mechanisms of the tire.
- Moreover, the time for which the machine saves the force and moment data plays an important role in the repeatability of the machine. It is recommended to have data for at least one complete rotation of the tire and the data points should be spaced such that the data has enough points from the contact of the tire. For the M-15 it is advised to have save time of 4 sec. (can be changed depending on tire

size) to have data for 2 revolutions of the tire. This can reduce the machine variability by approximately 65% of the current estimate. (11.46 N/deg for cornering stiffness)

- During this study, the machine was recalibrated completely very cautiously resulting in better accuracy. But a shift was observed in the new gain values of load cells (located in the hub of the machine) from the previously obtained gains. This was suspected to be a temperature sensitivity of load cells. A separate study is required to investigate this change and formulate a possible compensation in the calibration.

REFERENCES

[1] P. Haney, The Racing & High-Performance Tire, Warrendale: Aufl. SAE, 2003.

[2] H. Pacejka, Tire and vehicle dynamics, Third ed., Elsevier, 2012.

[3] Highway Tire Committee, "Force and Moment Test Method J1987," *SAE International*, 1998.

[4] Highway Tire Committee, "Residual Aligning Moment Test J1988," *SAE International*, 1994.

[5] K. P. R. P. M. a. P. W. Marshall, "The Effect of Tire Break-In on Force and Moment Properties," *SAE Transactions*, pp. 2986-2998, 1977.

[6] D. P. R. T. K. a. N. J. Tandy Jr, "Effect of Aging on Tire Force and Moment Characteristics," *SAE Technical Paper*, 2010.

[7] A. a. W. J. Gent, Pneumatic Tire, Washington DC: NHTSA US DOT, 2006.

[8] "Getting Started with LabView," National Instruments, Austin, 2013.

[9] J. Wong, Theory of Ground Vehicle, John Wiley & Sons, 2008.

[10] T. Gillespie, Fundamentals of Vehicle Dynamics (Vol. 400), PA: SAE, 1992.

[11] W. a. M. D. Milliken, Race car vehicle dynamics (Vol. 400, p. 16), Warrendale: SAE, 1995.

[12] A. Dwivedi, Development of Data Acquisition System and Calibration Protocol, Charlotte: University of North Carolina at Charlotte, 2018.

[13] H. Nair, "Optimization of Tire Testing Protocol Using LabView/PLC," The University of North Carolina at Charlotte, Charlotte, 2019.

[14] C. e. a. Kim, "Improvement of Tire Development Process through Study of Tire Test Procedure and Vehicle Correlation," *SAE Technical Paper*, 2018.

[15] D. Montgomery, Design and Analysis of Experiments, Hoboken, 2013.

[16] K. a. S. M. Chia, "Quantifying sources of variability in gait analysis," *Gait & Posture*, vol. 56, pp. pp.68-75, 2017.

[17] "Minitab Support," Minitab, [Online]. Available: https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/anova/how-to/mixed-effects-model/before-you-start/example/. [Accessed April 2020].

[18] H. a. L. Y. 2. ..,. 1. Peng, "Model selection in linear mixed effect models," *Journal of Multivariate Analysis*, vol. 109, pp. 109-129, 2012.

[19] T. S. P. A. S. a. B. P. Sankar, "Prediction of tread geometry influence on Ply steer Residual Aligning Torque (PRAT)". Apollo Tyres Ltd., Vadodara, India., 2011.

[20] S. Shrikanth, "Chapter 17: Mixed Effects Modeling," UIC, [Online]. Available: https://ademos.people.uic.edu/Chapter17.html. [Accessed March 2020].

[21] G. R. B. M. S. a. S. D. Vorotović, "Determination of cornering stiffness through integration of a mathematical model and real vehicle exploitation parameters," *FME Transactions*, vol. 41, no. 1, pp. 66-71, 2013.

APPENDIX A: GUIDELINES TO USE MATLAB SCRIPTS

There are mainly 2 MATLAB scripts used in this study. One analyzes the raw data (‘SAE_J1988_test_analysis.m’) to calculate the performance parameters at each test load and plots these parameters with manufacturer data in case of Continental tires. The variables can be saved to the MATLAB file to be used for further analysis. Another program (‘Combined.m’) was designed to plot the results of either multiple tests on a single tire or to plot tests on multiple tires. Plots from both of the scripts can be saved to the desired folder.

SAE_J1988_test_analysis.m:

First, it is to be noted that these scripts used many user-defined functions, and to run the main script successfully, all the functions should be in the same directory. All these scripts can be found in the folder ‘Repeatability M15’. Before running the above-mentioned program there are some steps to be followed.

1. First of all, the files that are generated by the machine are to be named according to this protocol (also given in section 3.2 with example) ‘Make_SerialNumber_slip_direction.xlsx’. The order of the files should be according to Figure 8 for the program to work correctly.
2. Further, the machine was recalibrated after all the tests were conducted. According to the new calibration of the machine signs of lateral forces for all the right rotation tests are to be reversed (uncomment lines from 23 to 25 from the code). And the sign of the lateral force for all the left rotation tests is to be reversed (uncomment lines 27 to 29 from the code) if the files before the recalibration are to be analyzed.

After these steps are followed according to the requirements, the program can be run. After running the code, a window is displayed to select the data files to be analyzed. 6 files must be selected (multi-select option is enabled in the code). These files represent one complete test on the tire. One can select the files from any order, but all the files must be in the same folder. Once the files are selected, a window is displayed to select the unit system to be used for the analysis. After the selection, the program generates the results and at the end pops up another window for saving the workspace variables. These variables are saved in a MATLAB file which should be named as 'Analysis Results_Make_Serial_Unit System_Test_ number_test condition'. Depending on the unit system selected by the user, the unit system automatically appears in the name of the file. This pattern of naming has to be followed strictly until the unit system part and can be changed after that according to the convenience. For example, Altimax tire will be named as 'Analysis Results_Altimax_90_SI_T1_cd' and Michelin tire analysis will be something like 'Analysis Results_Mich_77170_SI_T1_cd'. These results can be saved in any folder. Relevant graphs will be automatically saved in the same folder as the MATLAB variables.

combined.m:

This code can be used to plot the results of multiple tests on the same tire or tests on different tires collectively. Figure 14 to Figure 23 are some of the graphs produced by this script. Users can select the unit system for displaying the results. The following procedures are to be followed to run this script.

1. On running the code, the command window will display 'Enter of Tires/Tests:'. Type in the number of tests to be plotted and hit 'Enter'.
2. After step 1, a window will be displayed for the user to select the convenient unit system for the plots.
3. A window will open for the user to select the files. The MATLAB files which were saved from the previous code are to be selected in this script. (That is, the files with 'Analysis Results_Altimax_90_SI_T1_cd' such names). The script is designed such that an error message is displayed if the unit system of the selected MATLAB file doesn't match with the selection made by the user. The process continues until all the files to be analyzed are in the required unit system.
4. Depending on the number of tests entered, the window will continue to pop up and the user has to select every file individually every time. As this code can also be used to plot data for multiple tires, this repetitive process should be done.
5. After all the files are selected, code continues and plots the graphs which are required to observe the data. Finally, a window will be displayed where the user can select the directory where all these plots are to be saved. This step can simply be skipped if one doesn't want to save the graphs.

APPENDIX B: TIRE SERIAL NUMBER USED FOR EVERY SET OF TESTS

Set 1: (2.1 Randomized Order Tests)

Table 36: Tire Serials for Set 1

Continental	Michelin
ET392389, ET392390, ET392391, ET392392, ET392393	01077170, 01077171, 01078602, 01078608

Set 2: (2.2 Successive tests allowing the tire to cool down after certain tests)

Table 37: Tire Serials for Set 2

Continental	Michelin
ET392389, ET392390, ET392393	01077170, 01078608

Set 3: (2.3 Successive tests without allowing the tire to cool down during tests)

Table 38: Tire Serials for Set 3

Continental	Michelin
ET392390, ET392391	01077171, 01078602

Set 4: (2.4 Control tire tests)

Table 39: Tire Serials for Set 4

Continental Control Tire
ET391646

Set 5: (2.5 Tests Without Break-in)

Table 40: Tire Serials for Set 5

Continental
ET392389, ET392390, ET392391, ET392392, ET392393

Set 6: (2.6 Tests to analyze the effect of data acquisitions parameters on variability)

Table 41: Tire Serials for Set 6

Continental
ET392391