OPTIMIZATION OF TIRE TESTING PROTOCOL USING LABVIEW/PLC

by

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ABSTRACT

HARISH NAIR. Optimization of tire testing protocol using LabVIEW/PLC. (Under the direction of DR. PETER TKACIK)

Tires are one of the main components for the vehicle ground interaction. In order to accurately evaluate and determine the dynamic behaviour of vehicles various tire models are widely recognised. These tire models are generated through rigorous testing of tires on various testing machines. A tire force and moment testing machine is one such indoor tire testing machine. The main objective of any testing machine is repeatability in the testing process.The best way to achieve this is through automation of the process reducing human errors. The M-15, a tire force and moment testing machine at UNC Charlotte Motorsports Research Lab uses a high end programmable logic controller (PLC) DL-06 to perform various operations on the machine [1]. Using NI-LabVIEW and Modbus RTU protocol a human machine interface (HMI) is developed, to provide a platform to enable real-time process control, data logging and perform automated loading cycles. The M-15 can test tires for a variety of automobiles from FSAE cars to light trucks. The test data obtained later can be used to generated force and moment curves and PACEJKA Coefficients. In this comprehensive report a step by step procedure to calibrate, measure, test and interpret tire test data using industrially accepted tire test protocol, will be discussed upon. Along with the detailed description and methodology behind the programming process.

DEDICATION

This is for you Mom Dad and my friends. Thanks for always being there for me.

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I am immensely thankful to my fellow lab mate and graduate student Sudeep Agalgaonkar for his work on 'Force and Moment Tire Data Modelling', enabling me to visualize the data obtained from M-15 and generate neat and meaningful graphs for the same.

I would like to acknowledge the huge support my family provided both mentally and financially, encouraging me to pursue such challenging projects. A special thanks to Abhinav Mishra for all those midnight coffees, motivating me to work even harder and Ayushi Jain for being a constant encouragement and sometimes a harsh critique of my sub-par work.

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CHAPTER 1: INTRODUCTION

1.1 Brief Description on Tire Testing

The initial invention of pneumatic tire dates back to 1888 by John Dunlop, however the study of tires and vehicle dynamics did not gain momentum until the early 1920s. During the early stages of development of tire research, tires were largely seen as a suspension component and a source for power loss. This notion began to change after the very first publication discussing the behaviour of tire and the concept of slip angle by Broulhiet in 1925, [2]. The force and moment characteristics of tire were only beginning to be explored. In the years to come various other researcher papers were published discussing the importance of tires in automobile vehicle dynamics.

Even after more than one hundred years of tire evolution the demand for tire research and development is ever increasing. Many improvements have been made to the initial design of tire, such as reinforcement, vulcanization method, beads and thread pattern in an attempt to improve its performance. With the increasing demand for more fuel efficient and powerful automobiles, more the importance of extracting the most out of the available driving and braking torque of a tire along with prime cornering ability has been realised. Tires also serve as an important component in vehicle load-carrying capacity, cushioning effect against road irregularities, restraining abrasion and weathering effects and maintain dimensional stability. Improving all these characteristics at once is not possible as many have inter-dependencies which when increased beyond a certain limit causes negative effects on other parameters. Hence in-order to optimize these characteristics a lot of rigorous indoor and outdoor tests needs to be conducted. [3, 4]

In the early 1930s itself the on-road testing of tires had began, this method is accurate as the tire is tested in real world conditions, but the one big drawback is that the tests aren't repeatable. The control over road conditions, surface temperatures, pavement ages and exposure to dirt and sand are impossible. Hence the need of indoor tire testing. There are two main types of indoor tire testing machines (TTM), flat track type and drum type testing machine. Each type having its own advantage over another. Before discussing further on the various types of TTM and its functioning, it is important to know about the basic tire terminology, coordinates system and various SAE standards.

There are two main globally recognised platforms, SAE tire axis System and ISO wheel axis system to standardize the way the data is understood from force and moment measurements. Throughout this research, the SAE tire axis system is followed. The SAE tire axis system is defined at the contact patch and follows a right-handed coordinate system as shown in the figure below.

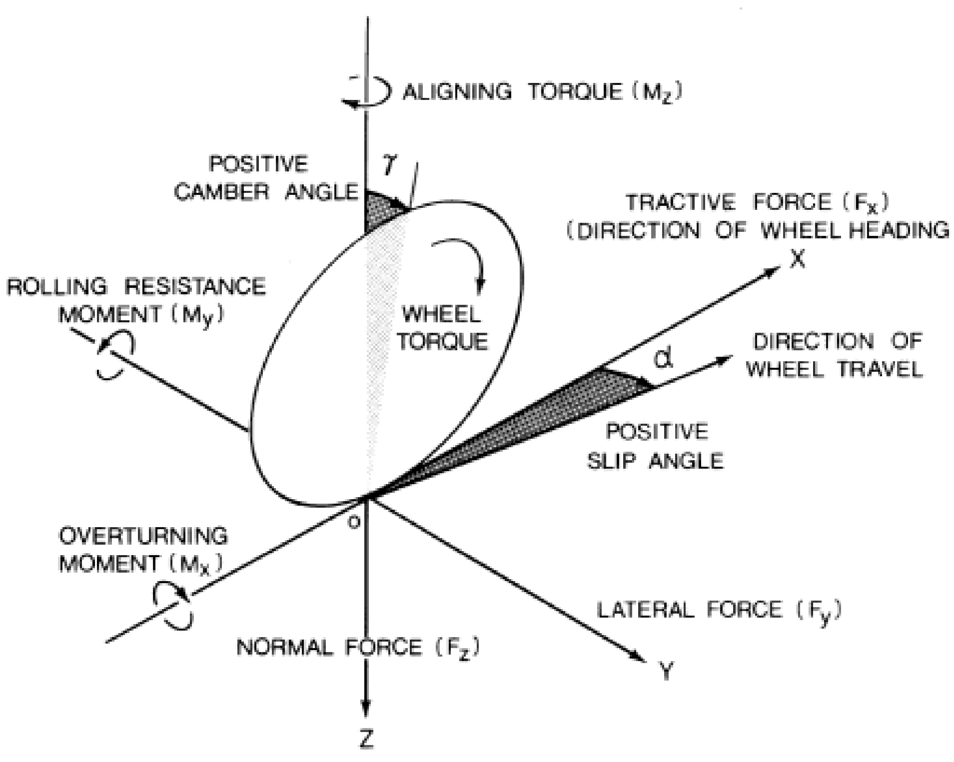


Figure 1.1: SAE Tire Axis. [5]

There are several forces, moments and angles that prove to be very important in tire behavior. These forces can be seen as forces and moments acting on the tire from the road. The two main angles to consider are, the camber angle and slip angle. The camber angle is the inclination angle from the vertical position of the tire while the slip angle is the difference in the wheel heading direction and the direction of the vehicle. The forces in the x, y and z direction are called longitudinal, lateral and normal forces respectively. The force and moments are shown below.

- F_x= Longitudinal Force-X
- F_y= Lateral Force-Y
- F_z= Vertical Force-Z
- M_x= Over Turning Moment-L
- M_y= Rolling Resistance Moment-M
- M_z= Self-Aligning Moment-N

Longitudinal force (F_x) is caused due to the tire exerting force on the road and its negative during braking. The Lateral force (F_y) is the result of forces produced by non-zero camber and slip angle during cornering. Normal force (F_z) is viewed as the negative of the upward vertical force. During cornering the lateral shift of the vertical load causes the Overturning moment (M_x). When the slip angle is non-zero it produces a restoring moment on the tire to realign the direction of travel with the direction of tire. This resulting moment is called the aligning moment (M_z) and is also known as self-aligning torque.

CHAPTER 2: LITERATURE REVIEW

2.1 Why Force and Moment Tests are Needed

Ever since the invention of first assembly line automobile 'Model T' by Henry Ford in 1908 the motor vehicle industry is working towards a complete understanding of factors effecting the motion of vehicles on the roadway [6]. This understanding is expressed in the form of predicting the vehicle response to various operator inputs and road variations. The more the accurate the prediction the more desirable it is to use this data for the design of various safety systems and utilities. As we know that the tires are the only desirable component of an automobile to come in contact with the road, the pneumatic tire becomes the primary control element in a ground vehicle system [4]. The tire design effects the manner in which the forces and moments are developed at the tire-road interface. These forces and moments provide the function of support, directional control, braking and acceleration capability and hence determining these various forces and moments is the key to a better vehicle dynamic design of an automobile [5].

The primary use of quantitative tire data from a TTM is in studying directional behaviour. With subtle differences to the front and rear tire, changes the shape or character of response to various forces and moments, affecting the control of an automobile [7]. Also changing the aspect ratio,the ratio of section height to section width of a tire has significant influence on the cornering ability of an automobile. Higher aspect ratio tires have improved hydro planning ability and improved performance on snow. While a tire with lower aspect ratio has improved cornering ability and better thread life but has to sacrifice on ride comfort. Through sophisticated vehicle directional simulation procedures the desired tire properties can be determined [8].

This would be of great help in the design of passenger cars and race cars as each would require a different type of tire. Tire force and moment data have aided in tire development and evolution, the poor performance of bias belted tires has led to the development of radial tires with superior ride quality and wear resistance [9]. The data from the tire testing machine is significant in determining the wear resistance of tire to various roughness grade of road wheel, this information has directly translated into the evaluation of road roughness [10].The tire force and moment data has greatly helped in understanding the physical principles of tire operation over a very broad range of conditions.

2.2 Various Types of Tire Testing Machine

In the previous chapter we had briefly discussed about the various types of indoor TTM, in this chapter a deeper and a much clearer picture would be painted about this subject.Basically, all TTMs consist of the following basic systems, a high stiffness tire loading system, a tire positioning system and specifically designed data acquisition and control system.

A flat track tire testing machine as the name suggests uses a flat belt conveyor system to test tires. They are essentially configured like a belt sander and typically consist of a steel belt for the roadway, that is running over two drums. To control the belt tension and position one of the drum carrying the belt is positioned by a feedback control system. The flat bed creates a road like surface for tire testing, this is done with the help of hydro-static air bearings. Although complicated, the test results are highly accurate. Some test machines are capable to reach speeds of 250 km/h along with surface coating and temperature control to simulate different road conditions. At the Calspan Tire Research Facility (TIRF) world's most capable TTM is situated. The customers at Calspan TIRF include NASCAR teams, Formula 1 teams, OEM tire manufacturers, automobile manufacturers and government agencies. [11, 12] It has the following capacities:-

- Normal Load: Up to 12000 lb. (53400 N)
- Normal Load rate: Up to 2000 lb/sec. (8900N/sec.)
- Tire Vertical Position Rate: Up to 7in./sec. (17.75cm/sec.)
- Roadway Speed: Over 200 mph
- Slip angle: 30deg. and up to 90 deg. with adapter.
- Inclination Angle: 30 deg. and over +50 degrees with adapter.
- Maximum tire outside diameter: 47 in. (119.4 cm)
- Maximum tire tread width: 24 in. (61 cm)
- Belt width: 28 in. (71.1 cm)

Figure 2.1: The Tire Testing Machine at Calspan. [11]

A drum type TTM uses a steel drum as the test surface, this drum is rotated using a high power electric motor directly coupled or using a gearbox system. The test surface is either internal or external surface of drum.In both cases the contact patch distribution is different than a flat track machine. Due to this there is no direct method to convert the data from one machine to another. The false curvature of the contact patch results in a pressure distribution that differs from the real one to road and hence the results are not as accurate as a flat track TTM. Despite this the strength of this setup is its simplicity and low cost, which is the reason why researchers still use it worldwide.[13]

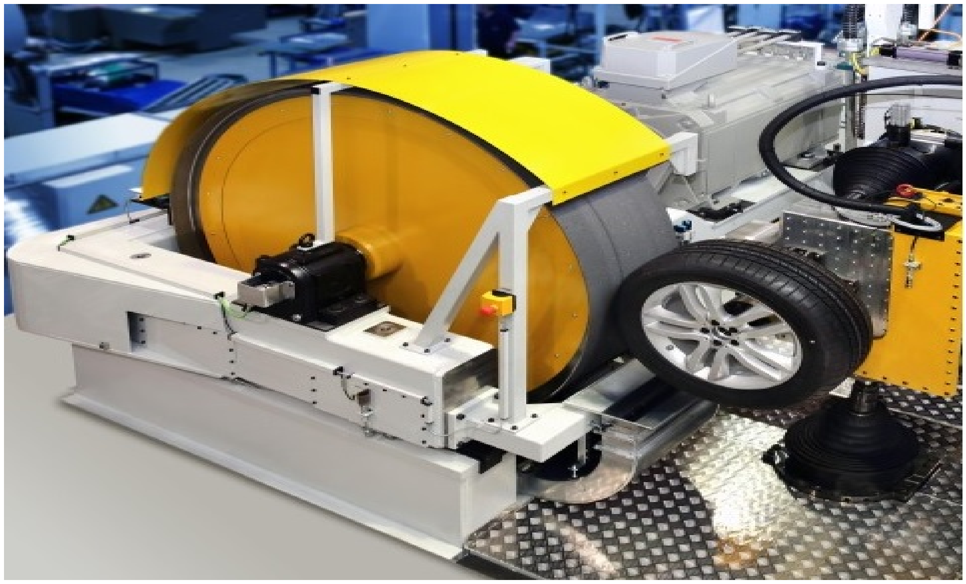


Figure 2.2: Drum Type TTM. [14]

An in-depth understanding of the design and functioning of M-15 is very important to better understand this paper. Hence we will elaborate a little about the Michelin's M-15 TTM. Originally this machine was made by Michelin in Clermont Ferrand, France in the year 1973. It was used in Michelin Americas Research and Development Corporation (MARC) in Greenville, SC tire testing facility. The M-15 was later donated to Motorsports Research Laboratory at University of North Carolina at Charlotte (UNCC) in the year 2015. Under the careful supervision of Dr. Peter T. Tkacik, professor at Mechanical Engineering and Engineering Scineces at UNCC the M-15 was rebuilt on a sturdy steel frame with modern electronics and data acquisition system.

The M-15 is a convex drum type TTM with 8.5m circumference road wheel. Few of the main components of the machine are the carriage, tire manipulator, main drive 3 *phi* motor and motor controller, DL06 PLC to control all the major operation on the M-15, National Instrument's (NI) SCXI for data acquisition and a highly powerful desktop PC to collect and manipulate the data received from the various sensors. The specifics of each component would be discussed in the coming chapters of this paper.

Figure 2.3: M-15 TTM

2.3 Factors Affecting Tire Force and Moment Tests

The force and moment properties of a pneumatic tire consist of two distinct categories the first being the geometric and material properties affecting shear-force potential (friction) at the tire-road interface and the other one being the elastic properties determining the shape and pressure distribution in the contact patch. Laboratory procedures used for tire evaluations are restricted to measure elastic properties of tire. While the frictional tire properties are severely confounded by synergistic interactions of tire road surface, temperature, speed, slip angle and interface contamination, measured only by research experimentation. For the measurements to be meaningful, it is necessary to establish controlled test conditions which do not differ from on road operating conditions in any aspect which significantly influences the tire's elastic response [5].

Some of the specific factors that affect are speed, temperature, road surface and contamination. Extensive research was conducted to determine the dependence of speed variations to steady state static properties of pneumatic tires. Despite of the common belief of speed having a major influence on force and moment tests and the requirement to conduct theses tests at highway speeds. The result dependence of speed over a threshold speed was found to be minimal and successful tests have been conducted at speeds as low as 1mph [15, 16]. Due to the changes in temperature some physical properties of rubber vary and hence the elastic properties of tire vary as well [9]. Also the affect of changes in road surface is highly implicating on the force and moment tests. A major determinant of a loaded tire's configuration is the shape of the road surface, distortions produced when a tire is loaded against a curved surface are different from that produced by flat surface [17]. A secondary determinant is the road surface frictional characteristics, If the tire treads become sticky during a test the results are not valid. Hence abrasive paper which of SAE specified grade can only used to retrieve useful data from TTM [10]. The presence of contaminates like water, dust, oil exert an substantial effect on the friction coefficient causing tire slip and error in data collection. Hence great care must be exercised to eliminate such contaminants during tire force and moment testing, this is generally done by the use of vacuum pumps and brushes. A careful control over these parameters have been kept throughout the test process to produce reliable results.

2.4 The Need of Developing a Tire Test Protocol

In the automotive industry tire force and moment data are often used as major inputs to mathematical models of vehicle response simulations. Error in force and moment measurements can be multiplied to produce significant errors in vehicle response simulations. The table below shows the effect of errors on vehicle response properties [5].

Table 2.1: Effect Of 5% Errors In Tire Data

Vehicle Response	Typical Car	Worst Case 5% Error in Tire Data	% Change in Response
Understeer	6.1°/g	5.2°/g	17
Steering Sensitivity	8.1°/g	6.9°/g	15
Lateral Acceleration Response Time	0.49 s	0.53 s	8
Yaw Velocity Response Time	0.15 s	0.17 s	13

It is evident from the above table that errors in force and moment data can be multiplied by a factor of 3 to produce large errors in vehicle response simulations. Such error multiplication have serious negative consequences on the overall design process and can cause severe damage to life and property. Hence it is very important for force and moment data to fall within the prescribed accuracy ranges. By the SAE standards an overall system accuracy of more than 98% is expected for a force and moment test data to be used for vehicle dynamics considerations. Overall system measurement inaccuracies can arise from several sources, the following list represents the major causes in tire force and moment measurements [5].

1. Inaccuracies in the Instruments
    - Single Transducer Inaccuracy
    - Transducer Channel Interactions

2. Test Repeatability Inaccuracies

Table 2.2: Accuracy Requirements

Variables	Transducer Range	Accuracy After System Compensation	% Full Scale Accuracy
Normal Force	-4000 lb (18000 N)	10 lb (44 N)	0.25%
Lateral Force	±4000 lb (18000 N)	10 lb (44 N)	0.25%
Longitudinal Force	±200 lb (900 N)	1 lb (44 N)	0.5%
Slip Angle	±30°	±0.05°	0.17%
Inclination Angle	±15°	±0.05°	0.33%

3. Tire Force And Moment Property Variation
    - Individual Tire Non-Uniformities
    - Tire To Tire Variations

Inaccuracies due to instruments can be eliminated or minimized by periodic calibration checks and using good quality measuring instruments and the inaccuracy caused by tire force and moment properties can be minimized by following the SAE specified tire selection process. However the errors caused due to test repeatability inaccuracies has the largest share and needs to be addressed. The only way to minimize such errors is by reducing the human interference and automating the tire testing process. On the M-15 this has been achieved by developing a LabVIEW test procedure to run and monitor the force and moment testing process. Currently the only human assistance needed on the machine is to change the Slip Angle, this will also be soon atomized. In the chapters ahead the results prove that the data received from the M-15 are indeed within the SAE prescribed standards.

2.5 Tire Testing Protocol

A test protocol is nothing but an official set of test procedure defined by standards or organizations like SAE, ASME, ISO, Tire Society etc. These protocols not only helps standardize the experiments and tests but also help compare the results between competing organizations. Without these standardized test protocols the results obtained form one force and moment test would be totally different from another force and moment test happening half way across the globe as the results from the test would vary according to the minimum and maximum limits set for the test and similarly would also vary with the type of tire being tested like for example a passenger car's tire would be different from heavy-duty truck tire and hence each should be subjected to a different type of test to obtain meaningful results. In this chapter we will discuss about the tire test protocol followed across this research paper, its specifications and the different test parameters [18, 16].

The SAE J-1987, 'Force and Moment Test Method' is the SAE recommended practice for all passenger car light truck tires. This test method describes the use of a flat surface test machines, however in this paper a drum type test machine would be used, namely the M-15. The SAE J-1987 is suitable for accurately determining five tire forces and moments in steady-state under free-rolling conditions as a function of slip angle and normal force which are incrementally changed in a given sequence. The normal force being the normal component of force between the tire and the road. The absolute value of tire design load is the 100% level of normal force and is also called the target normal force. The protocol also demands the need of three basic components a roadway with drive mechanism, a loading and positioning system and measuring system, which has been suitably sufficed.The simulated roadway is a continuous surface with 3M safety walk and is capable enough to operate at a speed of 3.5 km/h with an accuracy of $\pm$1km/h as per the protocol requirements. It also requires the test machine to have a loading and positioning system with an accuracy of ±1% of the maximum normal force and a loading capacity of 160% of the target normal load. The M-15s 24VDC linear actuator is more than capable of this load with an accuracy within the limits of the test method. The measuring system of the M-15 is capable to measure aligning moment, lateral force, longitudinal force, normal force, overturning moment and slip angle with an accuracy of 1% of full-scale range or better. Additionally the slip angle adjustment system has a full-scale range of ±15 degrees with and accuracy of ±0.05 degrees. The list in table below are the typical full-scale ranges for force and moment measurement [19].

Table 2.3: SAE J-1987 Load Cell Range and Accuracy

Measurement	Full Scale Range	Accuracy
Longitudinal Force	0 to ±1 kN (0 to ±225 lb)	±10 N (±2.3 lb
Lateral Force	0 to ±15 kN (0 to ±3370 lb)	±150 N (±33.7 lb
Normal Force	0 to -24 kN (0 to -5395 lb)	±240 N (±54 lb)
Overturning Moment	0 to ±10 kNm (0 to ±7375 ft-lb)	±100 Nm (±73.5 ft-lb)
Rolling Moment	Not Measured	-
Alligning Torque	0 to ±1 kNm (0 to ±737.5 ft-lb)	±10 Nm (±7.4 ft-lb)

According to the SAE J-1987, the tire inflation pressure before the test is set to 4 psi (28 kPa), in the unloaded condition. The slip angle is set to 0 degree and the tire is loaded in a linear ramp from 0 to 160% of the target normal load and then unloaded after reaching the maximum load.This is part of the tire preparation and tire selection process before the actual test. For the test the speed of the roadway is set to 3.5km/h before beginning the test. The test itself is carried out using two test formats, Full-Range slip angle procedure and Low-Slip angle procedure. Both test are conducted in a fairly similar manner by varying the slip angle in the increments of 1 degree from -10 degrees to +10 degrees and loading the tire incrementally. The only difference being in the Low-Slip angle procedure the slip angle is only varied from -6 degrees to +6 degrees. Cornering stiffness and aligning stiffness is obtained using this method. In both the test formats the tire shall complete at least 2.5 revolutions after each load change before starting the data acquisition, with a minimum of 32 equally spaced data pointed collected and the average of the reported data for a load and slip angle is taken.This type of data acquisition is called a fixed point testing, it implies that during the test period when data is being collected the independent variable remain fixed. Resting at each value long enough to record data helps eliminate tire relaxation errors and errors due to non-uniformity of tire. While developing the test protocol using LabVIEW these SAE standards were carefully taken into consideration [19].

CHAPTER 3: HARDWARE SETUP

3.1 Load Cells on M-15 and Calibration of Z-axis Load Cell

The hub of the M-15, has load cells embedded inside to measure the tire forces produced during the testing. With the help of various CAD drawings and section views of the M-15 it was conclusively proven that the hub of the M-15 has six pan cake type load cells at three different locations, namely D51, D52, E5, C51, C52 and D53 in sets of two. One set serving as a backup in-case of failure or damage to the first. The drawings also revealed the exact locations of the load cells inside the hub, making it possible to design a calibration jig to calibrate the load cells. After the successful calibration of the load cells inside the hub. D51, D52 and E5 were decided as the main set of load cells to retrieve data from as it was observed during the calibration process that, these load cells reacted better to load changes than the other set of load cells placed behind them. Apart from the load cells inside the hub, the M-15 has one other load cell situated at the bottom of the carriage, used to measure the vertical load on tires.

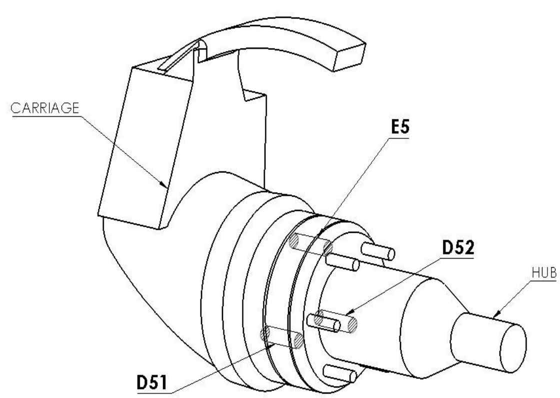


Figure 3.1: Hub Load Cells. [20]

The calibration process for the Z-axis load cell was much simpler as compared to the other load cells. The main reason for this was where the load cell was situated. The Z-axis load cell sits right below the carriage of the M-15 directly connected to the mounting plate of the linear actuator used for loading the tires. This eliminates the worry about its interaction with other load cells on the M-15. Also due to the location of this load cell the need for complicated calibration jig was eliminated. A simple four bar system which connects the reference load cell, mounted on top of the M-15 and the calibration jig of the hub was all that needed. This setup made sure that the bottom load cell was connected to the reference load cell at the top, any downward movement of the carriage caused a proportional pull on the reference load cell. In simpler words any compression load on the bottom load cell acted as tension load of the same magnitude on the reference load cell. Once this linear relationship was setup using the calibration jig, the next step was to connect the reference load cell to LabVIEW using the SCXI and configure it to the DAQ assistant. For this purpose a simple custom voltage setup was used in the DAQ assistant, as the load cell directly gave a voltage output to the applied load.After this manually the carriage was moved down by pressing the load push button on the operator dashboard. This caused the reference load to be in tension and bottom load cell in compression, the reference load cell was calibrated to display the load in the LabVIEW program front panel and since both load cells where under the similar load except for the direction of load being applied, hence it was possible to configured the bottom load cell using the same reference linear fit for the reference load cell. The details about the entire process of configuring would be discussed in detail in chapter 4. The calibration sheet provided by Load Cell Central, the organisation from where the reference load cell was purchased, came in handy for the configuration process [21, 22]. The details are tabulated below:-

Table 3.1: Reference Load Cell Calibration Data

Parameter	Specification
Model	LPSW-B-5k
Capacity	5,000 lbs
Compression FSO mV/V	-4.0742
Tension FSO mV/V	4.0741
Calibration Date	10/23/2018
Max. Excitation	10V AC or DC

Figure 3.2: Z-axis Load Cell Calibration Jig

3.2 Data Acquisition System

In this chapter we will talk about the National Instrument's (NI) SCXI system used for data acquisition(DAQ). The M-15 uses a NI SCXI-1000 chassis in combination with a 1520 module for reading the voltage values from the load cells and potentiometer. A high performance SCXI 1600 module is used on the chassis to receive analogue signals from the 1520 module, the analogue signals are amplified, digitized and sent through via a USB port to the operator PC. The capabilities of the SCXI 1600 module exceeds far beyond the scope of this project, it can read up to 352 analogue signals from various thermocouples, RTDs, strain gauges and other voltage sources. While this might look as an over kill for this project, the main reason for its selection was the ready availability in the test facility. The SCXI 1520 module can read up to 8 channels, with 3 of the channels being used by the load cells inside the hub of the M-15, one is used by an external load cell to measure the vertical load and one by a potentiometer to measure the slip angle of the tire being tested. The module is housed inside a SCXI 1314 terminal block providing quick and convenient way to attach the I/O signals, it attaches directly to the front of SCXI 1000 chassis making the entire wiring look clean and hassle free [23, 24, 25].

Figure 3.3: NI Data Acquisition System

3.3 3Φ Motor and Brush Setup

The 8.5m diameter road wheel of the M-15 is rotated using an AC 60 Hz 3*phi* induction motor. As the road wheel of the M-15 only needed to rotate at a speed close to 4km/h according to the SAE tire test protocol, the selection of this specific motor was based on availability. This 20Hp motor has a synchronous speed of 1750 rpm and a maximum speed of 5000 rpm, coupled with a 'Dura Pulse' 460V variable frequency drive (VFD) motor controller,makes sure that the motor is capable for now and future requirements of this project. The motor is connected to the road wheel using a HTD timing belt with a 4 to 1 reduction ratio, providing the necessary torque to rotate the heavy road wheel with ease.

As we discussed in the previous chapter about factors effecting tire testing, the presence of contaminants on the testing surface constituted a major part in the errors caused during the collection of tire testing data. Hence the need to maintain a clean testing surface is of prime importance. On the M-15 this is done with the help of vacuum pump and roller brush set up. The roller brushes are adjustable, so that with time when the brushes wear out it can be moved closer to the road wheel. Through PLC programming the roller brush is programmed to rotate in the opposite direction as compared to the road wheel. The entire roller brush system is mounted below the main structure of the M-15 and neatly ducted out using the vacuum pump attached to a shaker. The operator can switch on the vacuum pump by the push of a button on the main terminal along side the operator PC. The shaker shakes of the dust collected in the filters and the vacuum pump is run for at least 15 minutes post tire testing to get rid of any tire debris stuck on the road wheel.

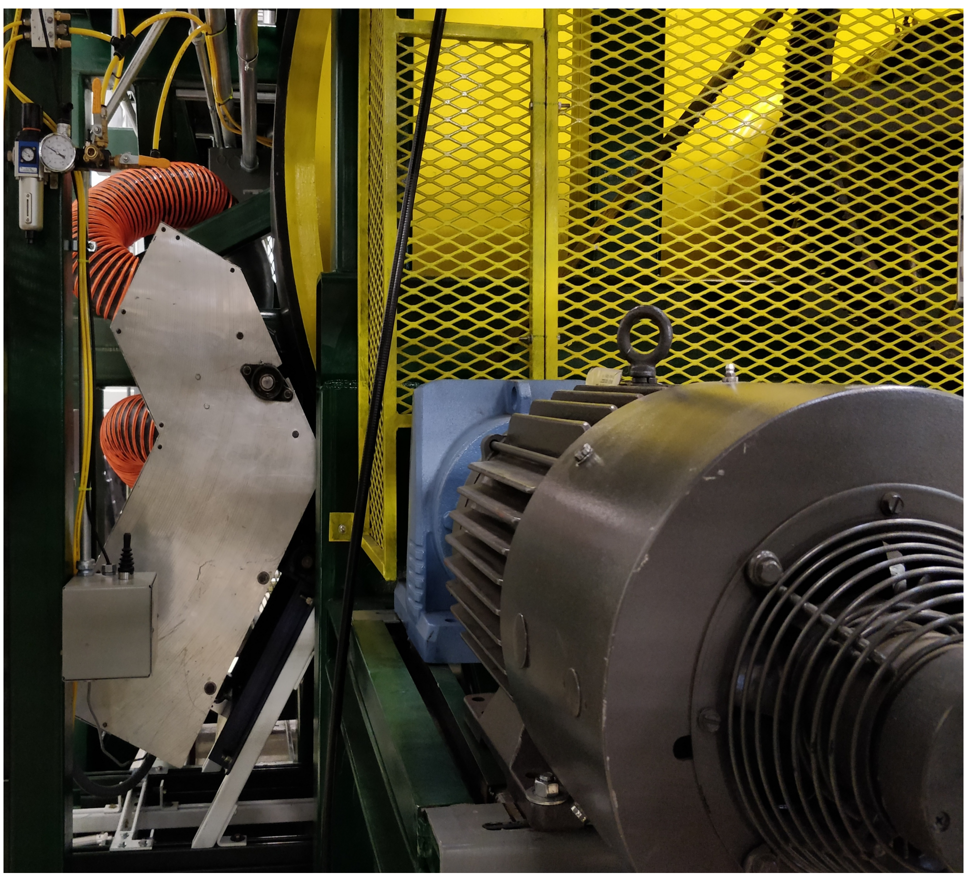
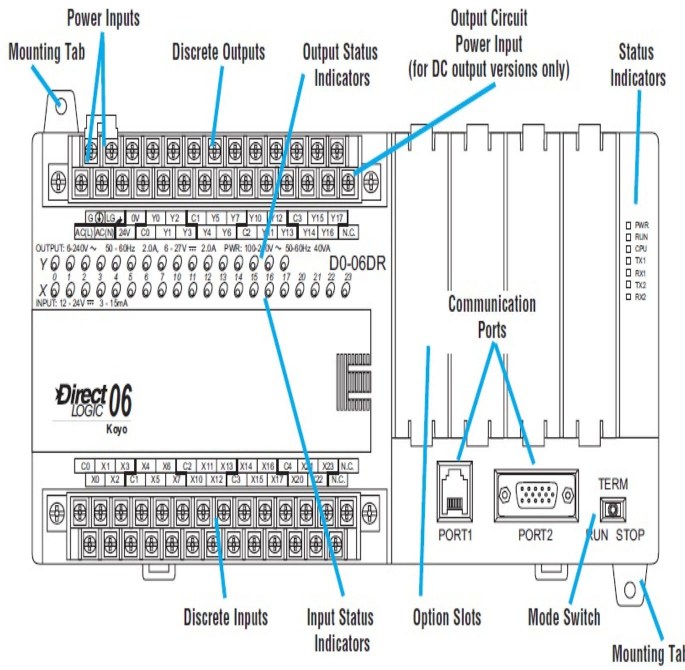


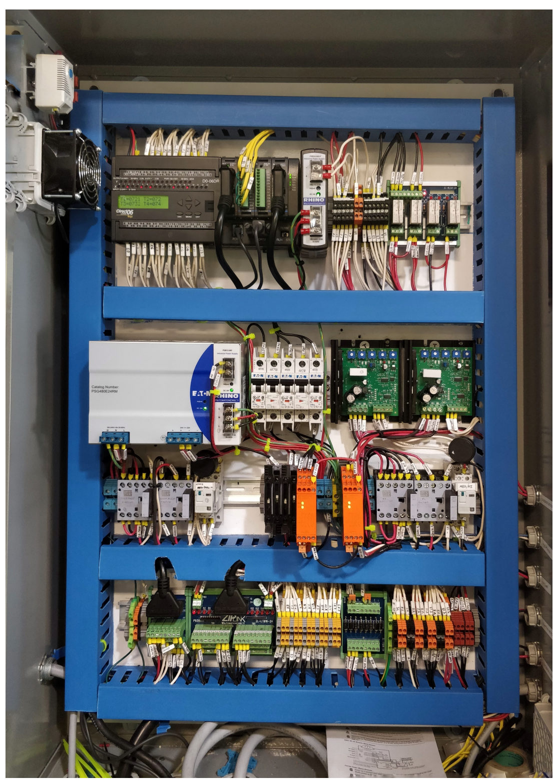
Figure 3.4: Main 3ϕ Motor Drive and Brush Setup

3.4 PLC-DL06

To automate any process, programmable logic controllers (plc) are widely used in the industry. Similarly a plc has been used on the M-15 to automate the various functions on the tire testing machine. A 240V AC Direct Logic (DL) DO-06DR plc is used on the M-15, the DL06 can handle 23 discreet inputs and 17 point outputs. The plc comes with a proprietary ladder logic programming software DirectSoft6, a very user friendly software for programming the plc.The software has a built in PID loop and timers to help program complicated relay ladder logic (RLL) with ease. The plc also has a high virtual memory making it capable to program and run large industrial level codes. DL06 comes compatible with communication protocols like DirectNET, Modbus RTU and K-sequence (proprietary), making it possible to connect the plc with operator PC. For accurate control of load and other key functions of a tire testing machine a high speed communication is required between the plc and various control actuators. Such high speed communications are easily possible on the M-15 due to plc having a high output pulse rate of upto 7kHz and baud rate of as high as 38,400 and default at 9600. Besides these features the DL06 comes compatible with various hardware extensions like temperature readers and analogue signal readers, which makes it a very versatile hardware unit on the M-15. Despite these high end features the DL06 has very a competitive price and is readily available with no wait time, making it an ideal choice for our project [1].



(a) PLC Wiring Diagram. [1]



(b) PLC Terminal Box

Figure 3.5: DL06 PLC with Wiring Diagram and Terminal Box Setup

3.5 Linear Actuator

In the test facility at Michelin, the M-15 had a hydraulic system to manipulate the load on the tires being tested. After shifting the M-15 to the UNC Charlotte Motor-Sports facility, it was decided after careful evaluation, the loading process be converted to an electric linear actuator. The main reason for this change from hydraulic to electric was due to the fact that the hydraulic system although, very accurate and prompt to respond to changes in load, it had a lot of moving parts and required an elaborate array of oil filters and pressure regulators to maintain the proper functioning of the entire system, all these equipment was prone to leak and needed constant attention to prevent it from doing so. These factors outweighed its advantages and hence an electric alternative was deemed appropriate specially in an workshop environment, where welding, gas cutting and grinding are a common occurrence.

The tire loading process on the M-15 is done by moving the heavy carriage at a controlled rate downward. This meant the new alternative electric linear actuator needed to constantly hold the carriage in position even when there was no electric power applied to the linear actuator, or this could cause the failure of the entire TTM. Hence it was crucial to select a self-locking screw type linear actuator. Progressive Automation's 24VDC linear actuator due to its industrial grade stainless steel build and high torque motor made it an ideal choice for our project. The stainless steel shaft accompanied with metal gears allows the actuator to push or pull up-to 3000lbs and hold up-to 3500lbs, ensuring no failure would occur and the selected actuator can lift the entire carriage for unloading the tire after the test. Also the high environmental protection rating produces a versatile unit able to withstand dust, water, and harsh environments. The linear actuator comes with a compatible 20Amp. rated control box, making the electric connection to the plc easier and hassle free. An additional speed control potentiometer was added to the linear actuator circuit to control the speed at which the carriage moves down, as the fast movement of the heavy carriage caused inertial errors while programming the load functions via LabVIEW, a detailed discussion about this error would be included in the chapter 4 of this report [26]. Here are the specifications of the linear actuator:-

Table 3.2: Linear Actuator Specifications

Parameter	Specification
Model	PA-13-8-3000
Voltage	24V DC
Stroke	8in
Force	3000lbs

Figure 3.6: 24VDC Linear Actuator

3.6 Steer Angle Setup

The M-15's steer angle setup is situated above the carriage, it uses a rack and pinion type setup to change the steer angle. The rack is connected via metal linkages and a steel cord which extends back operator control panel. This steel cord is wound up against a pulley and gear mechanism inside the control panel box, when the operator turns the steering wheel mounted in front of the control panel, this rotates the pinion and gear mechanism rotating the pulley and thereby pushing or pulling the rack, causing a change in the steer angle. This setup is accompanied by an air cylinder and stopper mechanism which serves as a steer lock, without this during high slip angles and load setting the extreme lateral forces push the tire back and change the slip angle rendering the data acquired useless. A linear potentiometer is connected to the system measures the change in angle and is calibrated to display the corresponding change on operator PC. The current system has an inherent slack due to the steel cable and this makes it tough for the operator to set an accurate slip angle for the tire testing process. Modification to the steer angle setup is underway but its outside this project's scope and part of a future modification for the M-15.

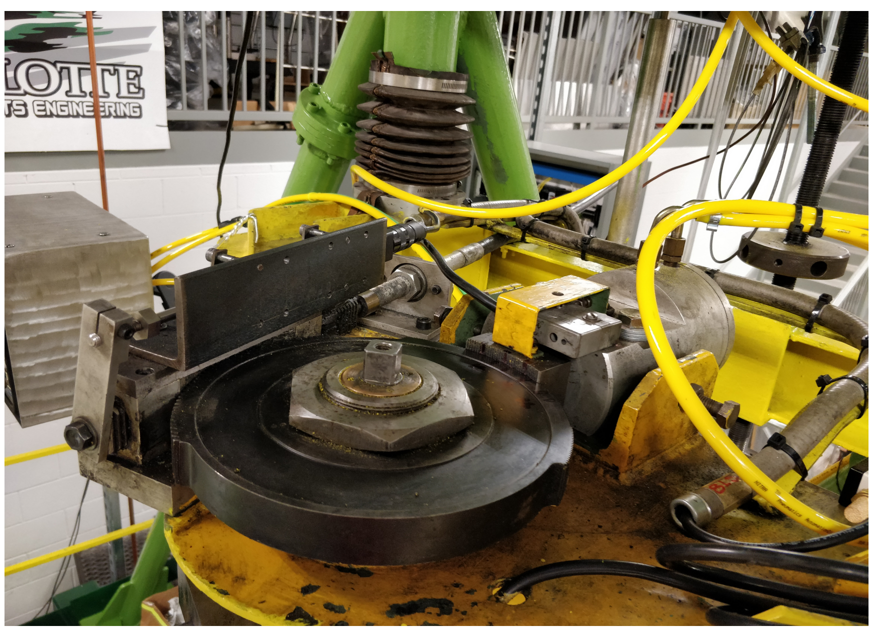


Figure 3.7: Steer Angle Setup

CHAPTER 4: SOFTWARE SETUP

4.1 PLC Programming

Automation or automatic control refers to an area where different control system components are used to operate machines with minimum or reduced human intervention. The key component of automating any process or machine is a plc. As we discussed in chapter 3 of this report the M-15 uses DL06 by automation direct as one of the main components to develop this automated tire testing machine. This section sheds some light over the ladder logic that has been programmed into the plc to execute the series of operations by just the press of a button on the operator control panel.

The plc can be imagined as large switch-board which makes or brakes connection on operators request or in a series of programmed steps. Ladder logic is the only one directly molded after electro-mechanical system relays, hence it is widely accepted in industrial applications. Ladder logic uses long rungs laid out between two vertical bars representing system power, thus looking like a ladder. Rungs are nothing but a term used to describe each line of the program. Along the rungs are contacts and coils, modeled after the contacts and coils found on mechanical relays. The contacts act as inputs and often represent switches or push-buttons, the coils behave as outputs this could be as simple as a light or a 3ϕ motor. Outputs don't always have to be physical though, it could sometime be writing to a virtual memory location in the plc and can represent a single bit. This bit can then be used later on in the code as another input. Contacts are placed in series to represent 'AND' logic and in parallel when using 'OR' logic. Just like real relays, ladder logic also uses normally open contacts or normally closed contacts depending on the physical type of push button being used.

Since discussing the entire ladder logic programmed in the DL06 plc used on the M-15 would not be completely relevant for our report, I would only be explaining few rungs which play a major role in assisting the modbus RTU communication through LabVIEW.

Rung 1 & 2:

Figure 4.1: Emergency STOP

In DL06 plc ladder logic programming and other major plcs, 'X' is considered as an input it generally is a signal from a simple a push button and 'Y' is considered as an output, like a light bulb or an electric signal to start the motor. Control relays, 'C' on the other hand are discrete bits normally used to control the user program. They do not represent a real world device, that is, they cannot be physically tied to switches, output coils, etc. Because of this, control relays can be programmed as discrete inputs or discrete outputs by assigning different discrete memory locations out of the 1024 locations. The emergency E-stop is one the most important safety feature on any modern day machine. On a machine of the size of M-15 it is crucial to have such vital E-stops at various locations as the operator visually can not detect problems all around the machine. Also due to the large amount of moving parts in the M-15 failure or breakdown of any part while the machine is running could cause serious threat to life and property. In rung 1 of the plc program, all E-stops are wired to X-105 of the plc which are 'normally closed', hence the symbol 'normally open' is used in the program and this setup in series with safety door limit switches of 'normally open' type. When the E-stop is not pressed and the safety doors are closed the circuit is complete and energises 'C2'. This control relay is used in other rungs of the program and is always connected in series, anytime the coil de-energies it breaks the circuit and stop the operation from happening. 'X2' is assigned to a physical switch on the operator control box, only when this switch is on any type ModBus communication can happen between the plc and operator PC, it also switches on a test acquisition light. This switch can act as a quick way to disconnect LabVIEW communications if due to some programming error the machine overloads the tire or doesn't stop running after the test is complete.

Rung 4,5 & 6:

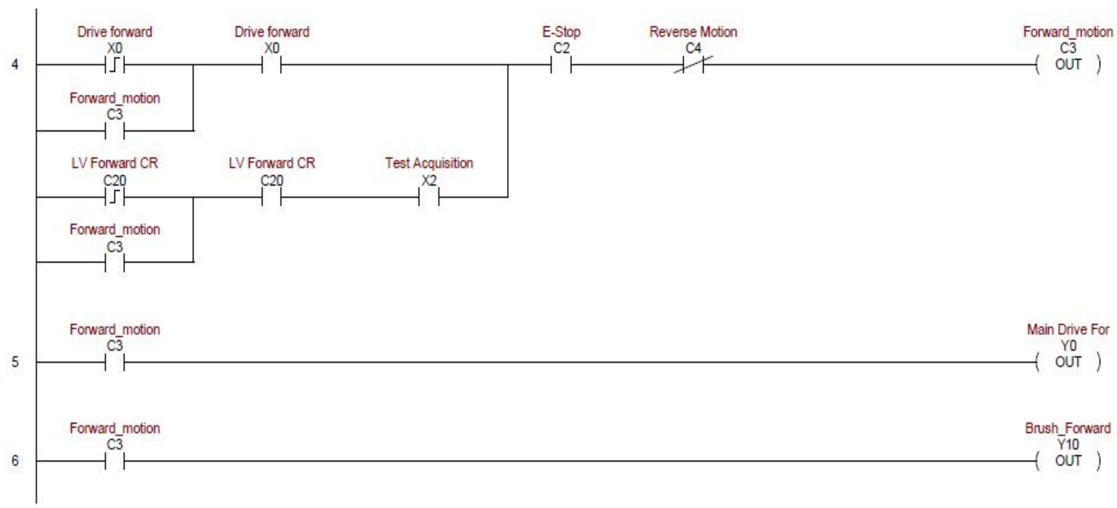


Figure 4.2: Forward PLC Program

As we had discussed in chapter 3 of this report the road wheel of M-15 is rotated with the help of a 3ϕ motor and VFD drive. 'X0' is the rotary switch on the operator control box of M-15 for forward motion. When this switch is turned on and E-stop is not pushed this completes the circuit to energise 'C3', also 'C4' reverse motion is connected to the same rung in series to break the circuit when C4 is switched on. On the same rung the LabVIEW commands are connected in parallel to energies 'C3' when 'X2' is switched on. In rungs 5 and 6 'C3' is used to energies 'Y0' and 'Y10' which commands the VFD to drive the motor and rotate the motor for the brush in the shaker assembly respectively.

Rung 7,8,9 & 10:

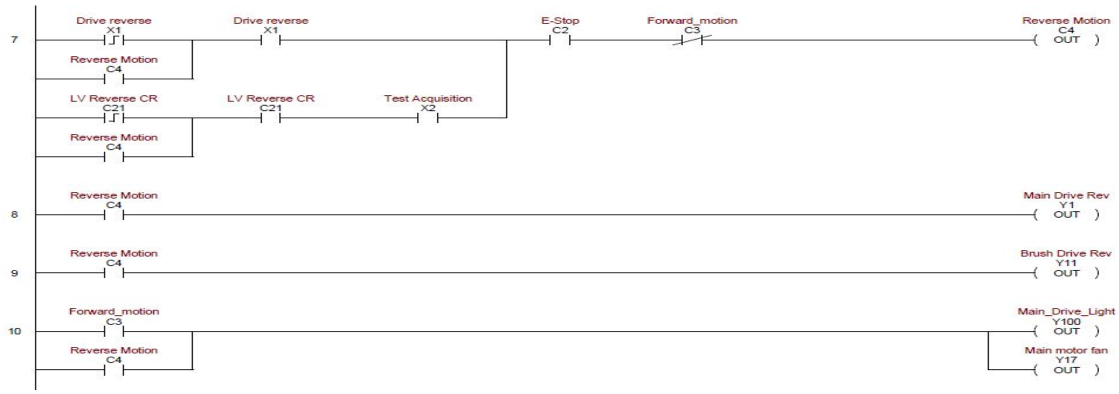


Figure 4.3: Reverse PLC Program

The rotary switch for the drive the road wheel in reverse direction is assigned to 'X1'. Similar to rung 4, rung 7 is setup in the similar manner to energies 'C4'. In rungs 8 and 9 'C4' like 'C3' controls the VFD for motor and brush. In rung 10 'C3' and 'C4' are connected in parallel, energising 'Y100' and 'Y17' the main drive light and motor fan.

Rung 18, 19, 20, 21 & 22:

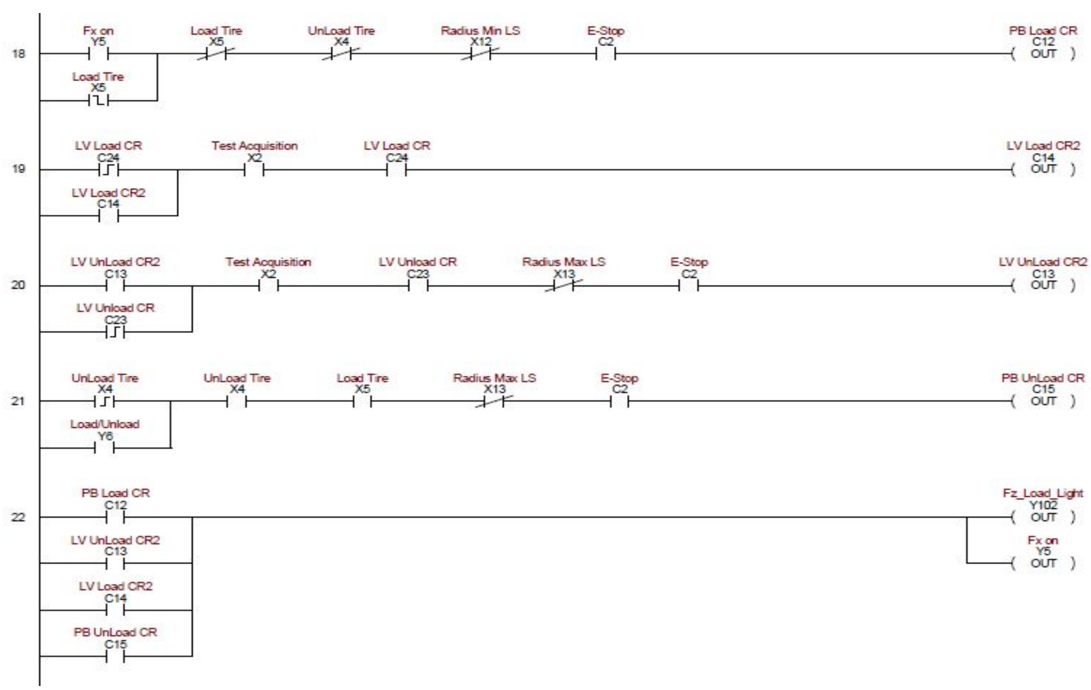


Figure 4.4: Load/Unload PLC Program

The load/unload functions are one of the crucial functions on the M-15, precise control over these are extremely important one for the accuracy of the test and secondly to prevent damage to tire due to excessive loading. 'X5' is normally open push button on the operator control box and 'X4' is a normally closed type push button on the control box these are connected in series on rung 18 on the plc program. 'X12' is another important limit switch which acts as a stopper to the linear actuator while loading, when the load push button fails or due to some programming error there is continuous loading this limit switch trips and breaks the circuit thereby stopping the linear actuator, hence it is connected in series as well to other push buttons. Similarly 'C24' is denoted for loading through LabVIEW and 'C23' for unloading. Rung 19 energises 'C14' and rung 20 energies 'C13', loading or unloading the tire respectively. In rung 21 'C15' is energised using push button for unloading the tie 'X4', 'X13' is another limit switch which acts as a safety for actuator runaway while unloading. All these outputs 'C12', 'C13', 'C14' and 'C15' are connected in parallel to energies the load light, 'Y102' on rung 22 of the program. These are just few rungs of the program to describe the general outline of the plc program on DL06.

4.2 ModBus RTU

Modbus is a serial communications protocol originally published by Modicon in 1979 for use with its plcs [27]. The Modbus protocol is used to exchange data between the plc and the computer. The Modicon controller use and RS-232C compatible serial interface which defines different parameters like transmission baud rates, parity checking, connector pin outs and signal levels. The controller uses a technique called master-slave technique in which the master can initiate any transaction called queries and the other device, the slave respond by supplying the requested data to the master or sometimes taking the action requested in the query [27]. The query has unique function code, this defines the kind of action to be taken by the slave as response to the query. If the slave responds normally, it is called as an echo function code. The echo can be data bytes the is collected by the slave as a register value. If an error occurs, the function code is modified and the data byte sent contains a code that describes the error [27]. The table below a set of functions codes commonly used in Modbus communication protocol.

Table 4.1: MODBUS Function codes

Function Code No. (hex)	Function to Perform
01	Read Coil Status
02	Read Input Status
03	Read Holding Registers
04	Read Input Registers
05	Write Single Coil
06	Write Single Register
15	Write Multiple Coils
16	Write Multiple Registers

The Modbus network has two serial transmission modes: ASCII or RTU. The user is free to select the desired mode along with serial port communication parameters. However the mode and serial parameters must be the same for all devices on the Modbus network [27]. Each mode has its own advantages and disadvantages, ASCII (American Standard Code for Information Interchange) uses two ASCII characters each 8-bit byte in a message. This mode allows time intervals of up to one second to occur between characters without causing errors, this can advantageous for instruments like bar code scanners, weight scales, serial printers etc. where there is only limited amount of data sent with a certain. RTU (Remote Terminal Unit) mode of communication is used when large amount of data needs to be sent continuously. In RTU mode each 8-bit byte in a message contains two 4-bit hexadecimal characters, allowing greater character density for the same baud rate [27]. On the M-15 the Modbus communications are configured using LabVIEW, its graphical programming interface simplifies the process. With simple user friendly commands like Modbus serial master query and Modbus serial int communication between the plc and LabVIEW is established. Simply the user has to specify the visa source name, baud rate, parity, mode and slave address as shown in the image below [28, 29]. Once these values are configured correctly, the communication between LabVIEW and plc would be established, allowing data flow between the two devices. This communication is done through RS-485 serial port connected to port 2 of DL06 plc. The reason behind choosing RS-485 over RS-232 is due to the long range capability of up-to 1000m compared with a distance of only 15m for RS-232 and also the fact it allows a maximum of 247 devices. These features eliminate the need of replacement of the RS-485 cable for the years to come justifying its selection over the RS-232 [1].

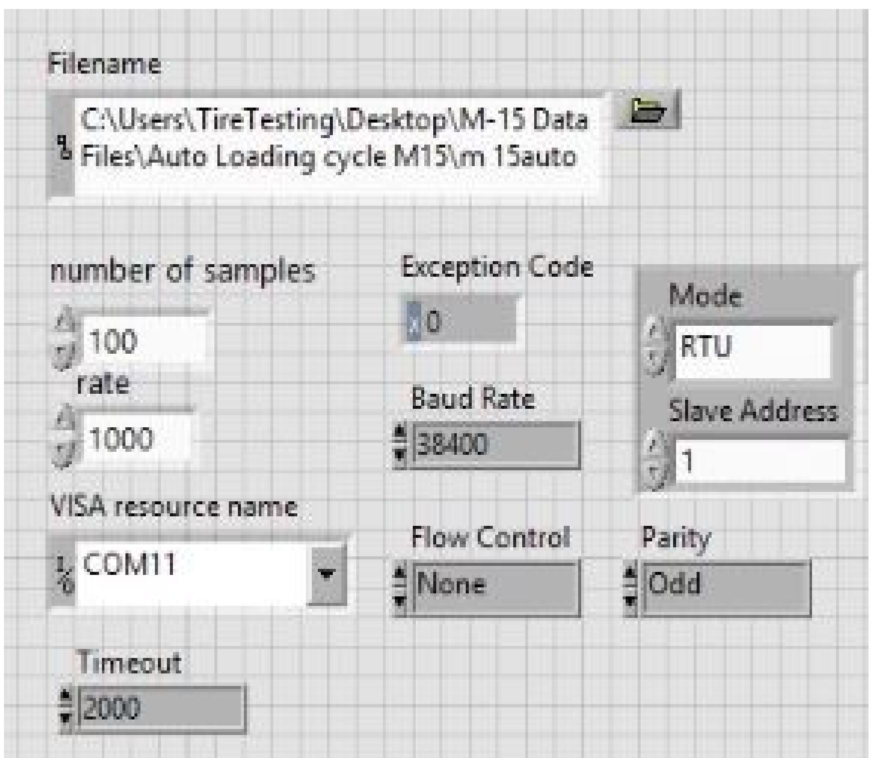


Figure 4.5: LabVIEW Front Panel View of Modbus Configuration

4.3 LabVIEW Programming

LabVIEW stands for Laboratory Virtual Instrumentation Engineering Workbench, a graphical programming language first released in 1986 by National Instruments (NI). It implements a data-flow paradigm in which the code is drawn or represented graphically similar to a flowchart diagram. Various processes are linked using wires and each function is stored as a virtual instrument (VI) having three main components, the front panel which essentially contains inputs and controls, a block diagram where the code is edited and represented graphically and an interface to the VI when it is embedded as a sub-VI. Writing a code on LabVIEW is as simple as dragging and dropping functions from a function palette onto the block diagram within process structures like 'for loop', 'while loop' or 'case structures' and wiring terminals. Unlike most programming languages, LabVIEW compiles codes as it is created hence any error that occurs during programming can be identified immediately and resolved, thereby saving a lot of time in debugging [30].Over the years, LabVIEW has matured into a general purpose programming language and is equipped with variety of design layouts such as 'Client-Server', 'Consumer-Producer', 'State-Machine' etc. In order to understand such high level programming features of which some them are used on the code developed for M-15 'Tire Test Protocol', the reader must be acquainted to some of the basic LabVIEW programming functions, of which some of them are described below.

While Loop:The 'while loop' allows the user to run the code continuous without having to press the run button each time the loop ends. It is similar to a 'for loop' the only difference being the 'while loop' only ends when the user presses the 'stop' push button wired to the loop.

Case Structure:This structures are used where the program or the user has to make a decision. The simplest of these will be to decide to do something or not to do it. Only one of the cases can run at any given time. When a case structure is first put on a block diagram it has two cases true and false and the user can program different functions to operate depending on the Boolean input signal.

Event Structure:It is similar to a 'Case Structure' allowing the user to perform different functions for varying inputs but unlike a 'Case Structure' where the user can only choose between a 'true' or 'false' condition, here the user can create as many event as he/she wants and perform various functions. This limits the CPU usage while waiting for user input. An input could be user defined like a mouse click, or keyboard entry or a simple list from where the user can select an event at his discretion.

Sequence Structure: LabVIEW follows data flow programming, meaning it executes a function as soon as it receives all its inputs. On occasion there is a need to absolutely ensure one function completes before another begins, in such cases a Sequence Structure is used.

Shift Registers: Shift registers save data in memory so it is accessible from one iteration of a loop to the next. It is shown as a downward blue arrow on the two sides of a 'while loop'.

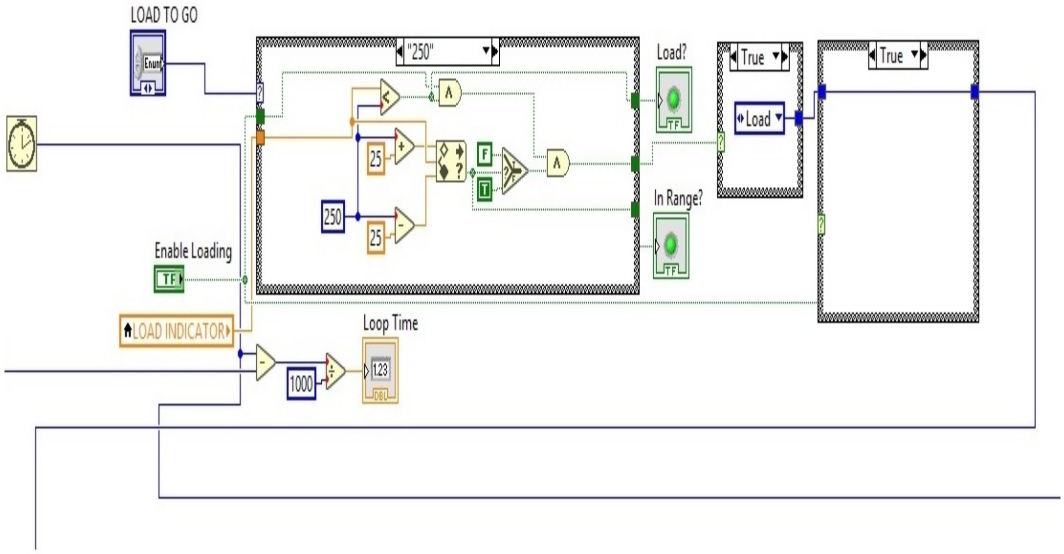
Wire Color: This may not seem as important as other key functions, but understanding it is very important for a programmer. LabVIEW has color coded different wires depending on the data it transfers. Wires of different data types cannot be joined or sometimes used as inputs to a functions causing errors in the program. The table below illustrates the type of wire and the designated color.

Table 4.2: LabVIEW Wire Colors

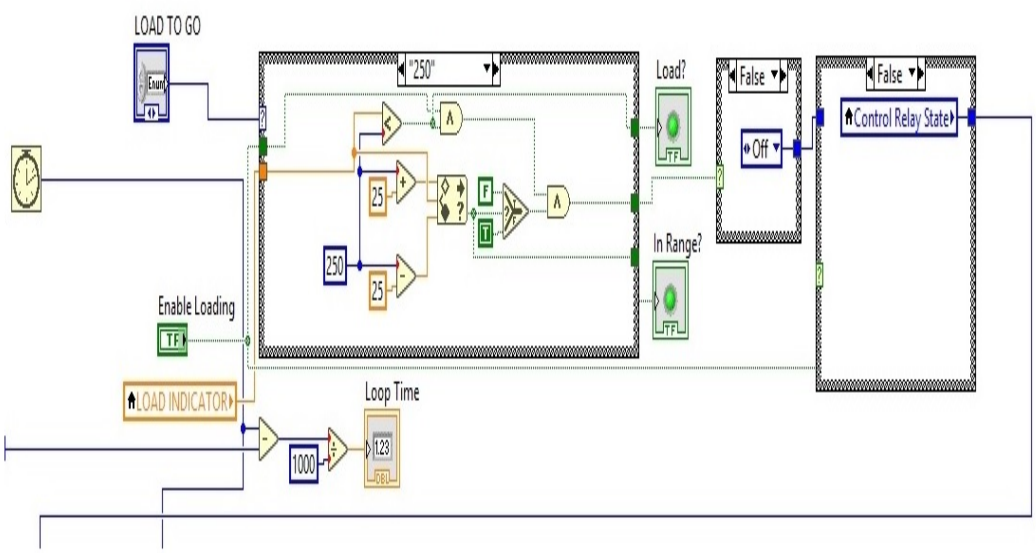
Type	Color
Floating Point	Orange
Integer	Blue
Boolean	Green
String	Pink
Path	Dark Green
Hardware Resource	Purple
Waveform	Brown
Class	Red

4.3.1 Load Control Algorithm

The load control algorithm of the M-15 is a very crucial part of the main program and also the one which consumed the most amount of time while programming. The main constituent of this algorithm is the event structure, this structure contains events for every load the tire needs to go to. Currently it contains ten events, out of which only five are used for the load cycle. Each of the ten events are similar except for the load value, which varies in every event. Like in the image shown below the load is set to go to 250lb. The functionality of the algorithm is pretty simple, it compares the current load from the 'Load Indicator' local variable with the desired load, in this case 250lb. If the current load is less than 250lb it gives a Boolean signal to load. However in reality its not that simple, the precise control of the linear actuator to stop at the desired load is extremely difficult. There is always a delay between detecting the load and responding to the change in load, although this delay was only a few milliseconds, it is enough for the load to overshoot a value more than 100lbs and in some cases around 200lbs. This issue was tackled using the 'range' function, where a signal was sent to stop the actuator even before it reaches the exact load in-order to overcome the effect of inertia of the heavy moving carriage and delay is signal transmission. In order to have control over the loading of the M-15 and to avoid loading of the tire as soon as the operator runs the VI a 'Enable Loading' push button is provided on the front panel. The Boolean input from the load difference is taken along with the Boolean signal from the 'Enable Loading' push button to an 'and' function on the program. When both the inputs are 'true', meaning that there is a positive load difference and 'Enable Loading' key is pushed, the 'and' function outputs a true value. The true value from the 'range' function is sent into a special 'Select Function'. This function accepts three inputs, the central one being the true or false selector and the top and bottom one being the desired output for true case and false case respectively. When the load is in range the true value is set to be false Boolean and when the load is not in range the false value is set to be true Boolean. This signal from the 'Select Function' is sent as input to again an 'and' function along with the input from the previous 'and' function. When both are true, a true Boolean signal is sent to a case structure asking it to choose the true case and perform the 'load' operation.



(a) Loading On



(b) Loading Off

Figure 4.6: Load Control Algorithm

When the desired value is greater than the 'Load indicator' the first 'and' function returns false and the range function outputs true, making the 'select function' output a false output and making the second 'and' function false as well. This makes the case false in the case structure, asking to switch off the linear actuator and stop loading. Also if the 'Enable Loading' push button is not pressed or switched to off condition, the linear actuator stops loading. It happens in this manner, although the load difference is positive and the range function gives a 'false' value making the 'select function' go true and ask the first case structure to 'load', the 'Enable Loading' is also wired to the second case structure's selector terminal making it go false and stopping the load command to go through. This can be observed in the figure below. There are two LED lights are wired, one to notify the operator that there is positive difference between the desired load and current load and the second one to notify the operator that the load is in range. These LEDs play a major role in the automated loading cycle algorithm explained in the section ahead.

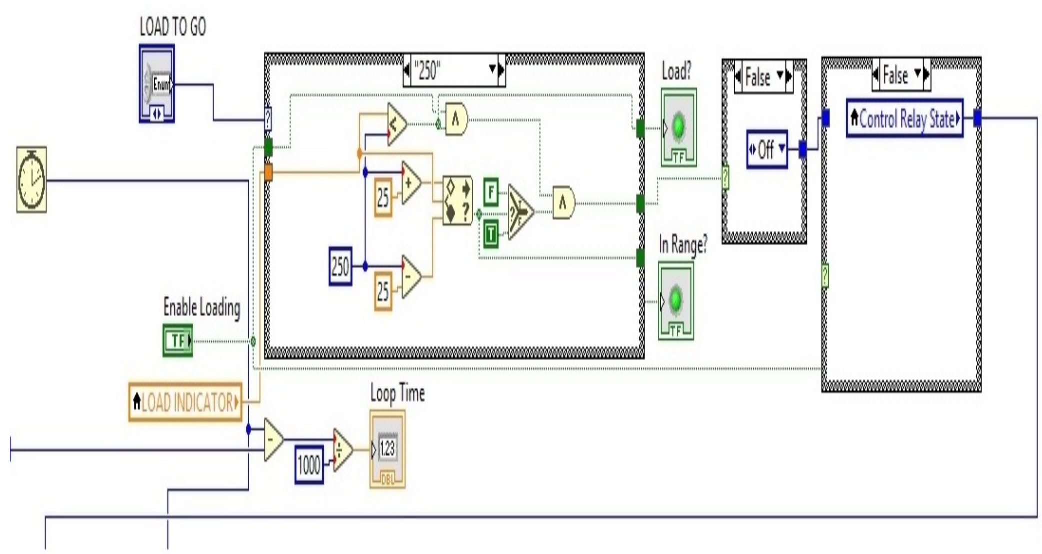


Figure 4.7: 'Enable Loading' Off

4.3.2 State Machine

A State Machine is just an 'Case Structure' inside a 'While Loop' and is used when different states are there to a machine or program and needs to operate in a programmatically determined sequence. On the M-15 the different states are 'Loading', 'Unloading' and 'off'. These states are created as different cases in the 'Case Structure' and the current state has decision-making code that determines the next state. Enumerated constants can also be used to switch between different states. An

'Enumerate Constant', commonly known as 'Enum' is nothing but a numeric value associated with a string data type, the string is displayed to the user to improve program readability. The code developed for M-15 has a special 'Sequence Structure' inside every case. This is used a safety feature, since a Modbus command is sent to load or unload the tire in each state anyway errors or conflicts in programming can cause damage to the hardware. Hence in-order to ensure one action performs after another a 'Sequence Structure' is used. The image below would help give a better understanding of the State Machine architecture used in M-15 LabVIEW program.

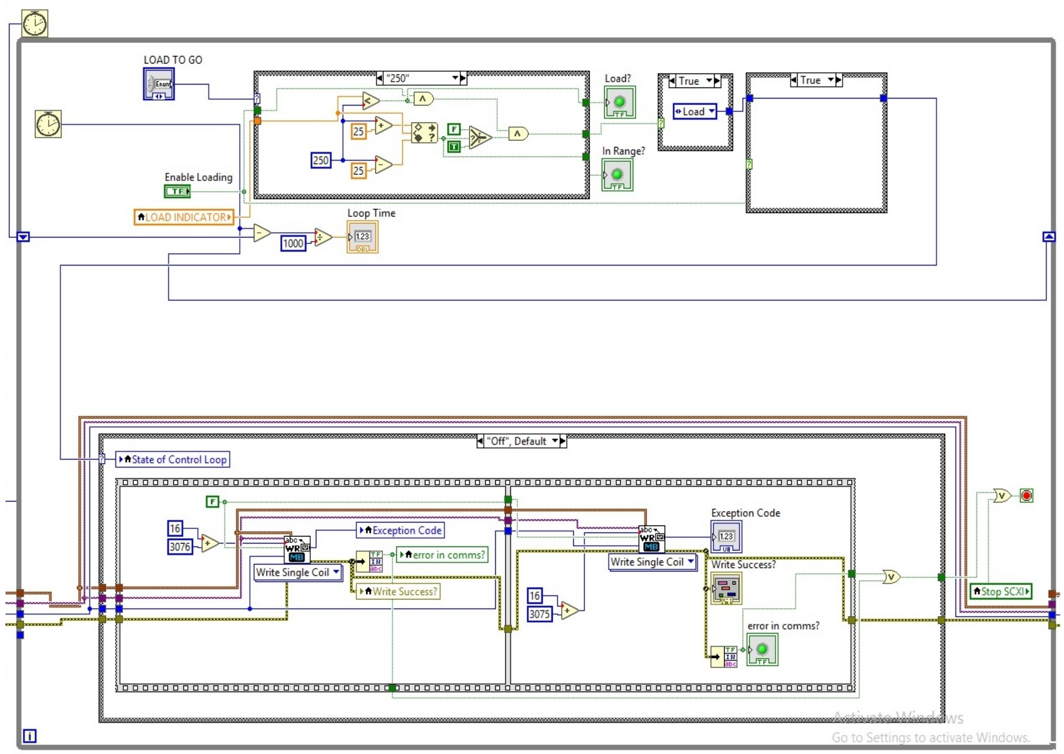


Figure 4.8: State Machine Architecture

As discussed in the load control algorithm section of this report, when a true Boolean is sent to the case structure 'Load' LED in the back panel of the LabVIEW program and the 'Enable Loading' push button is 'on' the conditions are favorable to load the tire. This happens when the 'Load' 'Enum' in the true case sends a signal to the case selector terminal of the 'State Machine' case structure, asking it to go to the 'Load' case. In this case the Modbus single coil write command is wired to a 'true' Boolean asking it to energies 'C24' coil in the plc. Also a 'true' Boolean signal is wired to another Modbus single coil write function in the adjacent sequence structure, energising 'C23' coil in the plc. These two signals make the linear actuator move downwards and load the tire. The image below would help develop a better understanding of the actual process.

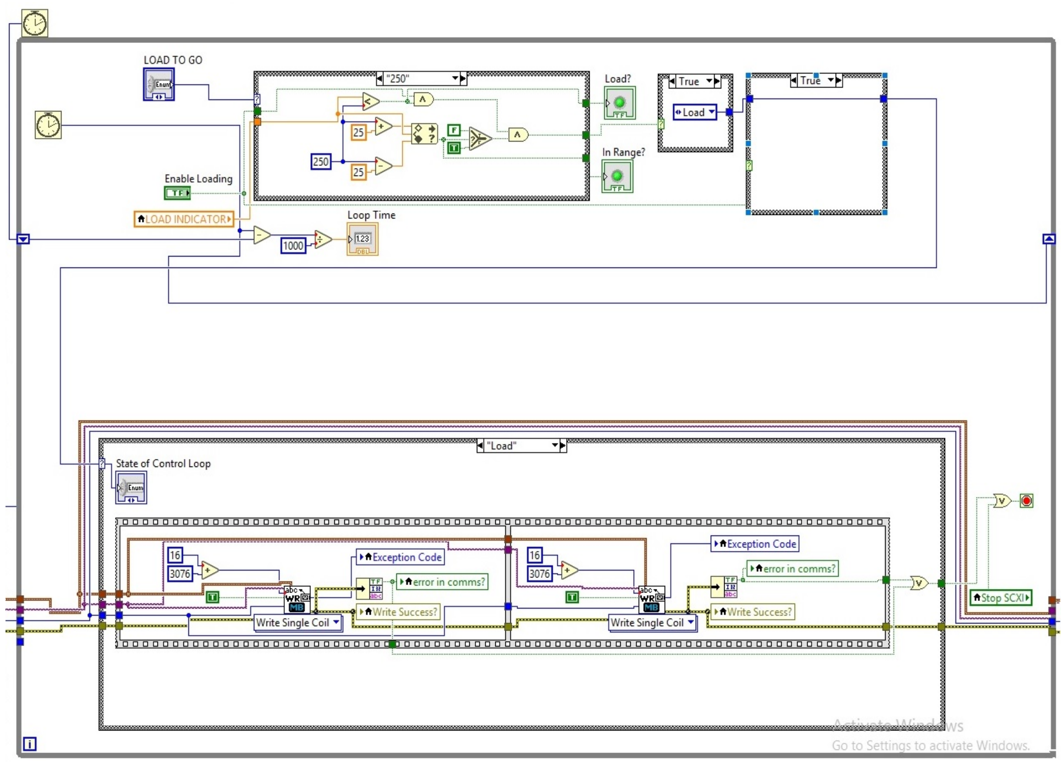


Figure 4.9: State Machine Load Case

Once the desired load and actual load are in range the Boolean signal turns false, making the case structure adjacent to the 'load' LED go to a false case. The 'Enum' turns to the 'off' state and commands the State Machine to go to the default 'Off' state. In the 'off' state a 'false' Boolean signal is given to the Modbus write coil, de-energising the coils 'C24' and 'C23'and stopping the linear actuator from moving any further down. The image below would help paint a clearer picture.

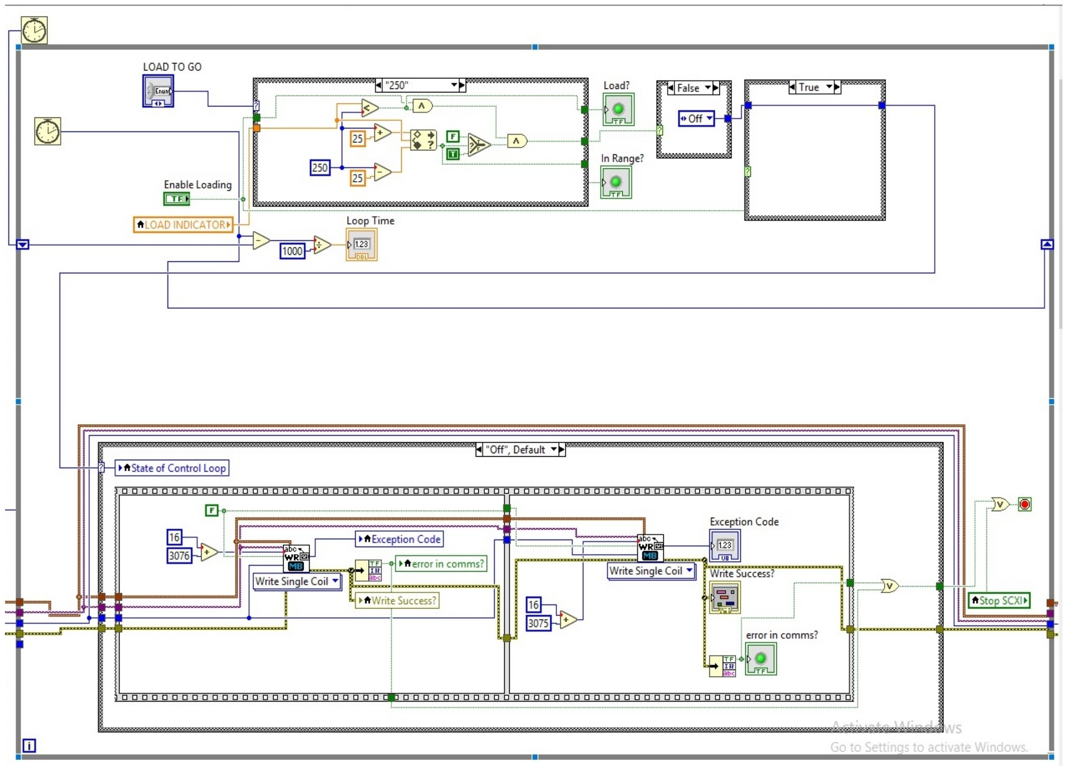


Figure 4.10: State Machine Stop Load Case

In-order to unload the tire, the Enum is set to unload condition, this takes the State machine case to unload condition as well. In the unload state the 'C24' is de-energised hence the false Boolean to the first Modbus write coil command and 'C23' is energised to make the linear actuator move upwards and thereby unload the tire as shown in the image below.

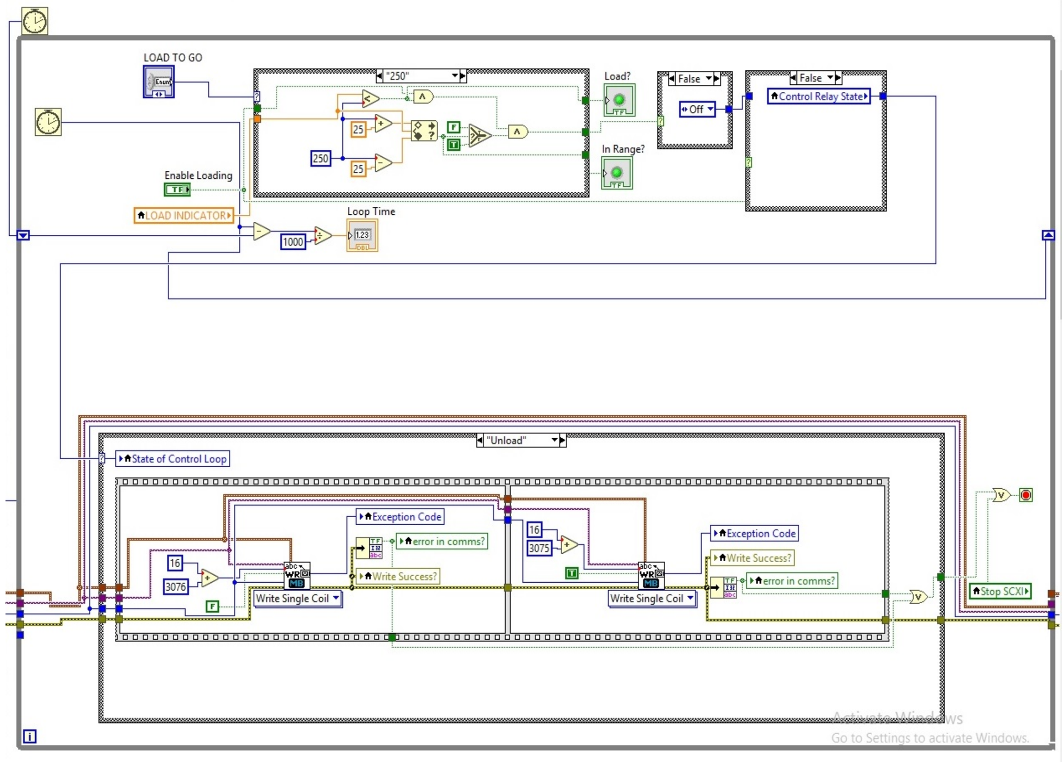


Figure 4.11: State Machine Unload Case

Error handling is another important part in writing a LabVIEW code, its very important to connect all your functions in program to the error in and error out in series, this helps to determine if there are any write or copy errors whenever something goes wrong. An error exception code is created each time there is one and the operator can take a look at the error out window in the front panel to understand why the requested function didn't perform as desired. Similarly all Modbus write commands are connected to error handlers along with a 'Error in Comms' LED for easy notification whenever a failure occurs on the M-15. Error handlers are nothing but yellow in black wires seen in the above images.

4.3.3 Automated Loading Cycle

This is another important section of the 'Tire Test Protocol' LabVIEW program developed for the M-15. In this section the code for automated loading of the tire is developed. As we had discussed in previous section of this report about sequence structures and how they are used when a sequence of operations have to be performed only in a specific order. The automated loading cycle also uses a sequence structure, each frame of this structure performs an important operation and only after completion of this operation it moves on to the next. The loading cycle goes through a set of five loads 250lb,567lb, 833lb, 1101lb and 1372lb. These loads are the test loads obtained from General Tire's Altimax tire test data. The main reason to use these specific loads is the fact that the tire test data obtained from Altimax tires is available with us. The test data obtained for the same tires on the M-15 can be compared to the available standard data and can serve as a validation for tire test machine.Since a flat sequence structure is used, it becomes difficult to illustrate the entire code in one image alone. Hence the program is divided into parts and snippets of these parts are attached below.

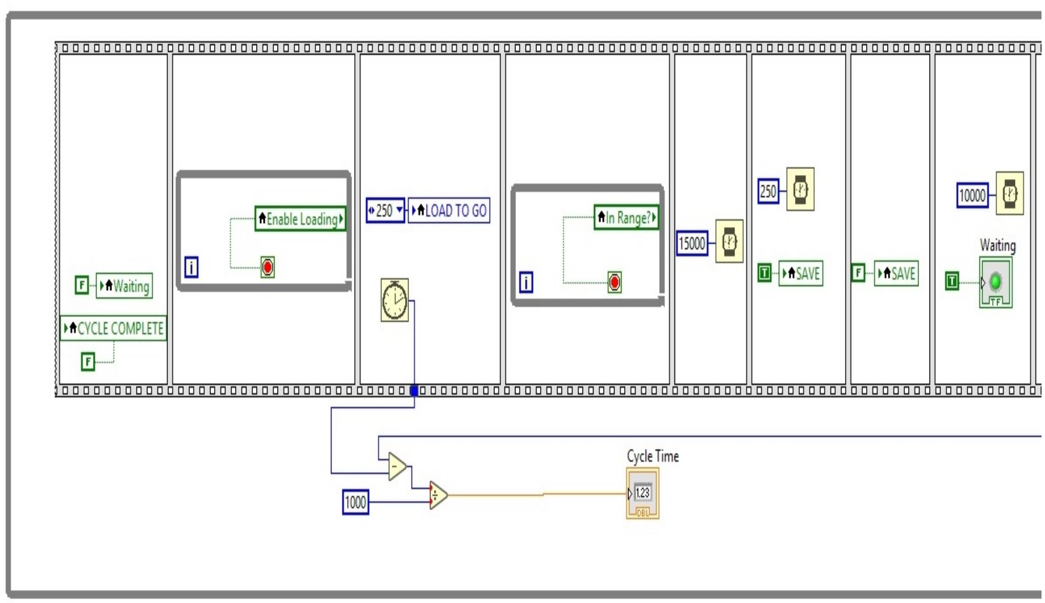


Figure 4.12: Automated Loading 250lb

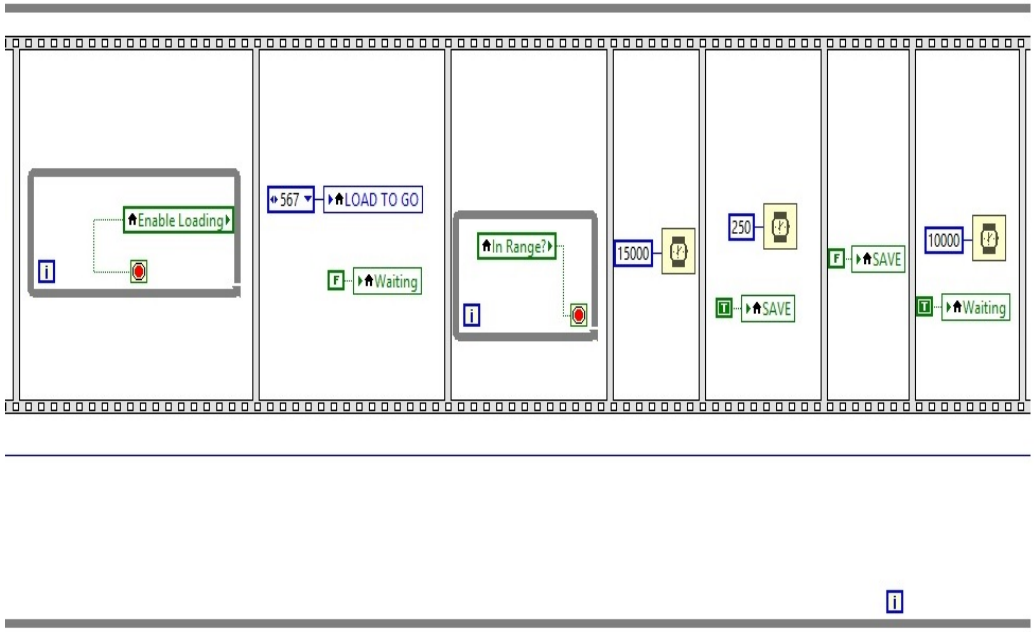


Figure 4.13: Automated Loading 567lb

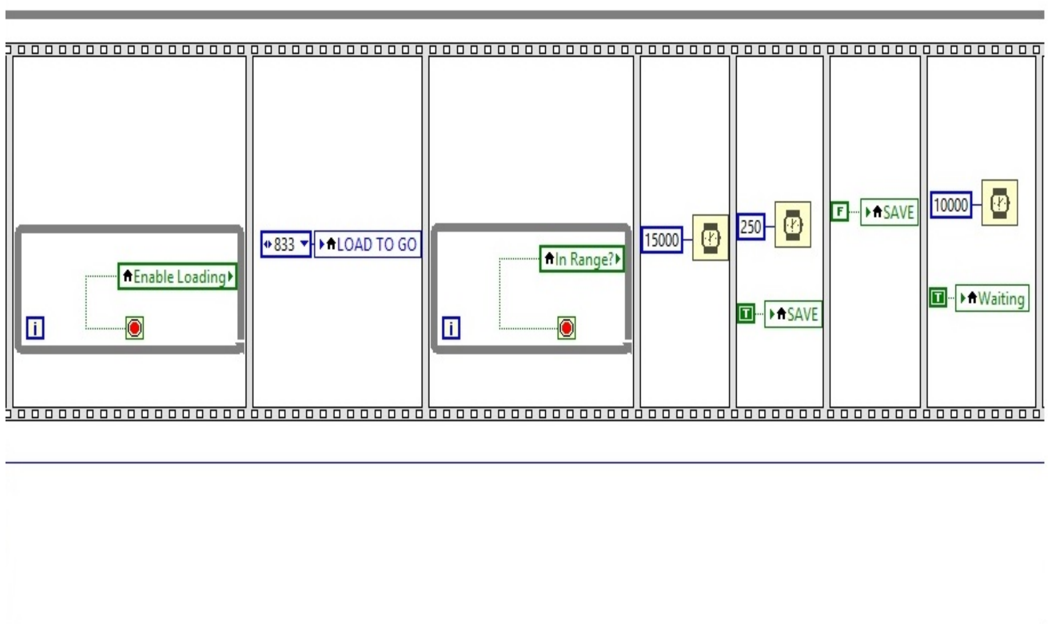


Figure 4.14: Automated Loading 833lb

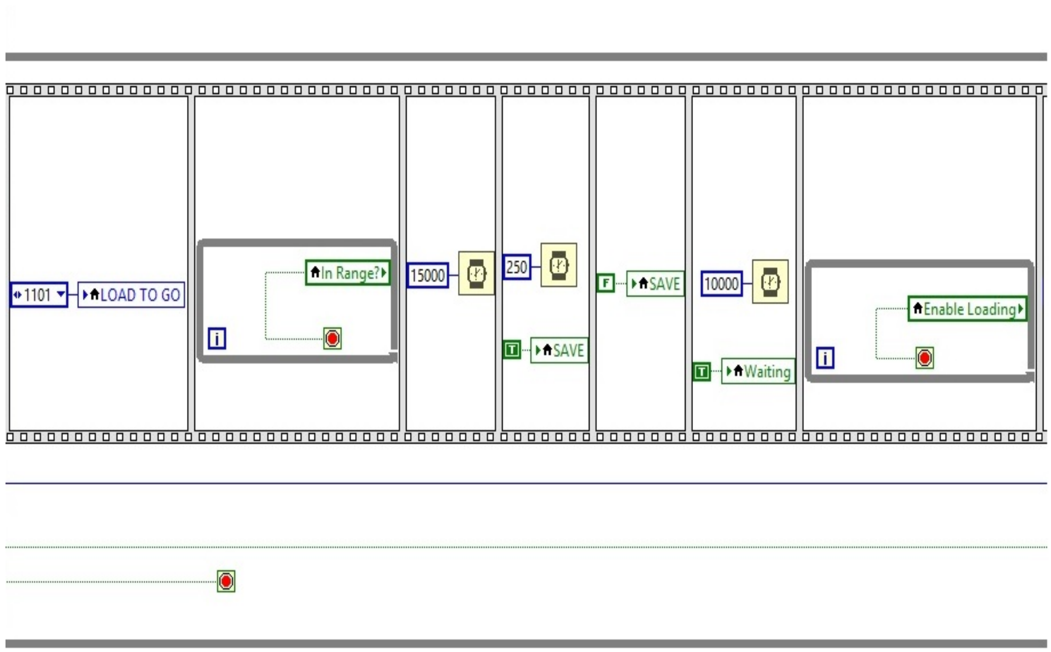


Figure 4.15: Automated Loading 1101lb

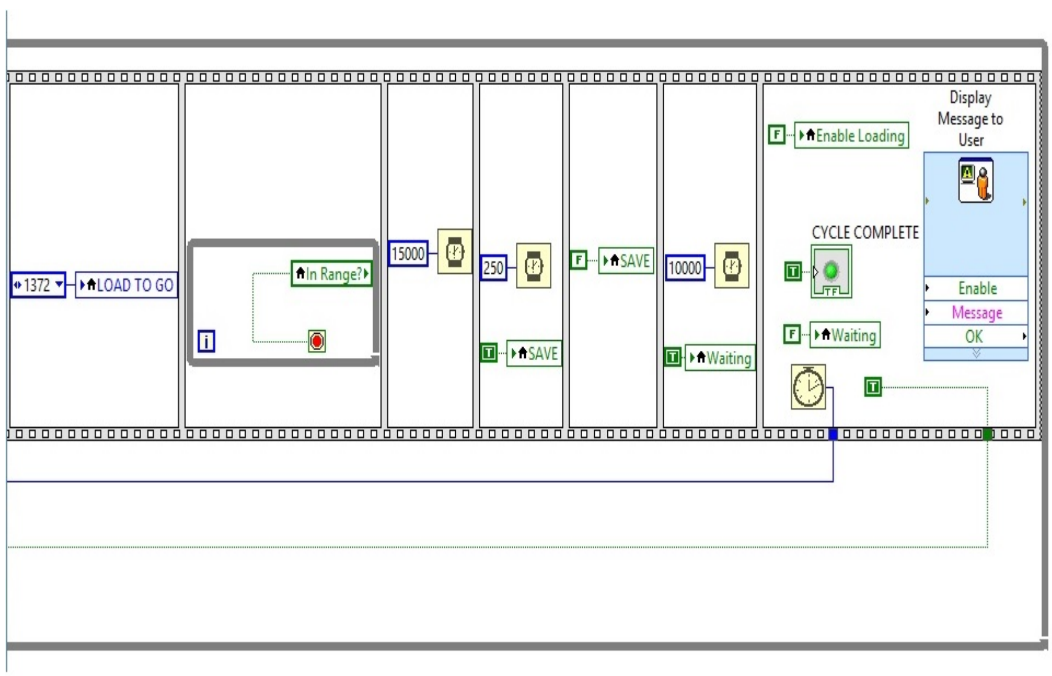


Figure 4.16: Automated Loading 1372lb

As one might have observed from the above images the series of steps followed to automate any load is identical expect for few changes. Hence describing the process for one load would help make the reader understand the process for the remaining load cycles. The sequence structure begins with a frame consisting of two LEDs one notifying the 'waiting' and the other notifying 'Cycle Complete' to the operator, hence as soon as the operator starts the LabVIEW program both LEDs go dead due to the false signal wired to them. The next frame is a crucial one, the program won't proceed any further without the operator pressing 'Enable Loading', this is very important without which the program starts loading the tire as soon as the operator runs it. After starting the program and before pressing the 'Enable Loading' key the operator can manually load and unload tire, set the slip angle and check tire pressure these changes are needed to be done before every test. The next frame commands the 'Load To Go' 'Enum' to go to the desired load in the first case 250lb. The 'Load To Go' is called in this frame as a local variable, meaning any changes done in this frame would cause a change in the main load control algorithm and cause the tire to load. After this in the next frame the 'In range' Boolean is kept inside a 'while loop', making the loop run until a true signal from the icon to stop the while loop. In the next frame a simple wait timer is used and asked to wait for '15000' milliseconds, this time is very important as it is compensates errors caused due to tire relaxations and ensures the tire rotates at least one complete revolution before data is collected as specified in SAE J1107 [5, 19].The frame after sends a true signal to save the data for a period of 250 milliseconds and the succeeding frame stops the save. In the next frame a true signal is sent to 'Wait' LED and the system waits a period of 10000 milliseconds and follows the same set of steps to go to the next load. At any point of time the operator decides to stop the automated loading then he can switch the 'Enable Loading' to off condition, stopping the sequence structure from moving forward to the next load. Once all the loads are cycled through in the last frame the operator receives a pop message on the front panel asking to unload the tire and set the next slip angle and also turns the 'Cycle Complete' LED to the on state notifying the operator.

4.3.4 Data Acquisition and Saving

Data acquisition and saving is one of the final stages of the LabVIEW program developed for M-15. It goes without saying that the saving the data for later data processing and graph generation is extremely important. The data acquisition process begins with transducers or instruments that convert physical properties, such as load, displacement into electrical signals. These signals are relayed back into the SCXI as described in chapter 3 of this report. By simply specifying the correct channel number and the scaling ratio the 'DAQ Assistant' a LabVIEW function becomes compatible to start collecting data from these transducers.

On the M-15 the processed data from the 'DAQ Assistant' still has a lot of discrepancies, hence its passed through a reduce the noise and improve the readability on waveform charts used to display the data. However it should be noted that sending the data through the filter introduces a time delay and hence the 'Z axis' load data is split into two parts one is sent through the filter and the other is sent directly to the waveform chart. The one which is not sent into the filter is used for 'Load Control Algorithm' to reduce the response time. Individual 'Waveform Charts' are used for each load cell and are wired with tare value control. A dial and digital indicator is used to display the Slip Angle along with tare value control in the program. For saving the data a 'Write to Measurement File' function is placed inside a 'Case Structure' and basic information such as the file path and file name prefix is fed into the function, the case structure ensures that the data is not saved continuously and would only save the data when a true Boolean is sent to the case selector terminal. This avoids unnecessary data and also reduces the CPU usage greatly improving the program performance. This is another important factor which came into picture when running such large LabVIEW program, despite the mammoth specification of the operator PC, the LabVIEW program used to crash. In order to avoid such a scenario in the future, care was taken to reduce the cycle time of each process and thereby reducing polling of data. It was due to the same reason a 'Producer-Consumer' design layout was opted for the entire program, where a initial loop would produce the data like in our case run the test protocol and a second loop would process the data produce like our case the 'DAQ Assistant'. This makes the entire program smooth and glitch free to operate.Lastly a 'Stop SCXI' local variable was created and wired across all the 'While Loops' running, hence once the operator presses one 'STOP' the entire program can be stopped without using the hard stop on the program window.

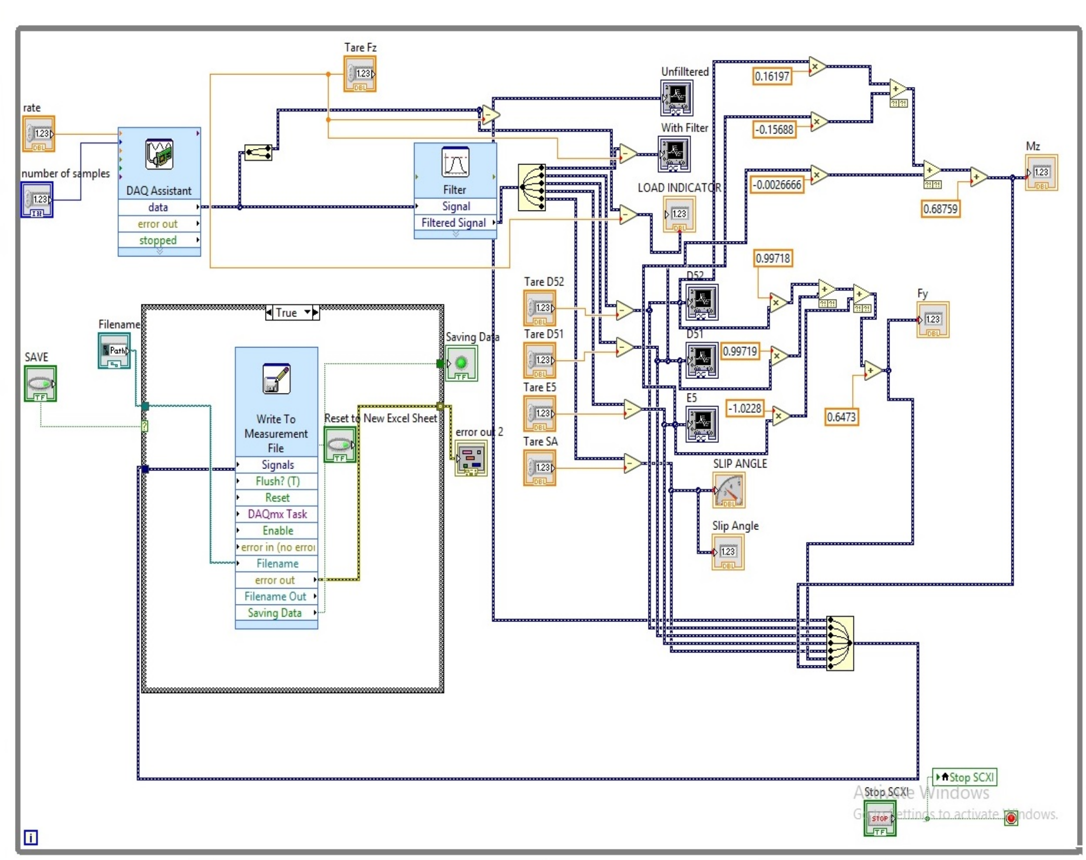


Figure 4.17: Data Acquisition and Saving Algorithm

The front panel of LabVIEW program is equally as important as the back panel, it is the main window where all the outputs and errors would be displayed. Hence in order to understand the complete program one must also understand the front panel.Once the program is complete there would only be few instances when the operator would have to go into the back panel, all the operations of the program can be completed using the toggle switches on the front panel of the VI. The operator can star the LabVIEW program by pressing the white arrow, once pressed it goes black until the program stops running. After running the program the operator would be able to see the various readings and graphs on the front panel, along with the current load. He can either press the 'Enable Loading' push button and start the automated loading cycle or using the 'Control Relay State' toggle between load/unload or keep it in 'off'. During this period the operator can set the 'Slip Angle' manually using the steering wheel and once set press the steer lock. Once everything is set, he can press the 'Enable Loading' push button and wait until the 'Cycle Complete' LED lights up and a pop up message appears on the screen asking him to 'unload the tire and change the slip angle' for the next test.

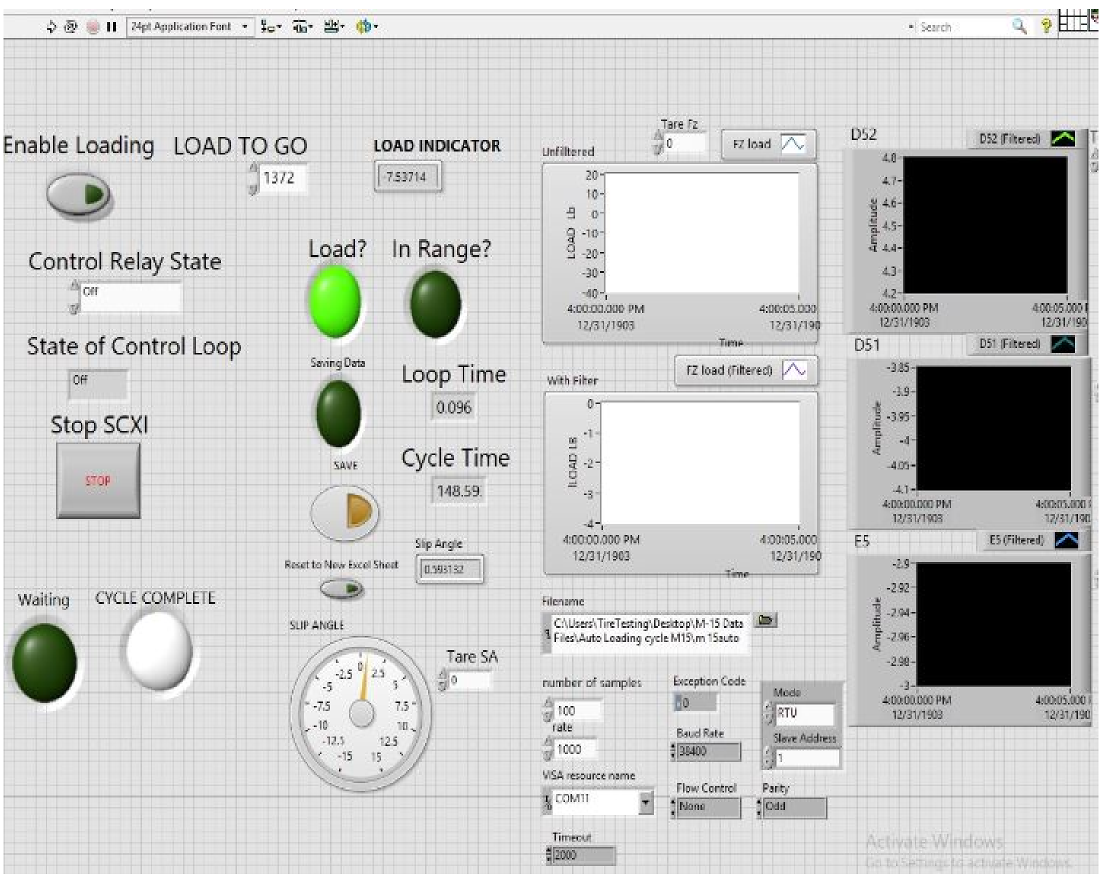
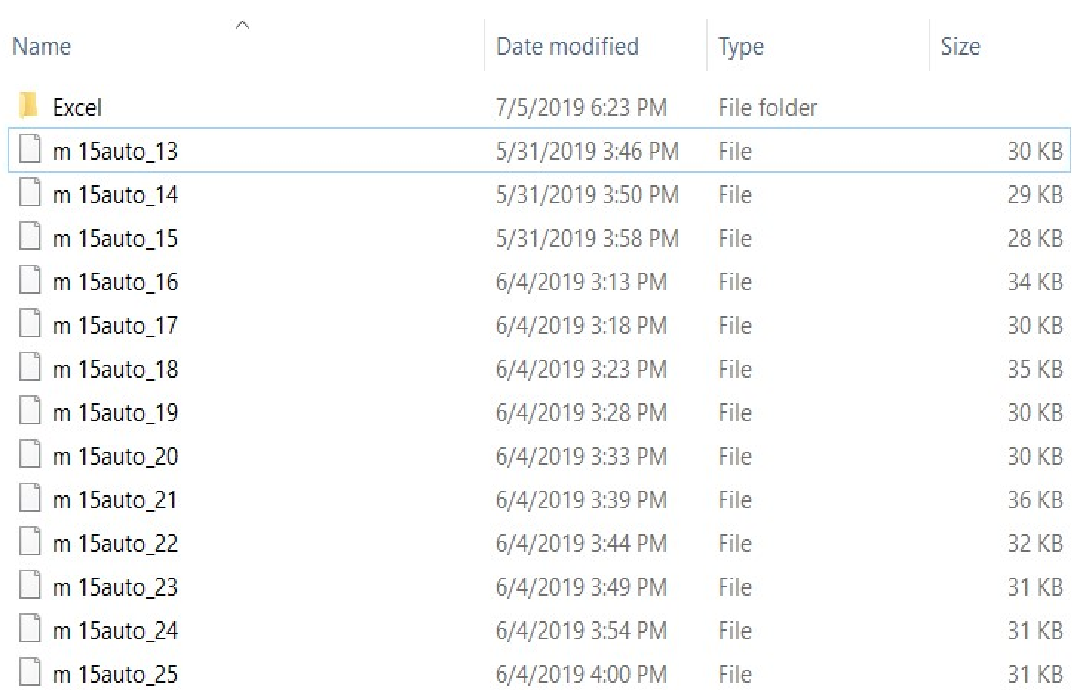


Figure 4.18: Front Panel of the LabVIEW program

CHAPTER 5: RESULTS

5.1 Data Compilation

The output file from 'Write to Measurement File' in LabVIEW is a '.xlsx' file format and is readable with Microsoft Excel. The data appends to the designated folder with the prefix ' m 15 auto_' followed by a number, a excel sheet is generated for every slip angle, meaning for the slip angles 0,+1,-1,+2,-2,+4,-4,+6,-6,+8,-8 a separate excel sheet would be generated with all five load cycles. This was done as per request of my fellow graduate student Mr. Sudeep Agalgaonkar, as his thesis involved data obtained from the M-15. The image below is snippet of how the data is appended to the folder after the test is complete.



Name	Date modified	Type	Size
Excel	7/5/2019 6:23 PM	File folder	
m 15auto_13	5/31/2019 3:46 PM	File	30 KB
m 15auto_14	5/31/2019 3:50 PM	File	29 KB
m 15auto_15	5/31/2019 3:58 PM	File	28 KB
m 15auto_16	6/4/2019 3:13 PM	File	34 KB
m 15auto_17	6/4/2019 3:18 PM	File	30 KB
m 15auto_18	6/4/2019 3:23 PM	File	35 KB
m 15auto_19	6/4/2019 3:28 PM	File	30 KB
m 15auto_20	6/4/2019 3:33 PM	File	30 KB
m 15auto_21	6/4/2019 3:39 PM	File	36 KB
m 15auto_22	6/4/2019 3:44 PM	File	32 KB
m 15auto_23	6/4/2019 3:49 PM	File	31 KB
m 15auto_24	6/4/2019 3:54 PM	File	31 KB
m 15auto_25	6/4/2019 4:00 PM	File	31 KB

Figure 5.1: Output Files from M-15

Inside the excel sheet the data is saved in seven columns five for each transducer and two for the calculated lateral force 'Fy' and overturning moment 'Mz'. For each load 100 readings are saved, for the purpose of understanding I have hidden few of the rows of each load to incorporate every load as shown in the image below.

	A	B	C	D	E	F	G	H
1	FZ load	D52 (Filte	D51 (Filte	E5 (Filtere	SA	Fy	Mz	Slip Angle
2	253.0352	5.900281	6.901408	-10.4552	-7.93485	2.719427	0.532686	-8.42105
3	253.5221	5.900239	6.90139	-10.455	-7.93485	2.719563	0.532682	-8.42105
4	254.7394	5.900201	6.901377	-10.4548	-7.93485	2.719706	0.532679	-8.42105
102	556.6161	5.091413	12.9899	-12.77	-7.93492	5.616632	-0.55966	-8.42105
103	555.8858	5.09143	12.98981	-12.7701	-7.93492	5.616454	-0.55965	-8.42105
104	557.103	5.091446	12.98972	-12.7702	-7.93492	5.616273	-0.55963	-8.42105
105	556.6161	5.091464	12.98963	-12.7703	-7.93492	5.616105	-0.55961	-8.42105
302	834.1479	2.621333	14.87557	-12.6197	-7.93563	5.1876	-1.25516	-8.42105
303	832.6872	2.621125	14.87549	-12.6198	-7.93563	5.18724	-1.25519	-8.42105
304	833.1741	2.620913	14.87541	-12.6198	-7.93563	5.186885	-1.25521	-8.42105
305	833.9045	2.620702	14.87533	-12.6199	-7.93563	5.186529	-1.25523	-8.42105
402	1099.994	-0.14344	18.9261	-13.2055	-7.93626	5.870625	-2.33998	-8.42105
403	1100.481	-0.14338	18.92593	-13.2055	-7.93626	5.870517	-2.33995	-8.42105
404	1099.994	-0.14332	18.92577	-13.2055	-7.93626	5.870424	-2.33991	-8.42105
405	1100.238	-0.14326	18.9256	-13.2055	-7.93626	5.870322	-2.33988	-8.42105
502	1372.414	-3.70433	23.25726	-13.5208	-7.93675	6.316263	-3.59705	-8.42105
503	1370.466	-3.70437	23.25739	-13.5208	-7.93675	6.316326	-3.59708	-8.42105
504	1371.196	-3.7044	23.25751	-13.5208	-7.93675	6.316384	-3.59711	-8.42105
505	1373.387	-3.70444	23.25764	-13.5209	-7.93675	6.316436	-3.59713	-8.42105

Figure 5.2: Inside Excel Sheet

5.2 Data Interpretation and Repetability

M-15's loading cycle accuracy is measured by how precisely the 'Fz' load values from the generated excel sheet is reached in comparison to the desired load values and its repetability is tested by how precisely it can duplicate the load values in multiple loading cycles. During this test the slip angle is set to zero and the road wheel is not run, in order to negate the effects of wheel non-uniformity. The linear actuator used in M-15 for loading the tires is connected to a pulse width modulator (PWM) to control the speed. For this test five voltage settings have been used 4.3v, 7.0v, 11.9v, 14.8v and 19.7v and for each voltage setting five tests each have been conducted going through each load setting 250lb, 567lb, 833lb, 1101lb and 1372lb as mentioned in the SAE tire test protocol. The table below represents the average values of each load attained at various voltage settings of the linear actuator through the five test runs.

Table 5.1: Error in lb Across Loads and Voltage Ranges

Voltages	250lb	533lb	833lb	1101lb	1372lb
4.3V	-18.14	-31.25	-17.12	-12.9	-4.2
7.0V	-0.56	-24.84	-8.3	-4.34	0.97
-11.90V	23.3	2.98	25.04	24.76	-0.4
14.8V	53.08	17.35	41.56	52.09	2.63
19.70V	55.4	46.02	80.24	61.72	23.58

The negative values indicated in the table mean the desired load value is undershot and positive values indicate the desired load value is overshot. Also the key thing to note here is the data received from these test runs are with a preset range value setting used in the LabVIEW load control algorithm as mentioned in chapter 4 of this report. These range values are tuned through numerous iterations of tire tests. The current value of range for each load are as follows:-

- 250lb - 25lb
- 533lb - 32lb
- 833lb - 27lb
- 1101lb - 25lb
- 1372lb - 15lb

In order to have a holistic understanding of the loading accuracy of M-15 the range setting for each load is removed and the results are tabulated below.

Table 5.2: Load Errors With Zero Range Setting

Loads	4.3V	7.0V	11.9V	14.8V	19.7V
250lb	6.86	24.44	48.30	78.08	80.40
567lb	10.75	17.16	44.98	59.35	88.02
833lb	9.88	18.70	52.04	68.56	107.24
1101lb	12.10	20.66	49.76	77.09	86.72
1372lb	10.80	15.97	14.60	17.63	38.58
Average	10.80	19.39	41.94	60.14	80.19

The average values of load overshoots clearly indicate the errors increase with increase in voltage setting. This is due to the fact that at a higher voltage setting the speed of the linear actuator is higher and with increase in speed precise control of the equipment becomes difficult and also the inertia of the heavy carriage comes into picture. But it would be wrong to assume that only the lowest voltage setting would give accurate results. This can be understood in the table below, in this table the overshot load values are subtracted from the average load overshoot value for each voltage and standard deviation for each voltage is calculated.

Table 5.3: SD of Load Error Across All Loads and Voltage

Loads	4.3V	7.0V	11.9V	14.8V	19.7V
250lb	-3.22	5.05	6.37	17.93	0.21
567lb	0.67	-2.23	3.04	-0.79	7.83
833lb	-0.20	-0.69	10.11	8.42	27.04
1101lb	2.02	1.27	7.83	16.95	6.53
1372lb	0.72	-3.41	-27.34	-42.51	-41.61
Standard Deviation (SD)	1.76	2.97	13.86	22.31	22.66

At 4.3V the standard deviation of 1.76 is the lowest but at this setting the voltage setting is so low that the linear actuator becomes incapable to lift the carriage while unloading the tire at fast enough pace. This damages the tire as it stay in contact with the road wheel for a longer time. On the contrary the voltage setting at 7.0V gives a standard deviation of 2.97 which is not that far off from 1.76 and also the linear actuator functions at satisfactory speed. Any further increase of voltage indicate a steep increase in the value standard deviation causing loading error to be more than the SAE prescribed standards. Hence it was decided to choose 7.0V voltage setting for the linear actuator throughout the tire testing process.

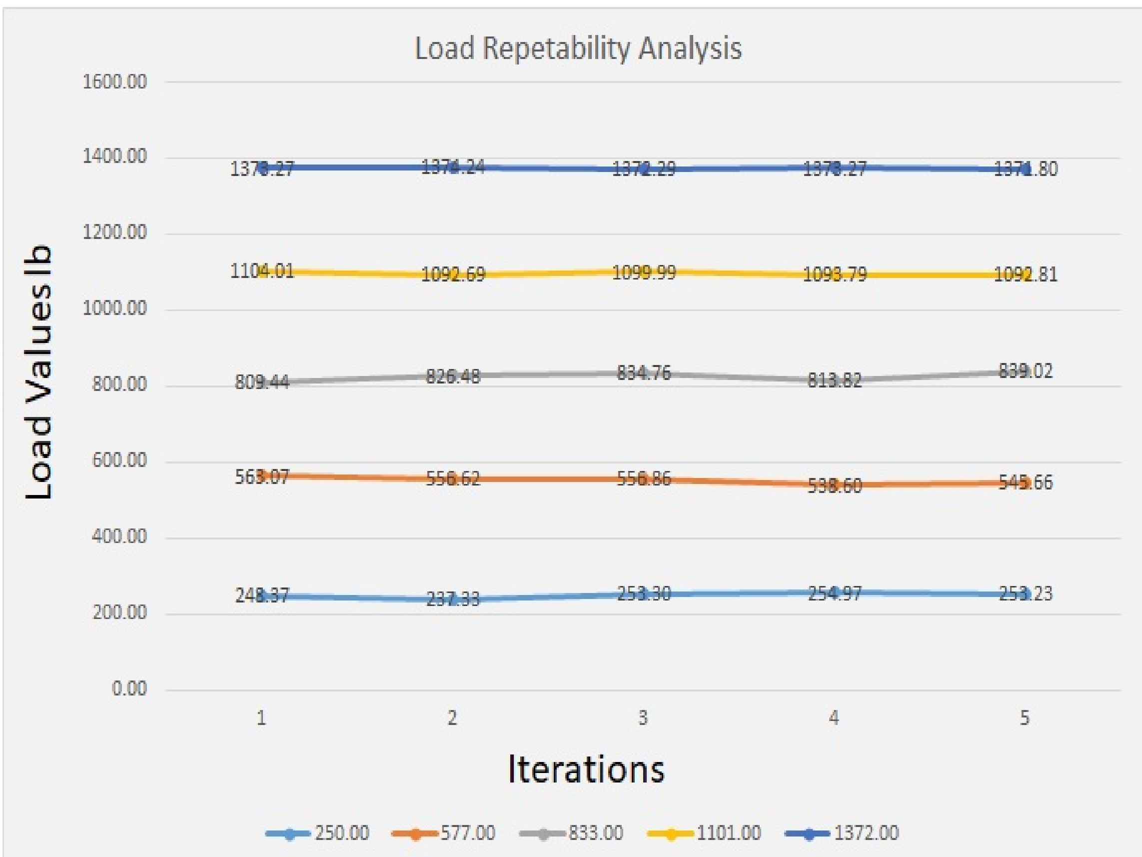


Figure 5.3: Load Repetability Analysis

The above image shows the load variations through the five iterations for 7.0V. This clearly indicates the current process of loading the tire is highly repeatable in nature.

5.3 Tire Performance Curves

The same trend of repetability is visualized in the tire performance curves generated for this particular 'Altimax' R16 tire with the same set of iterations. It must be noted that these graphs are generated with the help of colleague Mr. Sudeep Agalgaonkar using the 'MATLAB' code he wrote for visualizing the raw data obtained from the M-15. The minor anomalies observed due to the difference in tire temperatures, as the test was conducted in separate days and minor changes to the speed of the linear actuator. The graphs below indicate the CRAT, PRAT and Aligning Stiffness of tire. CRAT being the conicity induced residual aligning torque in 'N-m' and PRAT being plysteer induced residual aligning torque in 'N-m'. CRAT is also called as pseudo camber and is because of the conicity of tire, similarly PRAT is the aligning torque at slip angle where lateral force is zero. Both these characteristics are introduced by the manufacturer to counter act road crown and irregularities [4, 9].

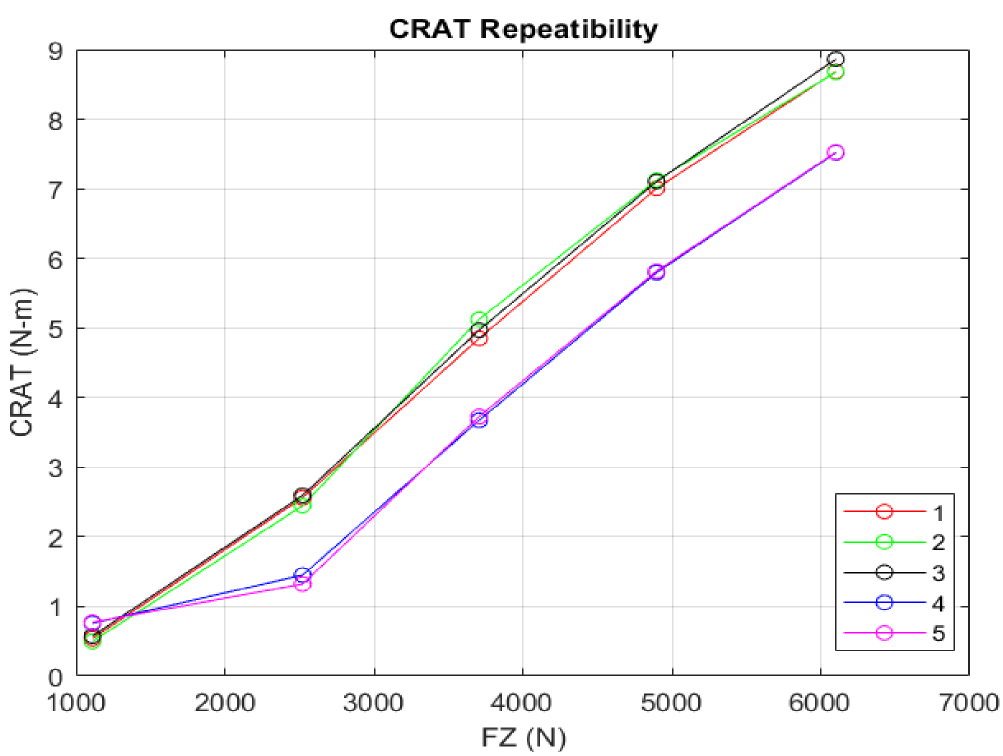


Figure 5.4: CRAT Repetability Test

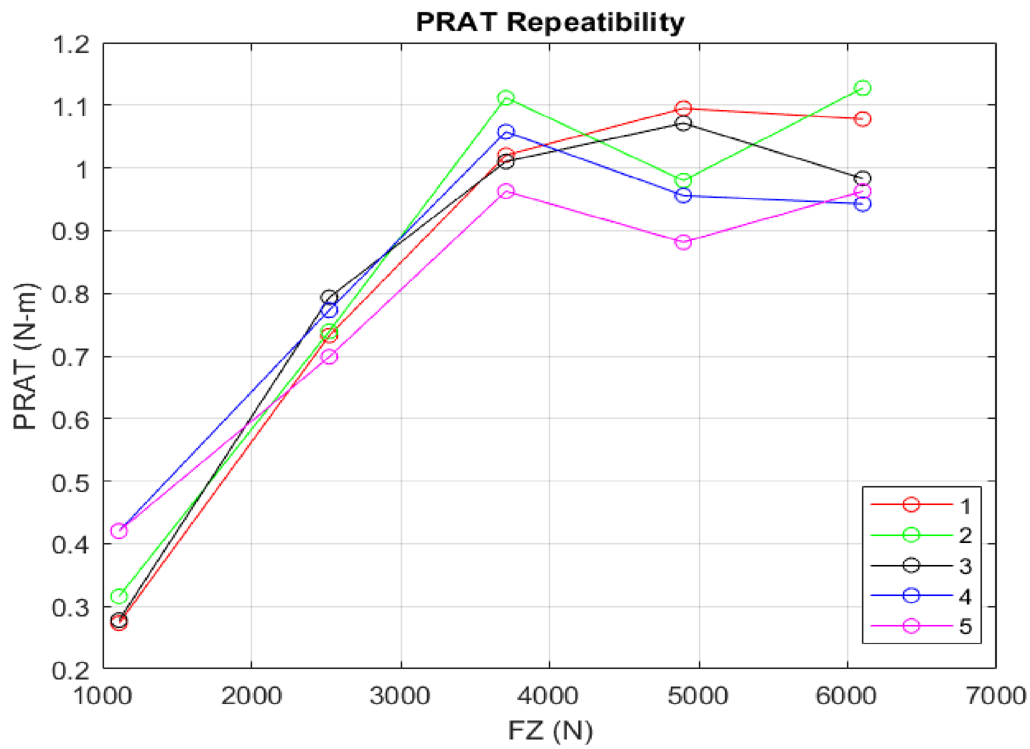


Figure 5.5: PRAT Repeatability Test

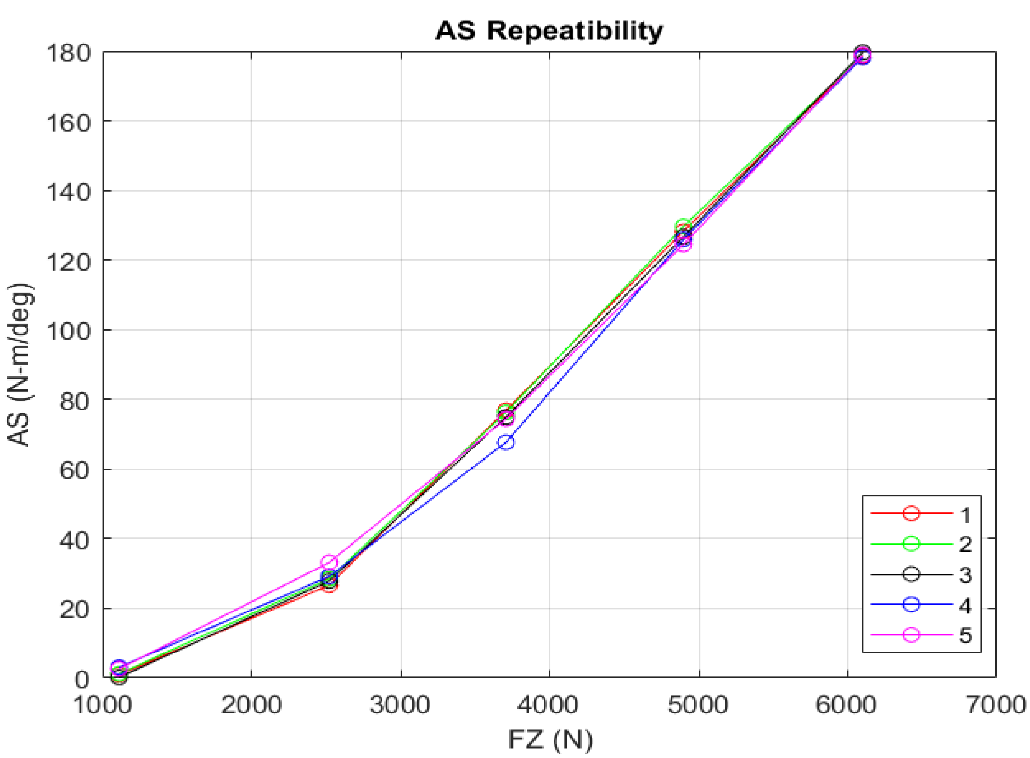


Figure 5.6: Aligning Stiffness Repeatability Test

Below are few more graphs portraying the tire performance curves, Lateral Force v Slip Angle (Fy v SA) and Aligning Moment v Slip Angle (Mz v SA), these curves have been curve fitted by the magic formula or Pacejka formula by Prof. Hans Pacejka [31]. These curves help visualize the tire performance across varying slip angles, the below figures shows a cumulative Fy v SA and Mz v SA for the five load conditions mentioned earlier in this report.

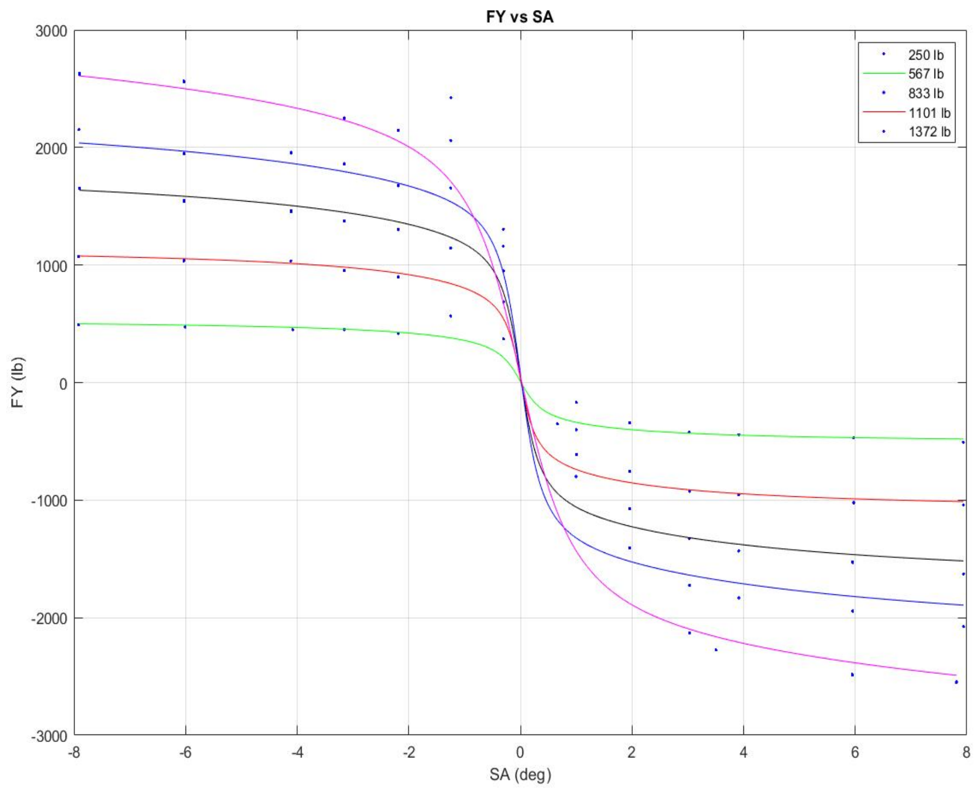


Figure 5.7: Fy vs Slip Angle All Loads

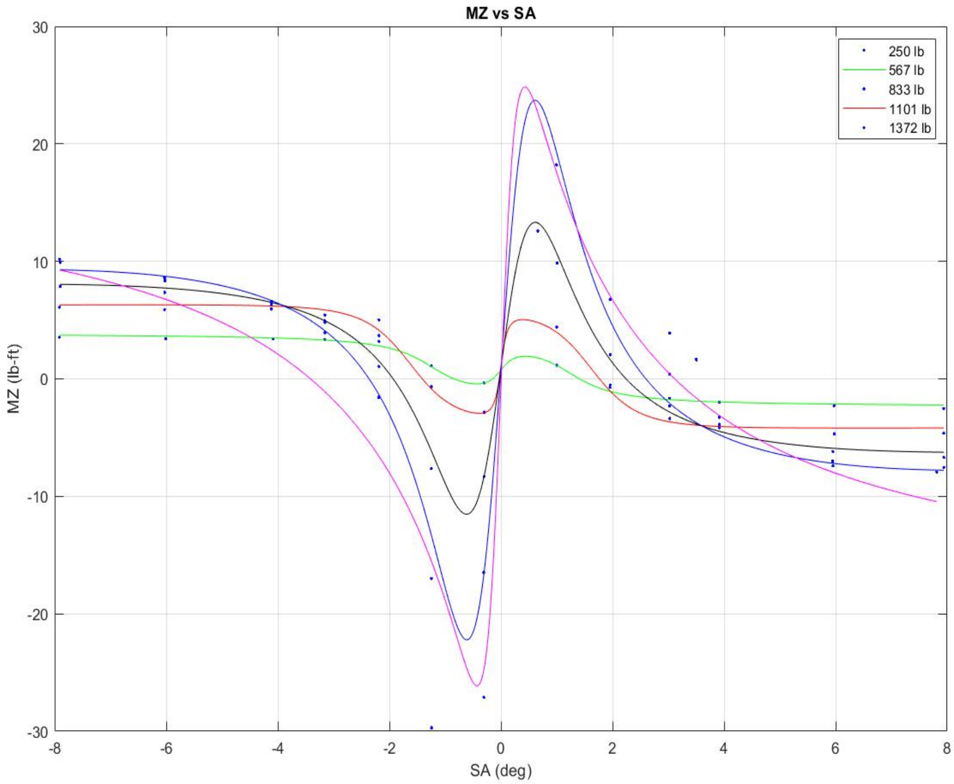


Figure 5.8: Mz vs Slip Angle All Loads

CHAPTER 6: CONCLUSIONS

I would like to conclude by saying that, according to the current test capabilities of the machine, the M-15 and the Tire Test Protocol has been successfully optimized. The data obtained from the machine are as per industrial standards and is comparable with test data obtained from other TTMs with high repetability. The loading cycle of the M-15 has been successfully automated and this has been achieved with very high accuracy and precision as per the SAE Standards. Human interference has been minimized but the machine still needs constant human supervision, reducing this would be the first step as part of the future scope for the M-15. After the completion of automated steer angle change steps for complete automation of the test protocol can be accomplished, further improving the quality of the data generated and increasing repetability even more. Also the safety standards of the test protocol and M-15 meet industrial standards, ensuring operator and inspector safety at all times during the tire testing process.

6.1 Future Work

Automation of slip angle is the first step towards complete automation of the M-15. Provisions to change the setup and accommodate the new linear actuator for Control of slip angle is complete.The linear potentiometer is being replaced by an absolute encoder for angle measurement. This is improve the accuracy of the angle measured on the M-15 and would give a angle measurement accuracy of $1/10^{th}$ of a degree. The signals from this encoder will be relayed into the SCXI system and using the DAQ assistant on LabVIEW the accurate angle can be shown on the operator PC. Once successful this will reduce human interaction to run tire tests on the M-15 and the machine will be truly automated and a dynamic measurement approach can be implemented.

A pressure transducer would be used instead of the current dial indicator to measure the tire pressure and with the help of solenoid valve the operator would be able to regulate the tire pressure before the test. This will reduce the time required to prepare the tire before the test and also help make a automated note of the tire pressure before the test. Current design does not support the measurement of rolling resistance on M-15, future plans to enable side ways loading opens up this prospect as well.

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