



University of Wales Trinity Saint David

School of Engineering

Christian Walker

2210144

Research Proposal

Research Methods and Professional Developments

Title: Physical Analysis of Lateral Forces Acting on a Tyre

ACFA7004

Abstract

This report covers the following research proposal for an Automotive Engineering Master's dissertation project, which researches the question,

“Physical analysis of lateral forces acting upon a tyre during a cornering event.”

During this project, the main focus will be to research the lateral forces which act upon a tyre, and compare the data to computer models such as the Pacejka Magic Formula. This is an area where little research has been undertaken, and provides an opportunity to accurately model and validate tyre performance. Previous research tends to be extremely expensive, utilising rolling roads and rely on computer modelling software. Therefore, the data collected may not be truly accurate or fully understand the characteristics of tyres and how they perform under lateral loads. Similarly, major research also focuses on the tyre deformation, rather than the force acting through the tyre. This clearly presents a gap within the field, where this project aims to analyse the forces on the tyre whilst using a much more cost effective process. This data can then be compared with published tyre data from Avon or Hoosier for example, along with computer models produced by the Magic Formula.

To conduct the project, a rig with two tyres attached will be manufactured, then using strain gauges and load cells, the forces acting on the tyre at various toe angles will be recorded and measures. This will be done with various vertical loads acting on the tyre, and the different toe angles will replicate the slip angles which occur during a cornering event. The tyres used will be Formula SAE manufactured by Avon or Hoosier depending on availability, as these have a large amount of published data along with their testing procedure.

Contents

Abstract.....	2
Figures.....	4
1. Project Introduction.....	5
1.1 Overview	5
1.2 Industrial Relevancy.....	7
2. Project Aims	9
3. Validation	10
4. Literature review.....	11
4.1 Computer Simulations	11
4.2 Previous Testing Rigs.....	12
4.3 FSAE Tyre Testing	14
5. Timeline.....	16
6. Methodology.....	17
7. Data collection and results.....	18
7.1 Strain Gauges	18
7.2 Load Cells	18
7.3 Data Analysis and Accuracy Methods	19
8. Evaluation (pros, cons, potential issues).....	19
9. References	21

Figures

Figure 1: Testing Rig, Option 2	5
Figure 2: Testing Rig, Option 1	6
Figure 3: Load Cell (Applied Measurements, n.d.).....	7
Figure 4: Strain Gauge (Welker, n.d.).....	7
Figure 5: TNO Delta-Tyre toolchain (Pacejka, Chapter 13.3 The MF-Swift Tire Model, 2012)	8
Figure 6: Simplified Diagram of the Pacejka Magic Formula Model (Metzler, 2019)	9
Figure 7: Lateral Force versus Slip Angle for R10 and R13 Hoosier Race Tyre (Salunkhe, Neeraj, & Joshi, 2017)	10
Figure 8: Tyre Testing Rig (Garcia-Pozuelo, Yunta, Olatunbosun, Yang, & Diaz, 2017)	11
Figure 9: Tyre Testing Rig used for FE development (Korunović*, Trajanović, Stojković, Mišić, & Milovanović, 2011).....	12
Figure 10: Tyre Deformation Analysis (Xiong & Tuononen, 2015)	14
Figure 11: Avon FSAE 13" Tyre Data (Avon Tyres, 2013)	14
Figure 12: Calspan Testing Machine on Avon FSAE Tyres (Kasprzak & Gentz, 2006)	15
Figure 13: Tyre Deflection Due to Slip Angles (Kasprzak & Gentz, 2006)	15
Figure 14: Rig used on Round 9 of FSAE TCC testing (FSAE Tire Test Consortium, 2022)	15

“Physical analysis of lateral forces acting upon a tyre during a cornering event”.

1. Project Introduction

1.1 Overview

The deformation of a tyre under typical loading across varying road surfaces is a crucial factor in understanding tyre performance and vehicle dynamics. In this Master’s research project, we propose to analyse the tyre deformation and lateral forces acting on a tyre using physical analysis methods. Two different design options have been considered so far. In the first option we will modify a front-wheel-drive car subframe to be loaded up, towed, and simulate typical car driving. The second option proposes to design and create or modify a trailer to fit our tyres and allow for all the necessary wheel adjustments, as seen in figure 1 drawn up in SolidWorks, wheel and tyre taken from (service, 2018) and the hitch taken from (Spinnerx, 2021).

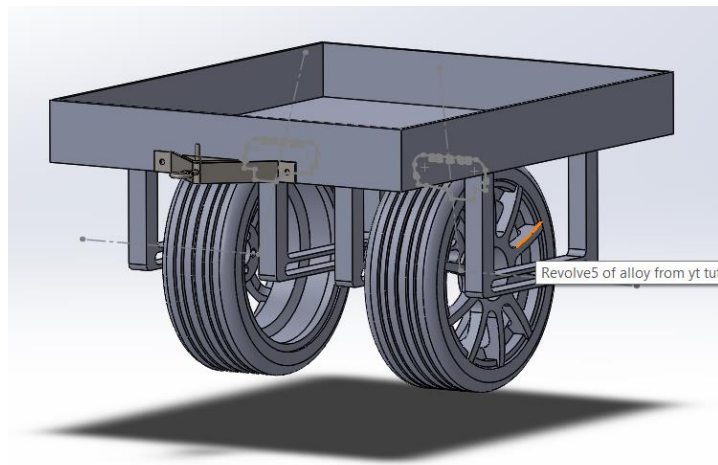


Figure 1: Testing Rig, Option 2

Currently, the preferred option is to use an existing FWD car subframe as this will come with all the correct mounting points and adjustment options. The subframe could easily be bought from a local scrapyard from a low value car which has been in a low speed rear end collision where the insurance had decided to scrap the car. This subframe will then only need a couple modifications, a brace of some type across the top to keep the frame stiff, a mounting point for towing the frame and a space to evenly distribute the added masses to simulate different tyre loading. Figure 2 shows this option

mocked up in SolidWorks. The hitch was from (Spinnerx, 2021), the wheel and tyre from (service, 2018) and the McPherson Strut was taken from (Bisht, 2019)

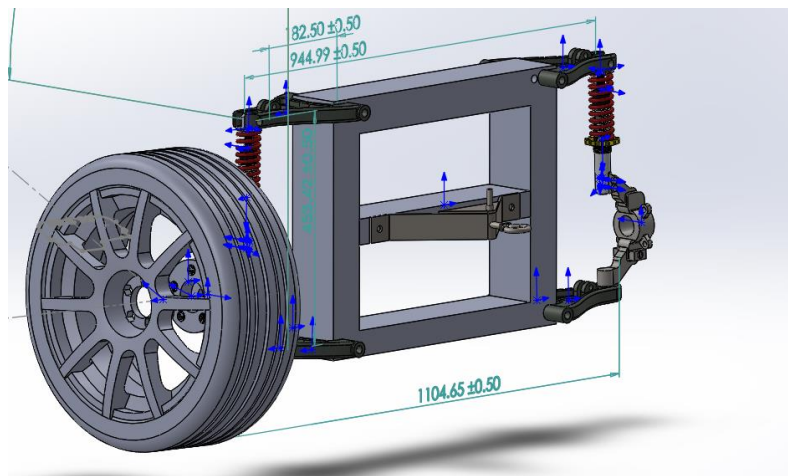


Figure 2: Testing Rig, Option 1

The frame will then be pulled along, and the deformation of side walls was measured at different slip, toe, or camber angles. A strain gauge and load cell will then measure the forces used to pull the subframe along and the tyre characteristics will be measured. By measuring the difference in forces to pull the subframe along with the wheels at certain toe (slip) angles, we can understand the difference in lateral forces acting upon the tyre and measure grip level and tyre deformation. This data can be analysed to match the curve described by Pacejka (lateral forces versus. tyre slip angle) and implemented into modelling software or used as validation for existing software. Current software has difficulty modelling a tyre due to the large number of variables, but by including typical road surfaces and different compounds, this research can provide valuable insights into tyre deformation and performance. Previous research has focused mainly on test rigs fixed to rolling roads, making this study unique in its approach and potential contributions to the field.

For this project, load cells (figure 3) and strain gauges (figure 4) will be used to measure the forces acting off the frame, and therefore the forces which act on the tyre as we place the tyres in the certain toe (slip) angles. The use of strain gauges and load cells is a critical aspect of the project to measure the forces acting on the subframe. By analysing the forces acting on the subframe, we can estimate the forces that are being applied to the tyres as they experience different toe or slip angles. This will

help us to determine how a tyre will perform when subjected to different conditions such as during cornering, and how lateral forces will affect the tyre's overall performance. By accurately measuring the level of grip, we can attempt to match the lateral forces versus slip angle curves put forth by Hans Pacejka. This information will be invaluable in optimising tyre performance and ensuring the safety of the vehicle. The different forces acting on the tyre during these different angles will then be compared and allow us to measure the level of grip. Different compounds and tyre sizes could then be compared.

1.2 Industrial Relevancy

Due to factors in this field such as cost, complicity in terms of the number of variables and general lack of research, there is little published information regarding the deformation of tyres under lateral loading. Therefore, when companies begin to make tyre and vehicle dynamic software packages, the data to use is limited. Similarly, when tyre manufactures perform their own testing, it is generally on expensive and large testing rigs which is not available for engineering research. These rigs test endurance, acoustics, preload and tyre characteristics when on a chassis dynamometer (CFM Schiller GmbH, n.d.). Currently, the main model used comes from Hans Pacejka in Tyre and Vehicle Dynamics. To model tyre and vehicle dynamics, Hans Pacejka developed the “Magic Formula”, which is a complex mathematical model which creates the main graphs of Lateral Forces versus Slip Angle which acts upon a tyre during a cornering event. The equation for this model can be seen in equation 1 . This



Figure 3: Load Cell (Applied Measurements, n.d.)

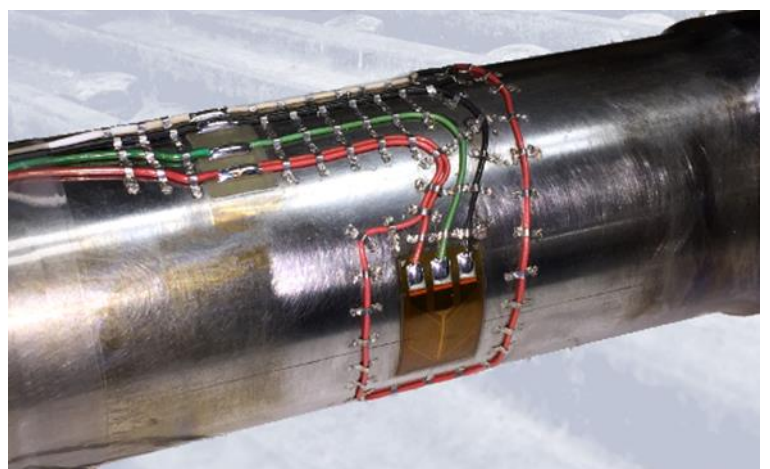


Figure 4: Strain Gauge (Welker, n.d.)

magic formula is the predominant model used in software packages such as Siemens MF-Tire /Mf-Swift. Siemens MF-Tire/MF-Swift is found within Simcenter Tire and is currently the only software package that uses the Magic Formula for the tyre model in all the vehicle dynamic simulation packages (Siemens , n.d.). However, with a lack of physical analysis and tyre testing, there is little validation to this model, highlighting a clear gap in the field which this project will fill.

Equation 1: General equation for Magic Formula (Pauwelussen, 2015)

$$F_y = D \cdot \sin [C \cdot \arctan\{B \cdot \kappa - E \cdot (B \cdot \kappa - \arctan(B\kappa))\}]$$

Equation 2: Additional Equations for use with Equation 1

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

$$x = X + S_h$$

Where F_y = side force acting on the tyre, Y = output variable, X = input variable, k and B = stiffness factor, C = shape factor, D = Peak value, E = curvature factor, S_h = horizontal shift and S_v = vertical shift (Pacejka, Chapter 4: Semi Imperial Models, 2012). The Dutch organisation for Applied Research, TNO worked on the software packages and came up with the following tool chain:

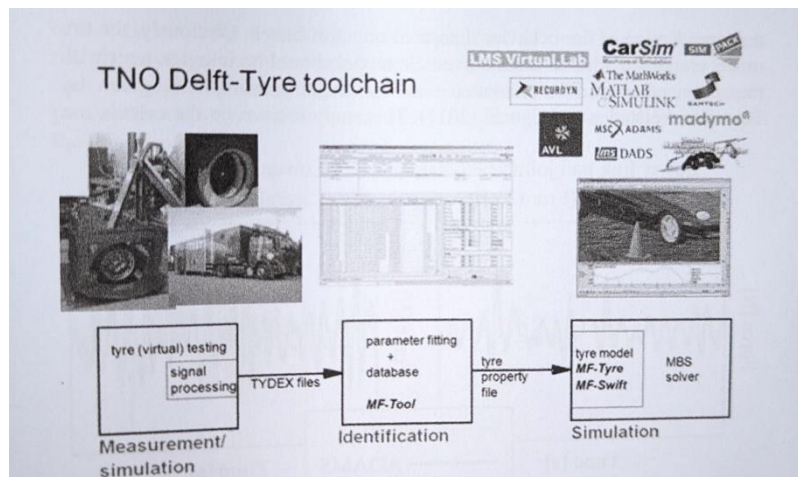


Figure 5: TNO Delta-Tyre toolchain (Pacejka, Chapter 13.3 The MF-Swift Tire Model, 2012)

2. Project Aims

The main aim of the project will be to design and modify a FWD car subframe, which will enable it to be loaded up using weights and adjust the wheel positions. The modifications will allow for lateral force measurements to be taken on the tyre, whereby the slip angles of the wheels can be changed to replicate different cornering forces. The data obtained from the tests will be analysed and compared to published literature in tyre software modelling such as from Hans Pacejka. This comparison will allow for the evaluation of different tyre compounds and their grip levels. By replicating these graphs, the models proposed can either be validated or disproved, which is crucial since they are the main models used in software packages such as Siemens MF-Tyre, a widely used software in the industry.

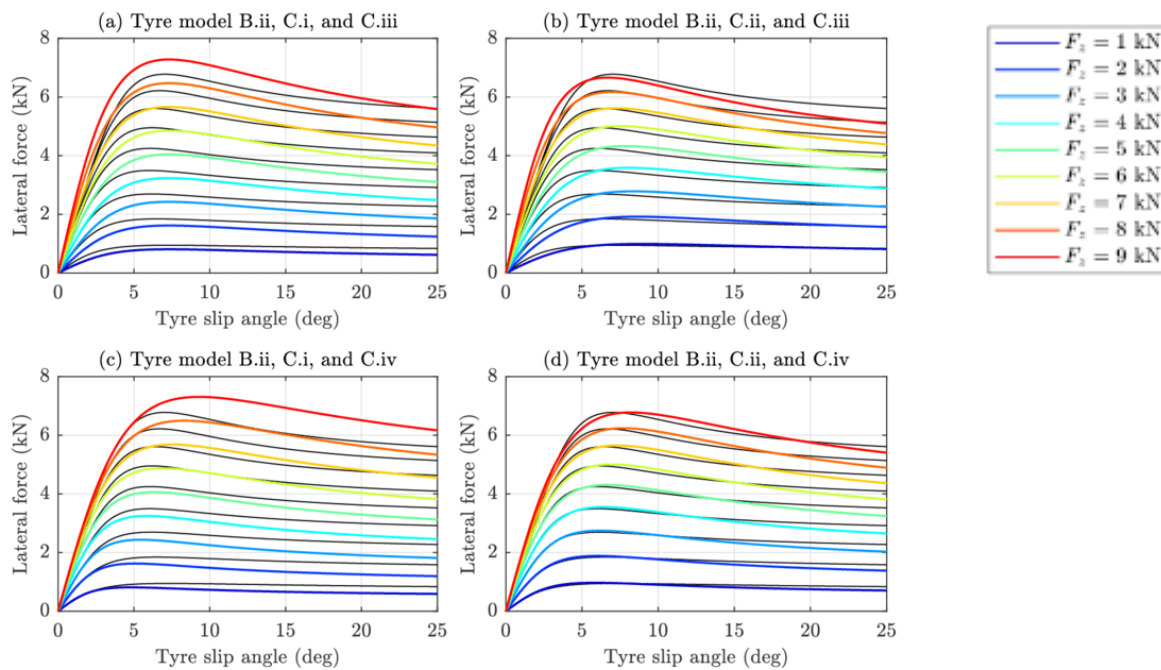


Figure 6: Simplified Diagram of the Pacejka Magic Formula Model (Metzler, 2019)

Figure 6 shows the graphs produced by Hans Pacejka which we will attempt to replicate using our own physical testing experiment. Looking at the graph, lateral force (y-axis) is compared against slip angle (x-axis), and the different lines indicate the various loads which have been placed on the tyre in the Z plane when modelling, where the larger the force, the more lateral force can be applied to the tyre at all slip angles, indicating the tyre's level of grip. In this project, these loads can be simulated with

various weights placed on the subframe. The graphs produced by the Magic Formula typically produce a curve that passes through the origin of $x = y = 0$ (Pacejka, Chapter 4: Semi Imperical Models, 2012).

3. Validation

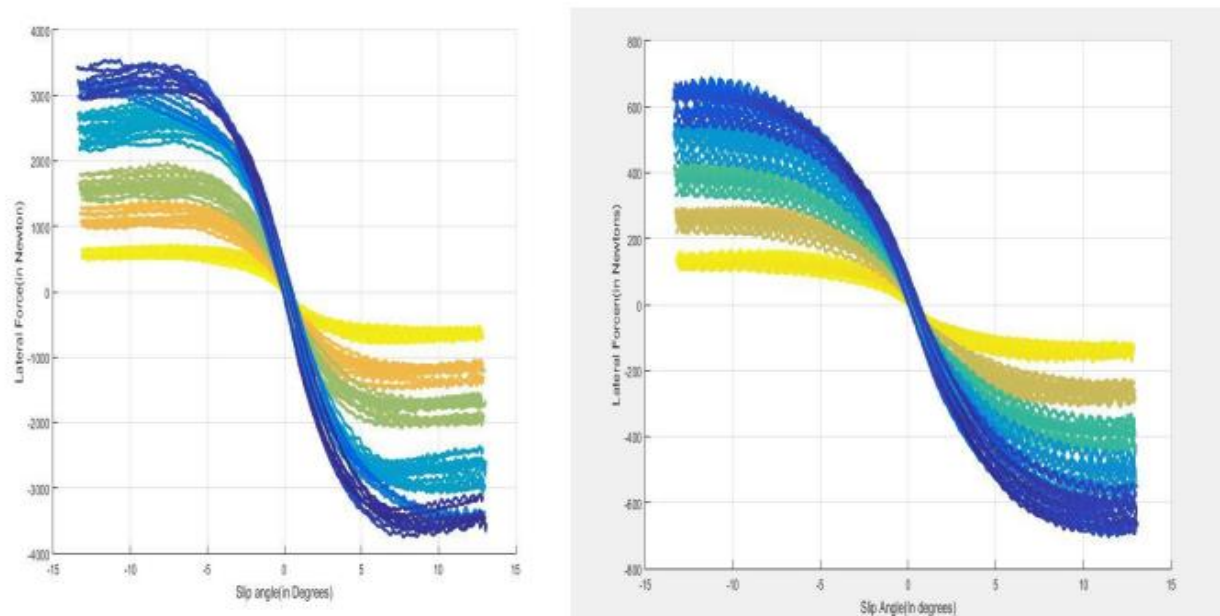


Figure 7: Lateral Force versus Slip Angle for R10 and R13 Hoosier Race Tyre (Salunkhe, Neeraj, & Joshi, 2017)

To validate the data created in this project, it will be compared to data that has already been measured by the manufacturer. The slip angle versus lateral force graphs for R10 and R13 FSAE Hoosier Race Tyres, as shown in Figure 7, will represent the type of data that will be collected during the project. The project could also use Avon Formula Student Tyres, as similar data has been published. Regardless, the project will use a set of Formula Student tyres as there is a large amount of published data available online.

In figure 7, the graphs represent lateral forces versus slip angle for two sets of the same tyre compound, however on the left, this shows an R10 tyre and on the right this shows an R13 tyre, with 10 and 13 being the diameter of the rims to fit the tyre, measured in inches. This is tyre data which has been collected by the manufacturer in a highly controlled and repeatable manner. Due to the highly controlled nature of the testing, it is easy to make comparisons between different tyre sizes and compound which have undergone the same analysis, making this reliable data to compare our

project to. However, this also means the data does not accurately represent how a tyre would perform under actual, real road or track conditions, something which our method aims to correct. Regardless of this, we would aim to create a graph of similar shape, which is comparable, however it will be likely that the specific lateral forces measures will not be identical.

4. Literature review

4.1 Computer Simulations

A research paper published in 2017 investigated the use of strain based sensors on the side wall of automotive tyres along with ‘Fuzzy Logic’ to assess the and estimate the slip angle of tyres based on the inflation pressure, rolling speed and vertical load of the tyre. They used a “strain based prototype and an indoor tyre test rig” to conduct the research, as seen in Figure 8.



Figure 8: Tyre Testing Rig (Garcia-Pozuelo, Yunta, Olatunbosun, Yang, & Diaz, 2017)

This provides an example of the type of equipment used in industry and shows clearly how technical and expensive it can become. During the research, they found that the slip angles of the tyre can be predicted as when the lateral forces drop, the strain values drop sharply. They then used a Fuzzy Logic approach to estimate the tyre working conditions and the simulation test results show feasibility of the use of strain sensors in this application to solve the non-linearity characteristic predictions of tyres.

A slip angle of 0-14 degrees was used with 250N-1000N of load. The lateral force acting on the tyre in the rig was also plotted and can be used as comparison data for this project, however also noting that for this project, different tyres will be used (Garcia-Pozuelo, Yunta, Olatunbosun, Yang, & Diaz, 2017).

The use of the Magic formula is extremely common for simulating tyre deformation, lateral forces and slip angle, however this also requires validation to confirm that the simulation does accurately predict what occurs in real world conditions. Many researchers have used MATLAB and Simulink to replicate this model. For example, a research paper from 2017 created this model and compared it to published Magic Formula data. They found that overall, the MATLAB code provided accurate data and correctly modelled the situations. However, the data they compared to was against the model they attempted to replicate and not real world data. Whilst this research proves useful and a more efficient way of modelling tyre data, this does not model physical tyre testing (Shi, Zhao, Zhang, & Ye, 2017).

4.2 Previous Testing Rigs



Figure 9: Tyre Testing Rig used for FE development (Korunović, Trajanović, Stojković, Mišić, & Milovanović, 2011)*

Most of the physical tyre analysis is conducted on a rolling road rig, where the tyre is placed at certain angles and certain loads on it. Measurements of the forces acting upon the tyre can then be made to assess how the tyre performs. This data can then be used for various applications, like for assessing

the Pacejka Magic Formula model, or it can be used to create Finite Element (FE) models of the tyre which can then be used to create different tyre models more easily. From a research paper published in 2011, they used this method, and the tyre testing rig could be another form of measuring lateral forces versus slip angle. In this paper they successfully created a FE model to be used in future tyre design, however this method does pose some accuracy concerns. The data collected may be repeatable, which although important, it will not accurately measure true surface conditions, and therefore tyres designed using this model will not act as closely to the model as expected. Figure 9 shows the rig used.

Previous physical analysis of tyre loads and forces acting is limited. This is due to a number of factors but mainly the cost, and the overall number of variables which occur when collecting this type of tyre data. When physical analysis is conducted, it normally occurs on a rig and rolling road set up, which provided repeatable data but not necessarily representative of real road conditions. However, from a paper in 2015, (Xiong & Tuononen, 2015), the deformation of a truck tyre was measured as it drove on the road. This research was conducted to understand the rolling resistance force of a truck tyre at different loads, inflation pressures and tyre wear conditions. Whilst this does not measure the same data that will be collected in this project proposal, it can provide ideas and understanding for how tyre deformation is collected, and then how it can be applied to a lateral force investigation. An optical sensor was used to measure the sidewall deformation and was found that depending on the inflation

pressures, different areas of the tyre are deformed, and therefore generate different levels of wear.

Figure 10 shows the instrument assembly.

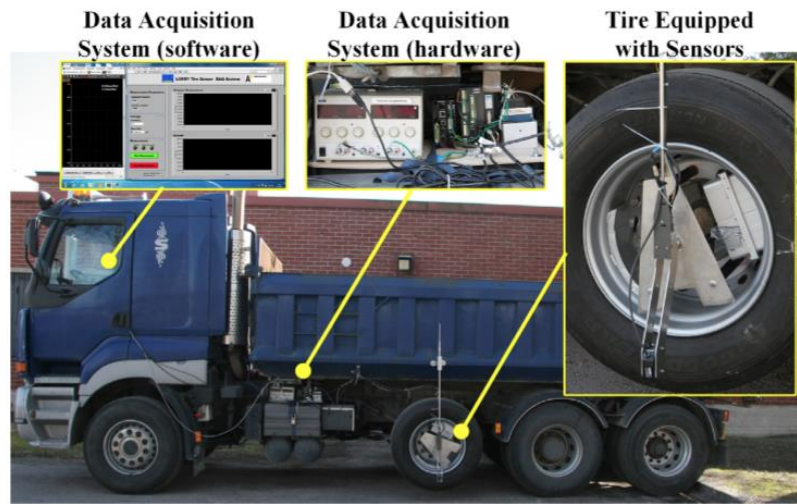


Figure 10: Tyre Deformation Analysis (Xiong & Tuononen, 2015)

4.3 FSAE Tyre Testing

Current tyre manufactures have published their own data for lateral force versus slip angle at several loads which is data which we can use to validate against. The majority of this data comes from Formula Student tyre manufactures as the main focus of Formula Student is an engineering exercise for future Engineers. Avon and Hoosier are the two manufactures used and Figure 11 presents an example of this data which they have published.

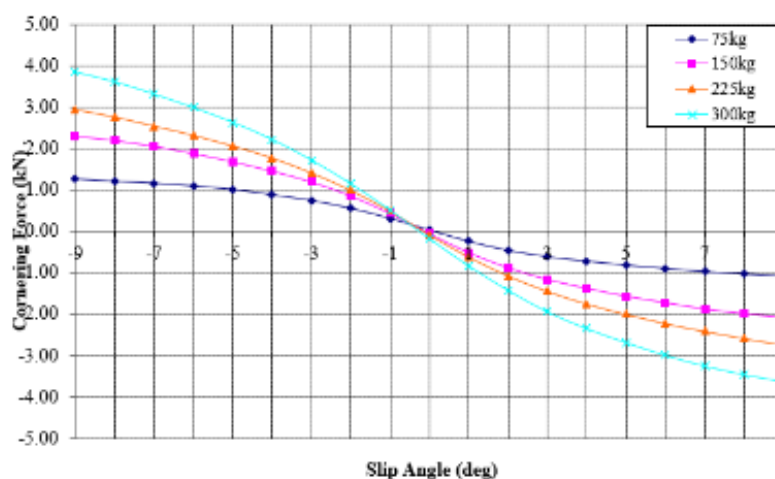


Figure 11: Avon FSAE 13" Tyre Data (Avon Tyres, 2013)

The data shown in figure 11 was from a Avon 6J*13" FSAE Tyre at 21 psi and 20kph. This is an exact set up which can be replicated using the method proposed in this project (Avon Tyres, 2013). However,

for accuracy and repeatability reasons, the manufacturers use a rolling rig and frame set up to conduct the testing.

The FSAE Tyre test was developed in 2006 by the Formula SAE Tyre Test Consortium (FSAE TCC) to produce high quality tyre data from the ones used in the racing series. The compounds and results have changed over the years, but the general format has been maintained. FSAE TCC developed a low capacity flat-bed tyre testing machine, along with the team at Calspan Tyre Research Centre. Tyres were then loaded up on the machine, where a test matrix of different loads, inclination, slip angle, inflation pressures and temperatures were developed.



*Figure 12: Calspan Testing Machine on Avon FSAE Tyres
(Kasprzak & Gentz, 2006)*



*Figure 13: Tyre Deflection Due to Slip Angles
(Kasprzak & Gentz, 2006)*

However, the same rim was used throughout all the tests which means rim choice effect was not investigated. Two free rolling tests and one drive/brake tests were used to evaluate different tyres. The first free rolling test investigated a series of sweeping slip angles, and the second investigated the effects of inflation pressure; longitudinal forces were then recorded under braking and driving. Tyre wear was also photographed, and pyrometer (temperature) readings were taken following each test (Kasprzak & Gentz, 2006). Figure 12 shows the testing equipment used, and figure 13 shows an example of tyre deformation due to slip angles. Every year the testing procedure is slightly tweaked, with the latest being Round 9 from 7th February 2022, this test was identical to the previous round (8) with the latest inclusion being low speed transient tests and traditional sweeps at various roadway speeds from round 6, which is also the latest testing round to include Avon Tyres. The cornering test

place of round 9 which measures lateral forces acting on the tyre involves two runs of slip angle, a break-in block and initial spring rate test. This is done at multiple pressures and inclinations of a free-rolling tyre. here are also slip angle sweeps at 15 and 45 mph to compare with the standard 25 mph test data. The 350 lb load for 10-inch tyres is replaced with a 200 lb load, and there is a 12 psi block to compare performance due to wear or heating. Infrared sensors were used to measure surface temperature, shown in figure 14 (FSAE Tire Test Consortium, 2022).



Figure 14: Rig used on Round 9 of FSAE TCC testing (FSAE Tire Test Consortium, 2022)

5. Timeline

Table 1: Proposed Project Gantt Chart

Tasks	Dates															
	May				June				July				August			
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16
Literature Review																
CAD Drawing																
Frame Construction																
Testing																
Data Analysis																
Report Write Up																

Table 1 outlines the suggested Gantt chart for the project. The project will start in May after the final exam from Part 1 of the course and will last around three to four months from start to finish. To start, I will conduct a thorough literature review, which will allow me to fully understand the field, and all

the previous research which has been conducted; areas surrounding physical tyre testing, lateral force measurements and simulation modelling validation will be focused on.

Following this, during the next three or four weeks, a design for the FWD subframe and the included modifications will be finalised, drawn out in Solidworks, allowing for a smooth process in terms of manufacturing and building the testing rig. For the frame construction, extra time has been allocated to allow for sensor wiring and configurations to be properly fitted, as this is expected to be the main source of any holdups, however spending this extra time will allow us to produce the most accurate and reliable data. Testing will then take up the next four weeks, where all the data to be analysed will be collected, including all the various slip angles and loads. I will then spend the majority of the time left to analyse the data and finish writing up the paper. A week at the end has been left to account for any unexpected errors and during the whole project I will slowly be writing up the paper.

6. Methodology

To begin with I will conduct a comprehensive literature review of the current and previous research in the field of measuring forces acting through a tyre. The literature review will help identify key areas that have and have not been previously investigated, along with understanding the different methodologies that have been implemented. I will then create a CAD drawing of the subframe assembly in Solidworks, including all necessary adjustments and modifications needed for the project. Following this will allow for us to manufacture the subframe based on the CAD drawing, ensuring that all necessary modifications are included, such as bonding strain gauges to the subframe to measure the forces acting through the tyre and installing a load cell between the subframe and towing vehicle to measure the force required to move the subframe. I will then conduct testing with various toe and camber angles, ensuring sufficient time for the sensors to work accurately and collect data on the forces acting through the tyre using the strain gauges and load cell. The data will then be analysed and compared with published tyre data and software modelling, either by running the software ourselves

or comparing against published literature. We will use the Pacejka model as a comparison tool for the analysis and conduct our own validation test, running the test in a simulation and comparing the results (if it is within the scope of the project). To finish, a write up of the investigation and findings in a report format, including a discussion of the results, limitations, and recommendations for future research will be produced.

7. Data collection and results

The data collection process for this project will involve the use of both strain gauges and load cells.

7.1 Strain Gauges

The strain gauges will measure the deformation of the frame by applying resistance to the electronic circuit as the frame is loaded up through the forces acting on the tyre. For example, when the frame is loaded up with a certain mass, and the tyres are set at an equal toe angle and pulled along, the tyres will grip the road by a certain amount. This force will then be transferred through the frame at the wishbones in either compression or extension depending on their location. The strain gauge will then read this data, which we can then directly compare and calculate the loads being produced through the tyres. The control module will then convert this resistance information into readable data.

7.2 Load Cells

Meanwhile, the load cell will measure the forces required to pull the frame in a straight line. This force will change depending on the tyre loads and slip angles. When testing different toe angles, the force measured by the load cell will directly correlate to the force acting on the tyre, and it will measure how the force changes depending on the slip angle and load on the tyre through the masses placed on the frame. This process works in a similar manner to the strain gauge. The data collected from both the strain gauges and load cells will then be compared across different toe and camber angles. The load cells will be placed on the suspension components to allow for an accurate reading of longitudinal forces and to describe the lateral forces acting on the tyres when comparing different toe angles. In

theory, this testing equipment will allow for similar lateral force versus slip angle graphs to be produced.

7.3 Data Analysis and Accuracy Methods

When collecting data from strain gauges and load cells, various issues can arise, for example the data can often be noisy, the sensors can drift or radio frequency interference (RFI) can occur. For the accuracy of this project, it is important to minimise these errors either during the data collection or in post processing.

Noisy data can often be caused by the interference of 60/50Hz data to the analog input, using a 6Hz - 2 pole analog filter can reduce this by a factor of 100. The two poles ignore these higher frequencies, leaving the data clean, with data from AC/DC converter behind (GW Instruments , 2017). RFI is another reason for data noise and is caused by background radio waves interfering with the wires. According to maxwells equation, when the change in current of a wire occurs (60Hz), this creates a magnetic field which flows to the second wire and induces a current, which is then converted to a voltage after the resistance occurs (inductive coupling) (GW Instruments , 2017). Software integration is normally the best solution to this problem (GW Instruments , 2017).

For strain gauges, wiring, signal conditioning and data acquisition components are factors for data accuracy. Signal conditioners provide a constant voltage of 3 – 10V to the bridge (National Instruments, 1998), and allows for the strain gauge data to be converted to a digital signal to then be read by the data acquisition tool (Smith, 2021). The signal is often amplified as a strain gauge outputs around 10mV, the signal conditioner then boosts this to 100mV, which still requires a signal amplifier, and can output up to 2000x more than the original signal (National Instruments, 1998).

8. Evaluation (pros, cons, potential issues)

Previous research has explored the investigation of tyre deformation; however, most of it has been within a rolling road setup, making it inaccurate in real-world situations and expensive. Furthermore,

previous research lacks an understanding of tyre slip angle versus force and how the level of grip falls away aside from in the aforementioned computer modelling methods. Therefore, there is a clear scope for physical analysis to validate the Pacejka Model. This project aims to enhance our understanding of how a tyre performs during cornering and provide a realistic idea of where the limit of grip occurs along with verifying the tyre models used in computer simulations. However, due to the project's size, data collection would have to be limited, meaning assumptions about the tyre deformation will have to be made since only the forces acting upon the tyre through the frame will be measured. Despite these limitations, a thorough investigation of previous literature has been conducted, and a clear structure for the project has been developed. The data collected in this project would contribute to further understanding of the lateral forces and overall tyre performance. While some limitations may exist, including assumptions in the tyre and the forces acting through the frame rather than solely through the tyre, there are sufficient justifications for this project based on the extensive investigation of previous literature.

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