



**A Design Study on the Physical Analysis of Lateral Forces Acting on a Tyre**

**University of Wales Trinity Saint David**

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**Final Dissertation Paper**

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***Date: 10/09/2023***

## Abstract

A design study of an automotive tyre testing assembly, utilising physical data collection was conducted. This project is designed to aid in validation of current tyre models and allow for the generation of new tyre models to be used in further research investigations. This rig was based on a Ford Transit subframe and matching front suspension struts, where the initial set of tyres to research were Avon 6J\*13" FSAE tyres. With previous data being published from physical analysis, this allowed for validation of the data collected using the rig developed in this study. To collect data, strain gauges and load cells have been implemented, used to measure the forces acting laterally and longitudinally through the frame and the tyres. The design included various modifications, including new wishbones and wheel adapters to convert the Formula Student rims to fit onto the Ford Transit Hub, which have been manufactured during the course of this project. The work conducted during this project was the initial design for this new tyre testing concept, meaning that several projects can start where this project finished, with the ultimate goal to validate and generate new tyre models.

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## 1. Introduction

The deformation and lateral forces which occur on a tyre under typical loading across varying road surfaces is a crucial factor in understanding tyre performance and vehicle dynamics. When analysing a vehicle's performance, whether a road car, a commercial vehicle or a professional motorsport car, the only interaction the vehicle has with the surface below is with the tyres. Similarly, changes to a tyre's position on the road in terms of toe, slip angle, vertical load and inflation pressure all affect the tyre's interaction and grip level with the road below. This highlights how important correct modelling of tyres is, since the manufacturers need to understand these characteristics to create a vehicle which can handle predictably according to the specifications and expected driving scenarios. However, there is little evidence to support that the computer simulations have validated data against real data collected on the roads. The main method of physical tyre analysis is done using a rolling road and a corresponding frame to hold the tyre in place, where loads are applied to the wheel and slip angles are created, to simulate a corner. This presents various issues such as how valid the data is when comparing the data to real roads. Also how accurate are computer simulations and the cost and flexibility of the testing equipment.

The most comparable work that has been done using physical methods and similarly measuring equipment such as strain gauges and load cells was done by McIntyre, Auburn University in 2015 (McIntyre, 2015). Within this research they designed and manufactured a tyre testing rig, pulled along by an ATV. Load cells were then used to record force data on the wheels at varying toe angles, camber angles, inflation pressures and wheel loads. Lateral and longitudinal forces which act on the tyre were recorded along with tyre angular velocity data and friction ellipses to create a well rounded idea of tyre performance. Whilst this research is similar, key differences such as using an ATV tyre, basing the research on off-road surfaces and also powering the wheel using an electric motor. These differences

further highlight that research surrounding on-road and motorsport based tyres have limited research and where indeed this project can broaden the knowledge base.

This Master's research project will design a testing rig which will analyse the tyre deformation and lateral forces that act on a tyre during a cornering event by utilising physical analysis methods and it will present a more cost-effective approach. A frame will be manufactured within the University's workshop, which will consist of a 2013 Ford Transit Custom front subframe, matching front uprights and wheel hubs. Two Formula Student wheels are then mounted to the wheel hubs, allowing the deformation to be measured. This will then be pulled along and the deformation of side walls will be measured at different slip, toe and 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. When the tyres are set to different slip angles, the grip between the tyre and the road surface will change. This will then be translated into the force acting through the wishbones and subframe, along with the force required to pull the rig along. Since all the tests will be conducted at the same speed, the difference in measured force will be down to the friction on the tyres. Therefore, we can begin to understand the maximum amount of lateral force a tyre can take, given a certain slip angle, as it is expected that, as the slip angle increases, peak forces will be seen and then will slowly drop off. This data will then be analysed to match the lateral force versus slip angle graphs described by Hans Pacejka. Due to the large number of variables current software has difficulty modelling a tyre during a cornering event,



Figure 1: Load Cell (Applied Measurements, n.d.)

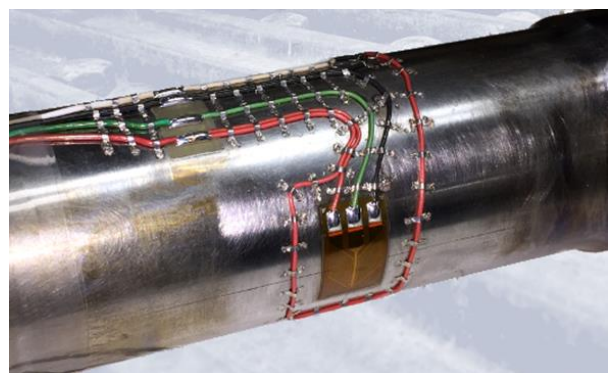


Figure 2: Strain Gauge (Welker, n.d.)

but by using a tyre which has already had some form of lateral force testing and by using the published data, this research will begin to validate this through a much more cost effective method.

In this project, load cells (Figure 1) and strain gauges (Figure 2) will be used to measure the forces acting on the frame of a vehicle. These forces will then be translated into the forces that act on the tyres as the tyres are placed in different toe (slip) angles. The use of strain gauges and load cells is a critical aspect of the project as it allows us to accurately 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 determine how a tyre will perform when it is subjected to different conditions. By accurately measuring the level of grip, we can attempt to match the lateral forces versus slip angle curves produced by Hans Pacejka and his model. This information will be useful in optimising tyre performance and ensuring the safety of the vehicle. A wide variety of testing can be done with this rig as there is flexibility in the compounds, sizes and tread patterns in the tyres tested, along with simulating different vehicles in terms of their mass and the different use cases. Similarly, this could easily be done on typical public roads, off-road surfaces and smooth high quality motorsport specification asphalt.

### 1.01 Current Tyre Modelling Software

There is currently little published information regarding the deformation of tyres under lateral loading. This is due to factors such as cost, complexity, and lack of research. As a result, when companies begin to design a tyre within a software package, the data to use is limited. Similarly, when tyre manufacturers perform their own testing, it is generally on in-house expensive and large testing rigs which are not available for engineering research.

Currently, the main model used to predict the behaviour of tyres under lateral loading comes from Hans Pacejka in his book 'Tire and Vehicle Dynamics'. Hans Pacejka developed the Magic Formula which is a complex mathematical model that 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.

Using the Magic Formula is currently the most accurate and thorough way of modelling a tyre on a vehicle. According to (Siemens , n.d.), Siemens MF-Tyre/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. This also supports the idea that there is very little validation within the field, where model results can be compared to physical tyre data that has been collected from testing on real roads.

*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*

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

$$x = X + Sh$$

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,  $Sh$  = horizontal shift and  $Sv$  = vertical shift (Pacejka, 2012).

However, there are alternatives such as OptimumTyre2 which is a software package that can generate tyre models from imported tyre test data. This software uses the Magic Formula to create tyre models based off the imported data, which can then be used to understand the performance of a tyre in varying conditions which may not have been physically tested. The software creates these models and can then be exported as TIR files, which can then be imported into vehicle dynamic software such as Vi-Car Real Time is used to simulate the dynamic behavior of vehicles in real time (OptimumG, n.d.). A MATLAB tyre modelling tool has also been developed by Tom Teasdale from the UPBracing Formula Student team, which used the Magic Formula tyre model (Teasdale, 2023). This has been designed as an open-source version to software like the previously mentioned Siemens MF-Tyre or OptimumTyre2

and can be downloaded from MathWorks as a MATLAB App. The app has been designed around Formula Student tyre data produced by the FSAE Tire Test Consortium (FSAE TTC). Tyre data can then be imported into the app, which is then used to create a new tyre model, where the Magic Formula code is used fit the model to the data, which again can be exported and used further as a TIR file. The use of the tool will be a great way of validating the data produced by our rig; by acquiring the corresponding data from the FSAE TTC, we can then compare our data with that and then compare it to the Magic Formula Model produced by this tool, depending on the accuracy of the model and the rig. We can then begin testing more tyres which don't have the data to validate against, such as the Sports 2000 MCR Yokohama tyres, and then using the data from our rig and this tool, tyre models can be developed to be used in Vi-Grade allowing for collaboration with current vehicle dynamics and aero research projects which are using the Sports 2000 car as their focus.

## 1.1 Literature Review

Understanding the fundamental mechanisms involved when a vehicle is cornering and the impact on the tyre is critical when developing a tyre testing rig. Therefore, along with this knowledge and by reviewing previous literature within the field of tyre testing, this allows us to take influence from previous research methods and testing rigs by understanding the advantages and disadvantages.

### 1.11 Vehicle Dynamics and Tyre Characteristics

When developing a road car, the most important link within the system is between the vehicle and the road surface, which is always done through the tyres. The level of grip which can be generated depends on the tyre and the surface, which is essentially the limiting factor when attempting to develop the handling of the car. These tyres also take the vertical load of the car and any harsh bumps within the road. As a car turns a corner, a lateral and longitudinal force is generated within the tyre, this distorts the tyre and affects the contact patch with the ground. This force will then continue to increase until the slip angle or force is too great, which is where the slip then occurs where the tyre begins to slide, rather than turn the car.

Figure 3 describes the forces which act on tyre during a corner. Many of these factors are dependent on the speed and mass of the vehicle, however, the lateral and longitudinal forces ( $F_y$  and  $F_x$ ) are the focus to this study.

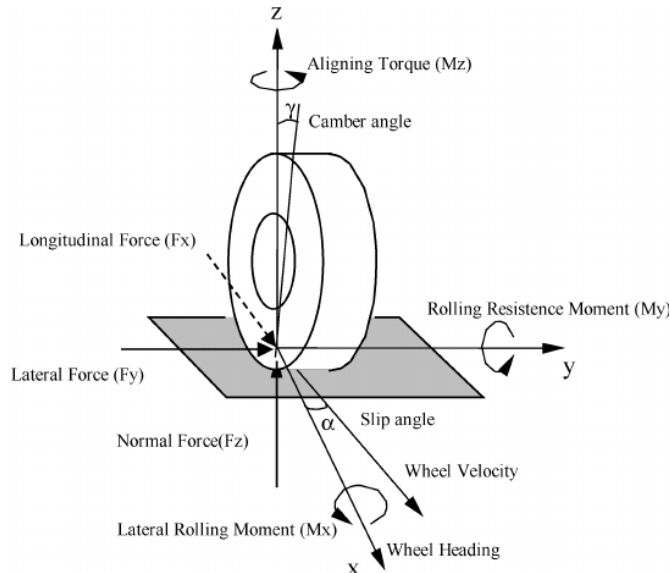


Figure 3: Forces acting on a tyre (Gonçalves & Ambrósio, 2005)

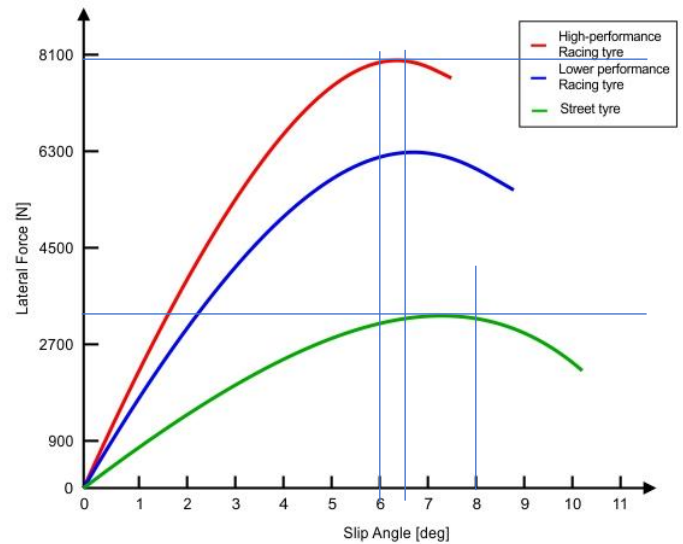


Figure 4: Lateral Force versus Slip Angle (Santos, 2014)

Figure 4 then shows a basic representation of how different tyres produce varying levels of peak lateral force. Firstly, the graphs show three different areas of a tyre's performance. This starts as a lateral force, increasing linearly with the slip angle, followed by a transitional phase where the tyre begins to slip, meaning that force and angle are no longer increasing linearly. Finally, the maximum lateral force at a given slip angle is shown and is represented by the peak of the curve. By looking at the green line, this represents a standard road going street tyre where the peak lateral force is around 2700N

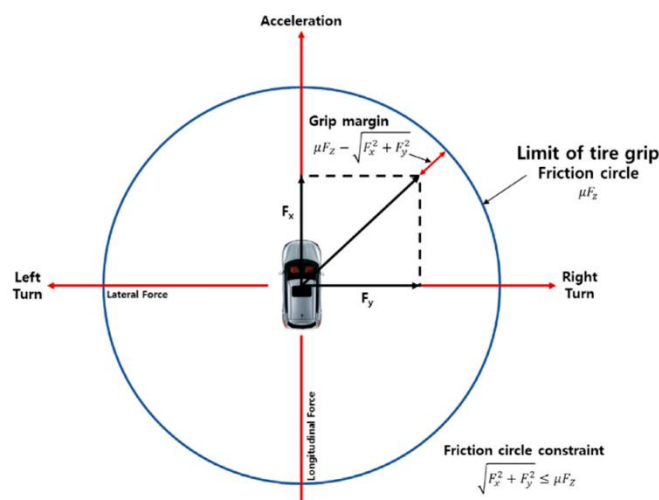


Figure 5: Friction Circle Concept (Park, Jang, & Hwang, 2018)

between 6.5 and 8 degrees of slip angle. The low peak lateral force means that there is a considerable limitation of the vehicle due to the tyre. By comparing this with the high performance tyre (red line), a much higher peak lateral force can be seen, which therefore means greater grip and higher cornering speeds. However, the angle at which this peak force is created is a much smaller window, between 6 and 7 degrees, meaning that the window for maximum grip is smaller, increasing the precision needed by the driver to extract the full potential out of the tyre. Similarly, if we extrapolate the graphs once the peak lateral force has been produced, a quicker drop off in grip can be seen for the high performance tyre compared to the street tyre. These differences in characteristics highlight how a tyre is designed and optimised for a particular use, but not necessarily indicating if one tyre is superior to another tyre. The data produced by the testing method designed within this project will shadow these diagrams, which will also allow for further validation by using computer generated models such as the Hans Pacejka Model or Magic Formula.

Friction Circles, shown in Figure 5 is another useful tool when understanding a tyre's performance. They show the limit of tyre grip depending on acceleration, deceleration and lateral forces (cornering harshness) left or right. They describe how the lateral forces which the tyre produces changes depending on the acceleration or the breaking force. For example, when acceleration increases less lateral force can be loaded through the tyre before the limit of grip is exceeded. The last points to consider when understanding the effect of lateral forces on a tyre is the inflation pressure, vertical load and the camber. All of these factors can affect the contact patch between the tyre and the road.

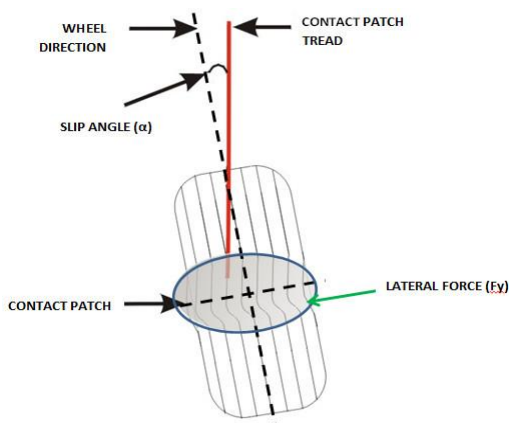


Figure 6: Contact Patch Deflection (Hoad, 2016)

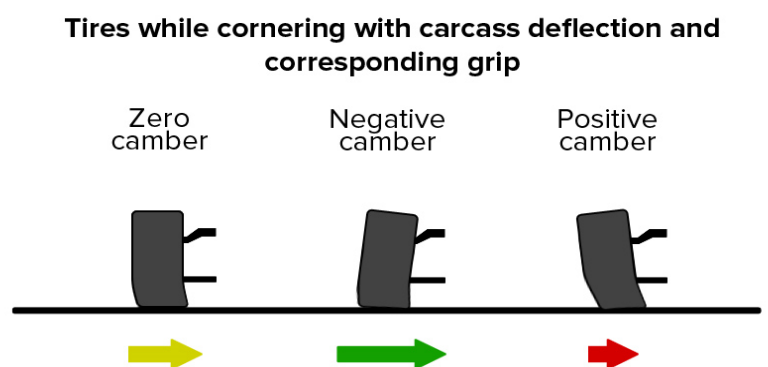


Figure 7: Effect of camber on contact patch (KRÖNKE, 2017)

The contact patch is the point between the tyre and the road and therefore can change the grip and rolling resistance.

Looking at Figures 6 and 7 which describes how the tyre deflects during a corner, along with how negative camber can increase the contact patch during a corner, which will then increase the lateral force acting on the tyre and increase the cornering speed. Specifically looking at Figure 7 a zero (neutral) camber will provide maximum grip in a straight line, and therefore will maximise acceleration or deceleration. However, the deflection of the tyre wall then reduces the contact patch during a corner. Contrast this to a negative camber, as the tyre is loaded up, the tyre deforms and becomes more in line with the camber, which increases the contact patch.



*Figure 8: Inflation pressure versus Contact Patch (Tyre Leader, n.d.)*

Figure 8 shows how the inflation pressure can affect the contact patch, where under inflation and over inflation can both reduce the area. However, it is important to consider the road surface, as off-road surfaces such as snow or soft sand, underinflation can help reduce the overall applied pressure to the surface and therefore improve traction. Similarly, the inflation pressure of the tyre also effects the contact patch produced. However, when changing the inflation pressure or the vertical load, it is key to make these changes in isolation. Generally, if a vehicle has more mass, then increasing the inflation pressure can counteract the effect, maintaining a consistent tyre contact patch. Similarly, to if a road car is at full load capacity, then the manufactures specify to increase the air pressure in the tyres.

When considering the contact patch of a tyre, the tread pattern will also have an effect. For example, asphalt track cars will generally use a slick tyre, which means a completely smooth surface, therefore creating a larger contact patch with lower deformation with the removal of tread blocks. Therefore, higher lateral forces can be loaded through the tyre at a more predictable rate which is ideal for

motorsport vehicles. Generally, these tyres also come with a much stiffer sidewall, increasing stability and cornering behaviour (Ing. Jan Sajdl). This higher predictability is a further reason for the initial use of slick formula student tyres for the initial phase of the development of the rig during this research, as this data will be easier to validate before using more standard road tyres. However, for road cars, the use of slick tyres is banned for safety reasons and therefore it is also important to consider treaded tyres and the noise, vibration and harshness which is produced by different tread patterns. From a journal article, twenty two different treaded road tyres were tested on a non-porous asphalt road and it was found that two major mechanisms contributed to tyre noise. impact between the tread blocks and the road and air pumping due to the compression and expansion of the treaded grooves (Li, 2020).

Another important factor in the grip level of a tyre is the surface and carcass temperature. As tyre temperature begins to rise, the rubber compound begins to become softer which allows more contact between the tyre and the uneven road surface below. This is a common issue in top level motorsport such as Formula 1, as their tyres have a fine operating window, meaning if the tyre is too cold or too hot, then the grip level massively decreases. At a fundamental level a tyre is made of a carcass from steel or Kevlar (this is typical in Formula 1 tyres), which is then surrounded by a rubber casing. This casing is made up of long chain polymers which are coiled up in their resting state. As the tyre is worked, deformation occurs which stretches the chains, known as hysteresis and, as the chains return to their original state, a portion of energy used to expand the chains is retained as heat, causing an increase in temperature throughout the tyre (Suspension Secrets, 2019). As the heat increases, the bond between the chains becomes weaker, which allows the rubber to become more pliable and stickier and therefore increasing the grip levels (Freudenrich, n.d.). Therefore, this needs to be considered during the data acquisition phase of the project as this could be a potential reason for the data not producing the same values as that which has previously been published.

### 1.12 Computer Simulations

Starting with computer simulations, this can be done solely through computer based modelling or using physical data and then computer programming to help predict how varying tyres will react in terms of size, compound, load and speed.



*Figure 9: Tyre Testing Rig (Garcia-Pozuelo, Yunta, Olatunbosun, Yang, & Diaz, 2017)*

In a research paper published in 2017, an investigation was carried out to explore the utilisation of strain-based sensors placed on the side walls of automotive tyres in conjunction with the application of Fuzzy Logic to assess and estimate tyre slip angles. These estimates were based on factors such as inflation pressure, rolling speed and vertical load of the tyre. To conduct this research, a 'strain-based prototype and an indoor tyre test rig' were employed, as depicted in Figure 9. The setup shown in Figure 9 exemplifies a typical testing rig used in the industry, highlighting its technical complexity and expense. The research findings indicated that predicting tyre slip angles was feasible, particularly as lateral forces decreased, leading to a sharp drop in strain values. A Fuzzy Logic approach was employed to estimate tyre conditions, and simulation test results demonstrated the viability of using strain sensors for addressing the non-linear prediction characteristics of tyres. Testing encompassed a slip angle range of 0 to 14 degrees, with a load range of 250N to 1000N. The lateral force acting on the tyre within the rig was plotted and could serve as comparative data for this project, whilst acknowledging the use of different tyres compared to this project (Garcia-Pozuelo, Yunta,

Olatunbosun, Yang, & Diaz, 2017). This information has also been used in the project research proposal cited as (Walker, 2023).

The Magic Formula is a commonly used approach for simulating tyre deformation, slip angles and lateral forces. However, its effectiveness requires validation to ensure accurate representation of real-world conditions. Previous researchers often employed MATLAB and Simulink to replicate this model. In a 2017 research paper, this model was created and compared to published Magic Formula data. The outcome indicated that the MATLAB code generally provided accurate data and effectively modelled various scenarios. Notably, the comparison was conducted against the model itself, not real-world data. While this research proves beneficial for efficient tyre data modelling, it does not replicate physical tyre testing scenarios (Shi, Zhao, Zhang, & Ye, 2017).

In the design of the tyre rig for the present project, the capacity to accommodate substantial weights has been taken into consideration and addressed, necessitating an understanding of the resulting effects. A study by Kunjunni, B., Zakaria, M.A.b., Majeed, A.P at the University Malaysia Pahang, focused on linking vertical loading effects with lateral and longitudinal forces acting on an electric vehicle's tyre (Kunjunni, 2020). While cornering force wasn't analyzed in this research, it provided valuable insights into the impact of vertical loading. A vehicle, tyre, and load transfer model were formulated using MATLAB. Varied masses and mass distributions were employed in testing, revealing that increased vertical mass caused tyres to rapidly exceed the friction circle at similar speeds, leading to potential crashes.

Within the design of the tyre rig from this project, the capability of loading up to significant weights has been considered and accounted for, therefore it is important to understand these effects. In a piece of research by Kunjunni, B., Zakaria, M.A.b., Majeed, A.P at the University Malaysia Pahang, this has been done which links to the vertical loading effect on the lateral and longitudinal forces which act on a tyre from an electric vehicle (Kunjunni, 2020). Whilst this research didn't analyse the force acting on a tyre during a corner, it provides valuable insight into the effects of vertical loading. A

vehicle, tyre and load transfer model were coded within MATLAB. Varying masses and mass distributions were used within the testing and it was found that the increase in vertical mass caused the tyres to exceed the friction circle quickly at the same speeds, which in some cases resulted in a crash.

### 1.13 Previous Testing Rigs

The other side of previous research is looking at the design of testing rigs which have already been manufactured and tested. This can then influence the design of the rig produced within this report, with a constant point of limited budget and time available.



*Figure 10: Tyre Testing Rig used for FE development (Korunović\*, Trajanović, Stojković, Mišić, & Milovanović, 2011)*

A significant portion of the physical analysis surrounding tyres is carried out using a rolling road rig. This rig involves placing the tyre at specific angles and loads to assess its performance, with force measurements taken to evaluate its behaviour. This gathered data serves various purposes, such as validating the Pacejka Magic Formula model or creating Finite Element (FE) models of the tyre for easier generation of diverse tyre models. In a 2011 research paper, this methodology was used, highlighting the potential of the tyre testing rig as an alternative means of measuring lateral forces in relation to slip angles (Korunović\*, Trajanović, Stojković, Mišić, & Milovanović, 2011). In their study, they effectively developed an FE model intended for future tyre design; however, this approach raises

concerns regarding its accuracy. While the collected data may exhibit repeatability, which holds importance, it may not authentically capture real surface conditions. Consequently, tyres constructed using this model may not precisely adhere to expected model behaviour. The setup used for this testing is illustrated in Figure 10. This information has also been used in the project research proposal cited as (Walker, 2023).

Prior physical analyses of tyre loads and forces are constrained by various factors, notably cost and the complexity of variables encountered when acquiring tyre-related data. Typically, physical analysis occurs within a controlled rig setup and rolling road environment, providing reproducible data but potentially deviating from real-world road conditions. Nevertheless, a 2015 paper authored by Xiong & Tuononen researched into measuring truck tyre deformation while the vehicle was driven on an actual road (Xiong & Tuononen, 2015). The objective of this study was to understand the rolling resistance force of truck tyres under varying loads, inflation pressures and wear conditions. While this research doesn't mirror the exact data collection in this project, it offers insights into how tyre deformation is captured and how this understanding can be applied to lateral force investigations. An optical sensor was employed to gauge sidewall deformation, revealing that distinct areas of the tyre undergo deformation based on inflation pressures, consequently leading to varied wear levels. The configuration of the instrument assembly is depicted in Figure 11. This information has also been used in the project research proposal cited as (Walker, 2023).

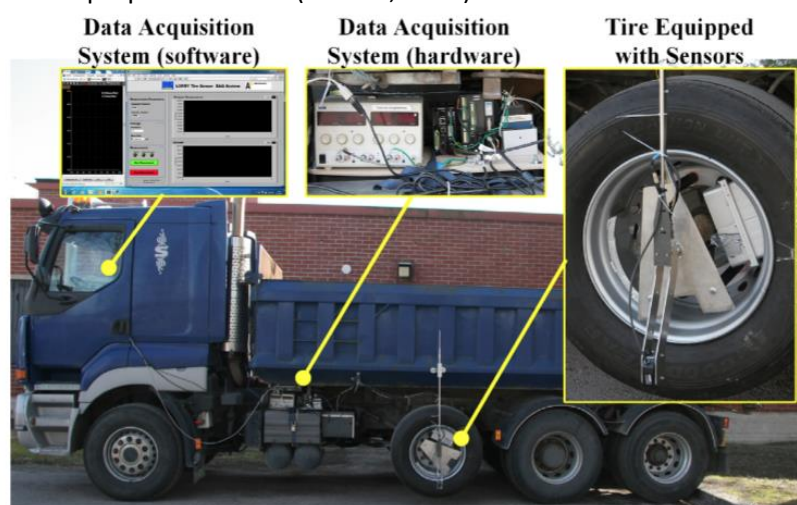


Figure 11: Tyre Deformation Analysis (Xiong & Tuononen, 2015)

### 1.14 FSAE Tyre Testing

Currently, tyre manufacturers have released their own datasets showcasing lateral force versus slip angle at various loads, providing valuable information for validation purposes. A substantial portion of this data originates from Formula Student tyre manufacturers, given that Formula Student primarily serves as an engineering exercise for aspiring engineers. Notably, Avon Tyres and Hoosier are prominent manufacturers in this context, as evidenced by the example dataset presented in Figure 11, derived from an Avon 6J\*13" FSAE Tyre with an inflation pressure of 21 psi and a speed of 20 kph (Avon Tyres, 2013). It's worth noting that while the method proposed in this project can replicate this setup precisely, manufacturers resort to a rolling rig and frame arrangement during testing to ensure precision and repeatability.

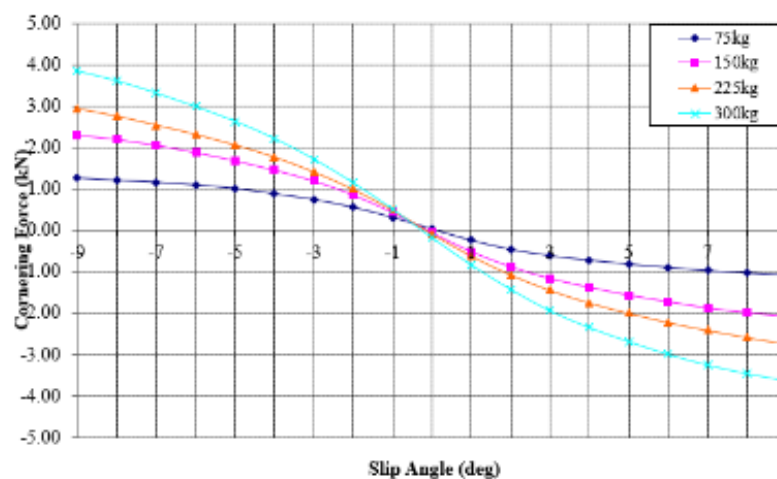


Figure 12: Avon FSAE 13" Tyre Data (Avon Tyres, 2013)

The FSAE Tire Test, originating in 2006 under the Formula SAE Tire Test Consortium (FSAE TCC) (FSAE Tire Test Consortium, 2022), was conceived to produce high-quality tyre data relevant to racing series usage. Although the compounds and outcomes have evolved, the fundamental structure has been retained. Collaborating with the Calspan Tyre Research Centre, FSAE TCC developed a low-capacity flat-bed tyre testing apparatus. This setup subjected tyres to diverse conditions encompassing various loads, inclinations, slip angles, inflation pressures and temperatures. A consistent rim choice was maintained throughout the tests, precluding an investigation into rim choice effects. The testing regime included two free rolling tests and a drive/brake test. The initial free rolling test scrutinised

sweeping slip angles, while the second explored the impact of inflation pressure. The drive/brake test documented longitudinal forces under braking and acceleration. Post-test assessments involved tyre wear documentation, along with pyrometer readings to record temperatures (Kasprzak & Gentz, 2006). Figure 12 illustrates the testing equipment employed and Figure 13 provides an instance of tyre deformation due to slip angles. This information has also been used in the project research proposal cited as (Walker, 2023).



*Figure 13: Calspan Testing Machine on Avon FSAE Tyres (Kasprzak & Gentz, 2006)*



*Figure 14: Tyre Deflection Due to Slip Angles (Kasprzak & Gentz, 2006)*

Yearly refinements to the testing procedure are made; the most recent being Round 9 dated 7<sup>th</sup> February 2022, identical to the preceding Round 8 (FSAE Tire Test Consortium, 2022). This iteration introduced low-speed transient tests and traditional sweeps at varying roadway speeds, borrowed from Round 6. The cornering test, constituting Round 9, centres on measuring lateral forces exerted on the tyre. The process entails two slip angle runs, a break-in phase, and an initial spring rate test. This procedure is executed at multiple pressures and inclinations of a free-rolling tyre. Additionally, slip angle sweeps are conducted at speeds of 15 and 45 mph serving as a basis of comparison with the standard 25 mph test data. Notably, the 350 lb load for 10-inch tyres is substituted with a 200 lb load and a 12 psi block is introduced to assess performance in response to wear or heating. Infrared sensors are employed to gauge surface temperature, as depicted in Figure 14 (FSAE Tire Test Consortium, 2022). This information has also been used in project research the proposal cited as (Walker, 2023).



*Figure 15: Rig used on Round 9 of FSAE TCC testing (FSAE Tire Test Consortium, 2022)*

## 2. Timeline

### 2.1 Gantt Chart

Table 1 shows the timeline for the project with all the key steps highlighted. As the project continued this chart was filled out from purple to grey as the individual tasks were completed. To begin the project a literature review was conducted. As part of the project a research proposal was written which is where the majority of the literature review was done, however this was extended into this report to provide a full overview of the field. Following this, the design of the project could begin, which is where each component and the overall rig was designed using SolidWorks. This led to the design of three specific components; the wheel adapter, wishbones and the overall frame structure to support the whole rig. This was then followed by specifying the materials needed, ordering, delivery and manufacturing of the components. Once the components had been produced, a test assembly of the rig was able to be done to show proof of the concept of the rig. Throughout the majority of this process, the report was slowly built, using information from the project proposal document and writing each section as it was completed.

Table 1: Project Gantt Chart

| Tasks (Week)                      | Timeline |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
|-----------------------------------|----------|---|---|---|------|---|---|---|--------|----|----|----|-----------|----|----|----|
|                                   | June     |   |   |   | July |   |   |   | August |    |    |    | September |    |    |    |
|                                   | 1        | 2 | 3 | 4 | 5    | 6 | 7 | 8 | 9      | 10 | 11 | 12 | 13        | 14 | 15 | 16 |
| <b>Literature Review</b>          |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Previous Tyre Testing Methods     |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Similar Rig Designs               |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Strain Gauges and Load Cells      |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Data Acquisition                  |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>CAD Design</b>                 |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wheel Insert                      |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wishbone                          |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Frame                             |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>Material Specification</b>     |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wheel Insert                      |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wishbone                          |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Frame                             |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>Material Ordering/Delivery</b> |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wheel Insert                      |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wishbone                          |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Frame                             |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>Component Manufacturing</b>    |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wheel Insert                      |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| Wishbone                          |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>Assembly</b>                   |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |
| <b>Report Write Up</b>            |          |   |   |   |      |   |   |   |        |    |    |    |           |    |    |    |

During this project, delays arose as expected, however this was accounted for at the beginning, meaning the project could be completed by the deadline. For example, there were delays in material processing and ordering, as well as manufacturing of the wheel adapter, as we needed to wait for an available time slot at the Wales Centre for Batch Manufacture (CBM) which is the inhouse Manufacturing Department at the University of Wales Trinity Saint David.

### 3. Experimental

#### 3.1 Wheel Adapter

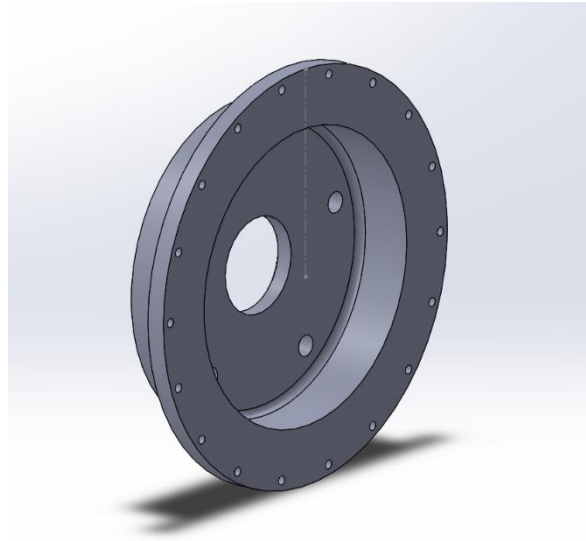


*Figure 16: CAD Drawing of Wheel Adapter*

An adapter was designed and machined to allow for the Formula Student wheel to attach to the Ford Transit wheel hub. The FSAE wheel rim is a 3 piece design, allowing a new centre to be designed which can then be fitted to the outer rim pieces, creating a completed rim. This new centre then matches up with the same bolt pattern as the Ford Transit wheel hub (5 x 160 mm), along with a 40 mm offset to clear the lower ball joint on the Ford Transit wheel hub and lower wishbone. The above Figure (Figure 16) shows the design of the component within SolidWorks and the mechanical drawing can be found in Appendix A. This is then machined on the CNC within the University out of a solid billet of aluminium.



*Figure 17: Comparison of the old wheel and new wheel adapter*

Figure 17 shows the Formula Student rim as standard (left), where the bronze centre is the piece that is being replaced and compared to the newly designed insert to fit the Ford Transit wheel hub (right).

To machine the component, a Mazak CNC lathe and miller were used within three separate operations. The first operation used the CNC lathe, which created the rear face and 40 mm boss offset. The lathe trimmed the surface of the aluminium to ensure a completely flat surface as a starting point, then in 1 mm increments, a right hand knife tool cut away at the piece, removing material slowly to leave behind the 40 mm offset which can be seen in the drawing above, this was done using an RPM of 439 and a Feed of 0.2 mm/revolution.

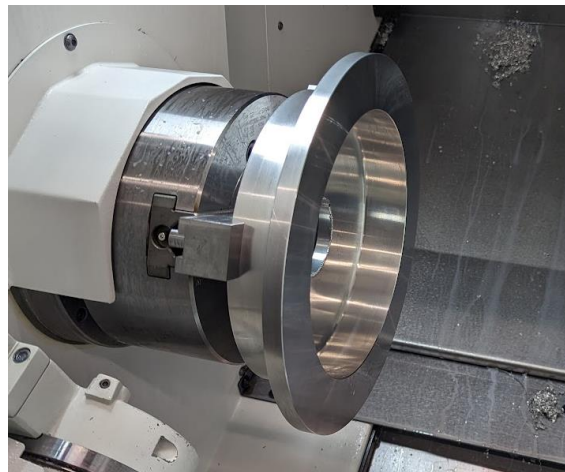
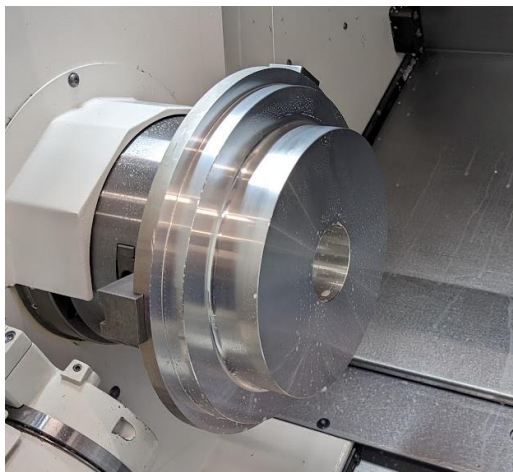


*Figure 18: Machining Process of Wheel Adapter*

To create the other side of the component, a second operation was needed. The piece was flipped by hand and then held in the jaws on the new 200 mm radius, where again the process started with trimming the surface. This was done to create the 280 x 13 mm outer edge. A 'Boring Bar' tool was then used to remove material from the inside of the component and create the inner 5 mm radii, along with a rough cut of 64 mm for the central bore. Figure 18 illustrates this process.

The piece was then placed in a CNC miller where the inner hole could be machined, along with the 5 x 160 mm holes and 13 x 266 mm outer holes which can be seen looking at Appendix A – Figure 30. The first hole which was created was the inner 65.225 mm centre bore, however beforehand a probe within the miller was used to measure the previous hole size of 64 mm. Since this is the centre and main locating point to the Ford Transit wheel hub, it was important to machine it accurately which

then allowed for it to be used as a reference point for the remaining holes. The probe was used again after the holes were cut to measure the diameter. This measured as 65.225 mm which is within the tolerances set. Due to the tight tolerances on these holes, it was important for the process to be taken slowly and to allow the operator to measure the holes in between cuts. During the entire process, a rough cut was done leaving behind 0.1 mm which was then taken off using a finishing cut. The mechanical drawing and final product can be seen in Appendix A.

### 3.2 Wishbone

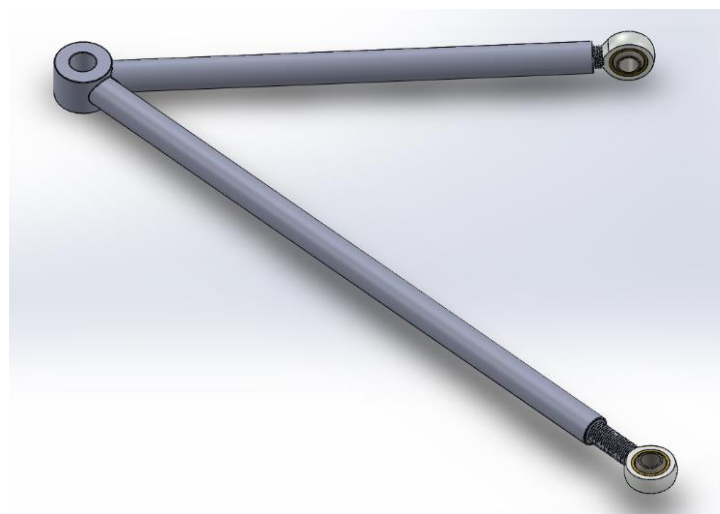


*Figure 19: Drawing of Redesigned Wishbone*

The lower wishbones which came with the Ford Transit subframe were made as one piece, stamped from a sheet of mild steel which needed to be replaced as the design would not allow for accurate measurements of the applied forces in specific directions, since a single component takes all the loading. Therefore, new lower wishbones are required. By using the above design, illustrated in Figure 19, these forces can more easily be measured by strain gauges. This also allows for a solid bushing to be machined where the wheel hub mounts to the outer wishbone, further allowing all the forces to be transferred to the wishbone arms and providing accurate data. Where the wishbone mounts to the subframe, rod end bearings supplied by McGill Motorsport are used to allow the wishbone to articulate and conform with the road surface. This wishbone is made from 25.4 x 1.63 mm wall

thickness CFS3BK cold drawn seamless mild steel tube, fabricated in the University workshop.

Similarly, the mechanical drawing and final product can be seen in Appendix B.

### 3.21 Force Calculations

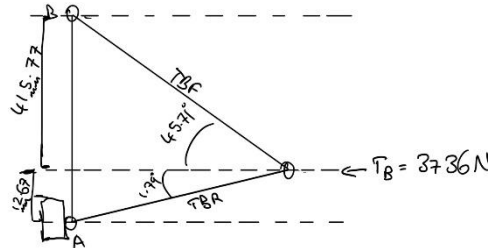


Figure 20: Wishbone diagram

Force calculations are required to understand the loads applied to the wishbone which occur during testing. Using data provided by Avon Tyres on their FSAE tyres, a maximum lateral and longitudinal load can be calculated (Avon Tyres, 2013). Then using Euler's buckling calculations (Maxfield, 2009), the maximum force that can be taken by the wishbone can be calculated and therefore calculating the safety factor which has been implemented into the design of the lower wishbones.

Equation 3: Force acting on Wishbone about A

$$TBF = \frac{aTb}{a + b * \cos(\theta)}$$

Equation 4: Force acting on Wishbone about B

$$TBR = \frac{bTb}{a + b * \cos(\theta)}$$

Equation 5: Formula for Force perpendicular to wishbone

$$Tb = \frac{Fb}{\cos(\theta)}$$

Equation 3 and Equation 4 are used in conjunction with data from Avon Tyres to calculate the maximum forces that are translated through the tyre into the wishbone which has been designed. Then the individual forces are exerted into each of the arms of the wishbone. These forces are dependent on the geometry of the wishbone. TBF and TBR are the forces in newtons acting about A

and B respectively. From the Avon data, a maximum slip angle of 9° (θ), 3960N (Fb) was loaded through the tyre. Then using Equation 6, 3739N would be applied perpendicular to the lower wishbone mount, known as TB. Taking TB as 3739N and using Equation 3 and Equation 4, 3627.29N is loaded through TBR and 158.22N is loaded through TBF. The published data used a maximum load of 300 kg and maximum slip angle of 9°, therefore we can expect to see larger lateral forces in our test rig by extrapolating this data.

*Equation 6: Euler Buckling Formula for a Tube (Maxfield, 2009)*

$$P_{cr} = \frac{\pi^2 E (\pi r^3 t)}{L^2}$$

Equation 6 shows the Euler buckling formula for a tube. This has been used to calculate the minimum force required to buckle the wishbone. E = Young's Modulus, r = tube radius, t = wall thickness, L = tube length. This can then be compared to the maximum force that will be exerted on the wishbone during testing, using data extrapolated from Avon tyre testing on their FSAE tyres. The Pcr values for the selected materials can be seen in Table 3 which are then compared to TBR to calculate if the material will be strong enough, as well as calculating the safety factor. The safety factor helps understand the maximum loads which can be applied before failure were to occur. Therefore, automotive structural parts such as this wishbone are highly important, as failure can result in injury. However, this is often balanced with cost and weight of the component. For example, in an aircraft, a Factor of Safety (FoS) would be anywhere from 1.5-2.0. However, for cast-iron wheels used in the automotive industry an FoS of 20 is used where weight is less vital (The Engineering Toolbox, 2010).

### 3.22 Material Choice

Looking at the calculations the maximum force applied to the wishbone, based on the Avon Tyre data, is 3627.29N. For this component four different materials have been compared and, within the buckling calculations, the same size tubing (1.00" x 1.6 mm wall) has been used to keep all the data consistent. The materials compared were as follows: Stakesys Motorsport UK & FIA Approved Bendable Roll Cage & Chassis Tubing, Express Metals S355 Mild Steel, metals4U CFS3BK and metals4U E220. The material

from Stakesys is a FIA approved roll cage and chassis tubing, however little information on the material grade is given. The material from Express Metals is a mild steel, graded to a minimum yield strength of 355MPa, hence the name. Then from metals4U, E220 is a cheap and basic material which is formed as a seamed tube. This is used as a baseline comparison for the cheapest material which could theoretically be used. However, metals4u also supply the CFS3BK steel which is a cold drawn and seamless tube, producing higher yield strengths and a more consistent strength around the

*Table 2: Material Considerations*

|                         | Tube Material       |                  |               |                           |
|-------------------------|---------------------|------------------|---------------|---------------------------|
| Criteria                | Express Metals S335 | Metals4U CFS 3BK | Metals4U E220 | Stakesys Roll Cage Tubing |
| Young's Modulus         | 200                 | 190              | 190           | 210                       |
| Tensile Strength (MPa)  | 510                 | 480              | 350           | 510                       |
| Yield Strength (MPa)    | 355                 | 360              | 250           | 370                       |
| Price (£/m) 1.00"x16swg |                     | 12.62            | 4.19          | 15.57                     |
| Availability            | Local               | Delivery         | Delivery      | Delivery                  |

circumference of the tube.

Table 2 shown above compares all the different and key factors from each of the chosen materials to aid in choosing an appropriate material from a cost-effective supplier. Table 3 below shows the minimum force required to buckle the material, ranking the materials from strongest to weakest. Stakesys is clearly the strongest material due to the highest Young's Modulus of 210MPa. The weakest material is then CFS 3BK and E220, where the same Young's Modulus of 190MPa has been used. However, when looking at previous research comparing the differences between seamed and seamless stainless steel pipe, a large difference in strength can be seen. ASME believes that a seamed pipe can only withstand 85% of the pressure which an equivalent seamless pipe can withstand (Permanent Steel Manufacturing Co. Ltd, 2017). This can then further be concluded when looking at a research paper from 2019 which conducted a fracture assessment of seamless and seamed pipes (Musrati, et al., 2019). By studying the fracture resistance of pipes using a Pipe Ring Notched Bending

*Table 3: Minimum forces to buckle.*

|         | Pcr (N)  |
|---------|----------|
| Stakeys | 61171.59 |
| S355    | 60416.39 |
| CFS3BK  | 57395.57 |
| E220    | 57395.57 |

specimen (PRNB), the Authors found that the seamless steel pipes had a much higher crack growth resistance compared to the seamed steel pipes. Therefore, we can confidently state that there is a considerable strength difference between a seamless and seemed tube and it is still therefore fair to rank CFS3BK above E220.

*Table 4: Tube Material Decision Matrix*

|                         | Tube Material       |                  |               |                           |
|-------------------------|---------------------|------------------|---------------|---------------------------|
| Score                   | Express Metals S335 | Metals4U CFS 3BK | Metals4U E220 | Stakesys Roll Cage Tubing |
| Young's Modulus         | 2                   | 4                | 4             | 1                         |
| Tensile Strength (MPa)  | 1                   | 2                | 3             | 1                         |
| Yield Strength (MPa)    | 3                   | 2                | 4             | 1                         |
| Price (£/m) 1.00"x16swg | 3                   | 2                | 1             | 4                         |
| Availability            | 1                   | 2                | 3             | 4                         |
| Total                   | 10                  | 12               | 15            | 11                        |

A decision matrix shown in Table 4 has been used to help identify the most suitable material based on a range of criteria. The first Table lists all of the values for each of the categories, which are then scored in the decision matrix. The scoring system ranks each material from 1 to 4 for each category with 1 being the most suitable and 4 being the least. The total is then calculated which shows which material would be most suitable. Looking at the Table, it clearly shows that Express Metals S355 is the best, and the metals4U E220 is the worst. The metals4U CFS3BK and Stakesys material are equally ranked between the other two materials. However, for this component, the chosen material was metals4U CFS3BK and this material was chosen due to the material being seamless, the delivery was the quickest and cheapest and the price was one of the lowest. Similarly, for Express Metals, whilst the company is local, supply for that particular material and size combination was limited, which would delay the project, hence this was the reason not to opt for this. Then comparing this to Stakesys, the material properties that were listed made this tube the strongest, however there was limited information of the material grade and combining this with the additional cost and delivery time provided enough reason to not to choose them for this project.

The above image as Figure 21 shows the fully made wishbone in comparison to the original wishbone and this shows how the design allows for accurate measurement of strain and easy modification for the use of load cells in between the tubes to measure direct applied load instead.

Strain Gauge  
Placement



Figure 21: Completed Wishbone, compared against the original

### 3.3 Frame

Then, to create the testing rig, a frame needs to be built around the Transit subframe. When the subframe is mounted on the Transit chassis, the front uprights which include the wheel hubs, suspension and mounting points for steering are connected to the top of the chassis, near the engine bay. Since this is a standalone subframe, a framework to mount the uprights to needs to be manufactured. This will be made from mild steel box sections, where welds will attach it in place at the bottom of the subframe.

The frame will be made from 50 x 50 mm box section mild steel with a 2 mm wall thickness. A standard mild steel material is adequate for this frame since most of the loads will act through the wishbones and subframe, the frame will then hold up the two front struts. Since the subframe came straight from

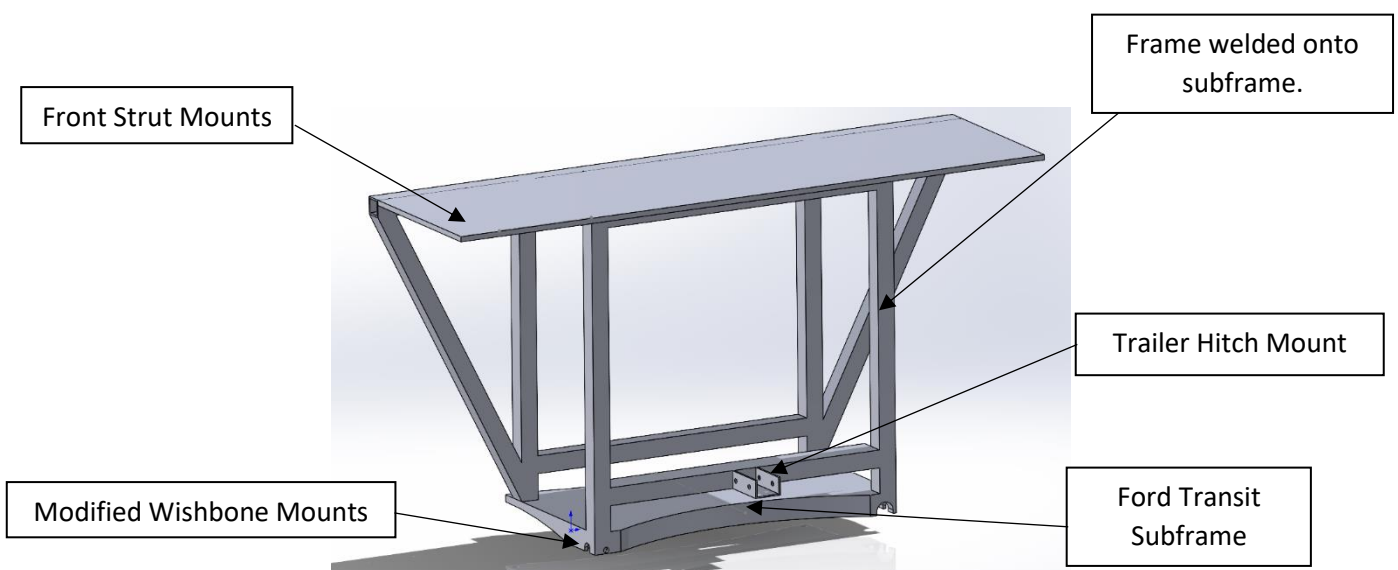


Figure 22: Frame Design

a Ford Transit it is reasonable to assume that it will take all the loads. Within the frame, the largest force will come from the trailer mounting point, where it will be towed from. With both wheels pointing inwards, there will be a considerable amount of friction and force acting against these points. Similarly, the steering rods will attach to the frame and the wheel hubs, allowing for the slip angles to be set. Again, due to the toe angle, a considerable amount of force will act against the wheel, counter steering and pushing the wheel straight, therefore loads in this direction need to be considered. A flat plate will then mount the struts, maintaining rigidity to the entire structure. Figure 22 shows the initial design of the frame, highlighting each mounting point and the original subframe, which the rig is based around.

### 3.4 Slip Angle/Steering

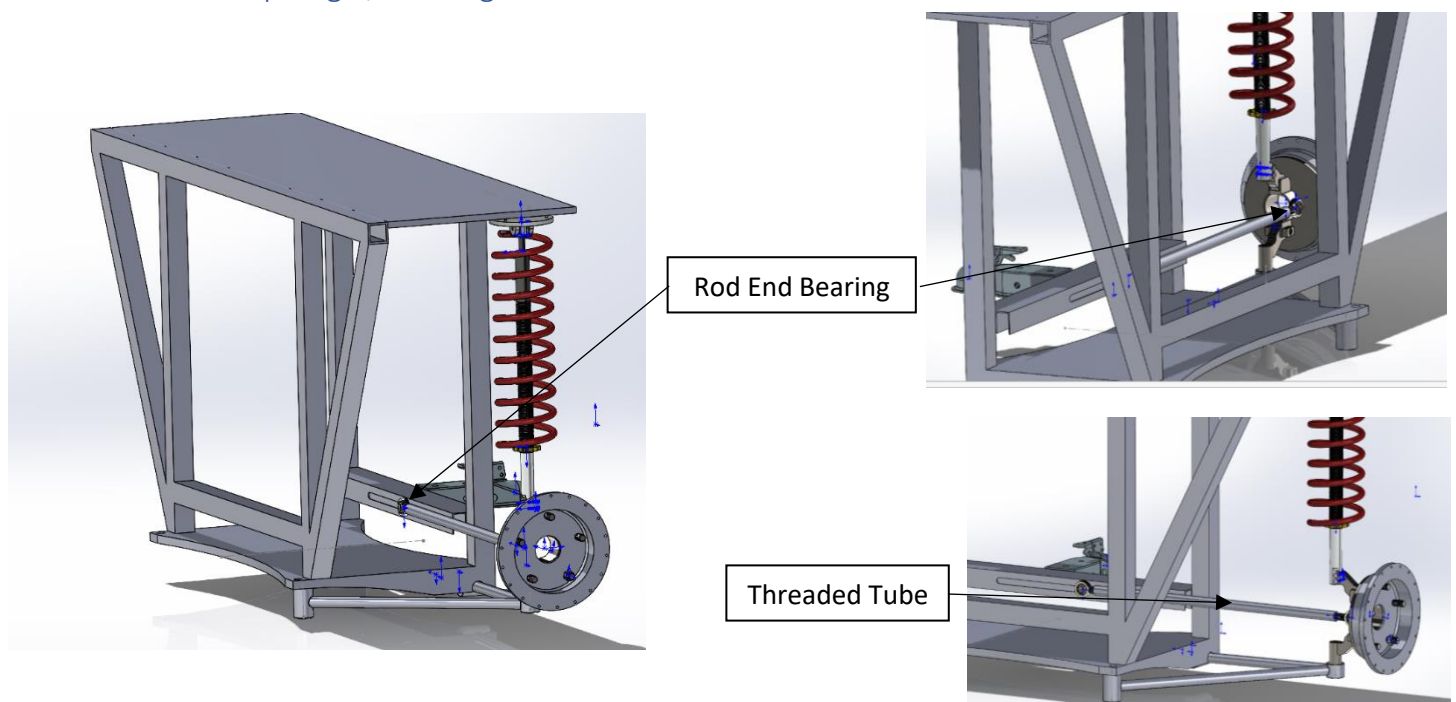


Figure 23: Slip Angle Adjustment Design

Figure 23 shows the design for a steering/ slip angle adjustment system to be used on the rig. The design involves a threaded tube and two rod ends either end. The rod ends are then mounted to the wheel hub at one end, and then to a slot which is welded to the front arm of the frame. This slot allows for large adjustment in slip angle to be made where the threaded tube and rod ends allow for finer movement. The slot is cut out of a piece of steel which will then be welded to the frame. The strength

of this material is not crucial since there will be no major loads applied to these components. The Figure above (figure 23) shows where the rod ends attach to the rig, and clearly allows for the same adjustment to be replicated on the other side.

### 3.5 Trailer Hitch Mounting

For the trailer to be pulled along, a trailer hitch system will be used. The hitch attachment point will be welded to the frame, where the hitch will then bolt to that point. This will then attach to the car and the rig. Similar to the specification of the wishbone material, the forces will be loaded through the frame, by dragging the wheel pointing in opposing directions, will be relatively high due to friction and therefore will need to be accounted in the design. Using the same equation and comparable data from the Avon Tyre data, we can work out the longitudinal forces produced by the tyre and therefore the force required to pull the rig along. This data can then be extrapolated to account for the larger slip angles that the testing rig is suitable for and therefore a trailer attachment can be specified which is rated higher than our calculations, providing an adequate safety factor.

When determining whether the trailer hitch can withstand the assumed maximum forces applied to the frame, it first needs to be considered what is the maximum force allowable load on the steel where the hitch mounts to. This can be done by assuming the box section as a free beam, pinned at both ends. A point load can then be applied to the beam which would represent the force applied to drag the frame along. The deflection value can then be calculated and the size of the tubing can be altered

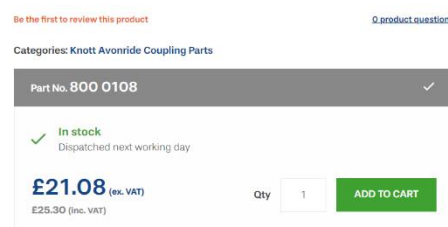


Figure 24: Potential trailer hitch (L&S Engineers, n.d.)

depending on if the deflection is great enough to permanently damage or cause the steel to fail. A trailer hitch can then be specified based on these calculations, along with the manufacture rating on the maximum load which the trailer can handle.

Figure 24 shows a potential trailer hitch that would be suitable. This is an unbraked hitch which lowers the cost and complexity, and the manufacturer has specified a maximum of 1400 kg of towed load. This works well for this use case as the maximum planned load would be around 1000 kg to allow for a wide variation in cars to be simulated in future.

### 3.6 Strain Gauges

Within material science strain is defined by the change in length/original length or rate of change of length. This is used to understand how a material will behave under load. However, strain can also be used within this project as the strain rate can be calculated, which can then be converted back into the force applied to the component. We know that stress ( $\sigma$ ) = Force (F)/Area(A) and  $\sigma = \text{Young's Modulus (E)} \times \text{strain } (\epsilon)$ . Therefore, by combining these two equations and measuring the strain of the material, we can understand the force applied to the component where  $F = E\epsilon \times A$  since strain is measured and E and A are properties of the component.

Strain gauges are placed on the frame at certain points to measure the load acting through the tyre as they create a force moving through the rig. Specifically, the strain gauges are mounted to each arm of the wishbone, which will then measure any slight deformation of the arms, which will be directly linked to the forces generated by the tyres at the specific slip angles. Within the strain gauge, a resistance is created which can then be converted into readable data using a control module.

There are various types of strain gauges depending on the direction of the strain that is measured. For example, the most basic is a linear strain gauge which only measures strain in one plane. However, the use of membrane rosette strain gauges allows for simultaneous measurements; rectangular rosettes measure at 0 and 90 degrees and 0, 45 and 90 degrees whilst delta rosettes measure at 60 and 120 degrees (ELPROCUS, 2023). This can go further to where strain gauges can be configured

within Wheatstone bridge circuits at configurations of quarter-bridge, half-bridge, and full-bridge (National Instruments, n.d.). A Wheatstone bridge works by balancing the output voltage from four connected resistors. Looking at Figure 25, within the bridge, two of the resistors have a known resistance ( $R_1$  and  $R_2$ ), the first is the variable resistor ( $R_3$ ) and the fourth is a strain gauge ( $R_4$ ) and when they are balanced, the output is 0V. Then when the material is loaded, the resistance in that material changes, which creates a non-zero voltage output. Therefore, the resistance of the variable resistor must be altered, and the amount that is changed is equivalent to the resistance of the material, and therefore the strain which is occurring on the component (National Instruments, n.d.). Equation 7 shows how the voltage output ( $V_o$ ) is calculated. In general, a Wheatstone bridge is used to amplify the voltage change produced by the strain gauges.

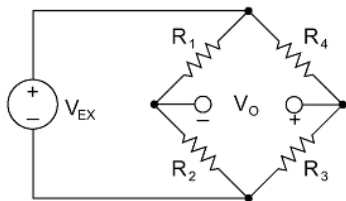


Figure 25: Strain gauge configuration within a Wheatstone bridge (National Instruments, n.d.)

Equation 7: Voltage Output of a Wheatstone Bridge (National Instruments, n.d.)

$$V_o = \left[ \frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] * V_{EX}$$

Within these bridge style strain-gauges the configuration is highly important depending on the application. The configuration is determined by the number of active resistors within the bridge and the orientation of the strain gauges. National instruments provide a helpful Table, comparing each of the configurations, found below:

Table 5: Comparison of Strain Gauge Configurations (National Instruments, n.d.)

| Measurement Type                  | Quarter Bridge |             | Half-Bridge |                | Full-Bridge    |                |                |
|-----------------------------------|----------------|-------------|-------------|----------------|----------------|----------------|----------------|
|                                   | Type I         | Type II     | Type I      | Type II        | Type I         | Type II        | Type III       |
| Axial Strain                      | Yes            | Yes         | Yes         | No             | No             | No             | Yes            |
| Bending Strain                    | Yes            | Yes         | Yes         | Yes            | Yes            | Yes            | No             |
| <b>Compensation</b>               |                |             |             |                |                |                |                |
| Transverse Sensitivity            | No             | No          | Yes         | No             | No             | Yes            | Yes            |
| Temperature                       | No             | Yes         | Yes         | Yes            | Yes            | Yes            | Yes            |
| <b>Sensitivity</b>                |                |             |             |                |                |                |                |
| Sensitivity at 1000 $\mu\epsilon$ | ~0.5 mV/V      | ~0.5 mV/V   | ~0.65 mV/V  | ~1.0 mV/V      | ~2.0 mV/V      | ~1.3 mV/V      | ~1.3 mV/V      |
| <b>Installation</b>               |                |             |             |                |                |                |                |
| Number of Bonded Gages            | 1              | 1*          | 2           | 2              | 4              | 4              | 4              |
| Mounting Location                 | Single Side    | Single Side | Single Side | Opposite Sides | Opposite Sides | Opposite Sides | Opposite Sides |
| Number of Wires                   | 2 or 3         | 3           | 3           | 3              | 4              | 4              | 4              |
| Bridge Completion Resistors       | 3              | 2           | 2           | 2              | 0              | 0              | 0              |

Looking at this Table, a Type 2 quarter bridge is suitable for this project, as bend and axial strain can be measured, whilst having a very fine sensitivity and only needing to bond one strain gauge to the component. The type of strain gauge must then match the expected strain produced by the wishbones, in order to accurately measure the strain. Once this has been selected, the signal is amplified by a Wheatstone bridge amplifier, which is then sent to the data acquisition equipment to record the strain produced. The most cost-effective way to collect this data is to utilise the facilities within the University. With this in mind, linear strain gauges such as the “Micro-Measurements Strain Gauge,  $\pm 3\%$  Range,  $350\Omega$ ” can be used on each leg of the wishbone arms (RS: Strain Gauge, n.d.) as seen in Appendix C – Figure 34. These strain gauges come with pre-attached wires and a gauge resistance of 350 ohms. An amplifier made by Leo Bodnar Electronics can then be used which will create a signal suitable for data acquisition equipment to read (Leo Bodnar Electronics, n.d.). This amplifier has two input terminals to connect the strain gauge. An output signal between 0 and 4.9v will be produced and can be seen in Appendix C – Figure 35. This signal will then be sent to a MoTeC device which can read and convert the signal into usable data. By creating a channel in MoTeC device, we can then manually define how the voltage read relates to the amount of strain being produced, which will then create a strain versus slip angle plot which can then be converted to force versus slip angle. For example, if the strain gauge at rest outputs 4.9V, then the MoTeC understands this as zero strain. Then if the voltage changes to 4.3V, the MoTeC will then see that and plot a change in the strain. However, the user will have to fine tune this and manually calibrate how voltage relates to strain. One negative to this amplifier is that it can only take in one signal at a time, meaning that during testing we would need to use multiple to allow for several sensors to be used at a time.

Within the design of this project, there has also been flexibility considered to allow for a varying range of sensors to be used. For example, the wishbones would allow for the use of a Force Transducer and an example of this would be the ‘RS PRO Load Cell’ found at RS Online (RS Pro, n.d.). This can be seen in Appendix C – Figure 37 and would fit in between the arms of the wishbone, measuring strain using compression and tension forces. Each end of the transducer has a threaded hole, this could then easily

connect to the wishbones using a matching threaded insert in the arms, a threaded rod and locking nuts to secure it in place. There are positives and negatives to this method, such as this would measure the force directly acting through the wishbone and would not rely on how the material is affected by these forces. However, this comes with a significant price increase of around £265.16 for a 500 kg rated sensor per unit compared to £21.212 per unit of the 350 ohm strain gauge. With such a high price increase, it would be difficult to justify the use of these Force Transducers in this application, however it is still important to consider alternative equipment.

### 3.7 Load Cells

As the frame is pulled along to measure the lateral forces acting through the tyre, a longitudinal force is generated due to the friction and rolling resistance of the tyres. This needs to be measured and can be done by using a load cell. Load cells can be found in many different configurations and it is important to understand the differences to specify the most appropriate one for this research.

There are four key types, such as:

- Strain gauge Load Cells
- Piezoelectric Load Cells
- Hydraulic Load Cells
- Capacitive Load Cells

Tension and compression load cells are commonly designed as strain gauge load cells, meaning that they also work on the principle that a change in load causes the strain gauge to deform which therefore changes the output voltage. However, these are produced as complete units where a strain gauge is bonded to a beam which deforms under load, creating the change in voltage (Omega, n.d.). Therefore, the same data acquisition method can be used, increasing the simplicity of the rig design. However, there are alternative load cells, such as a Piezoelectric load cell, this uses Piezoelectric crystal which deforms when a strain is applied. This compression then creates an output voltage which can be read as applied load. Piezoelectric load cells can provide a high output impedance and some natural

filtration, which could be positive when compared to strain gauge based load cells (CADENCE PCB SOLUTIONS, 2020). Similarly, hydraulic load cells are another option, where loads are applied which then act on a piston. This piston is sat on top of a diaphragm, above a fluid filled chamber, therefore as a load is applied the piston moves down, increasing the pressure in the chamber. This creates a load cell with no electrical components, meaning that it can be used in harsher environments (Tacuna Systems , 2023). However, this type of load cells only performs well in compression applications, therefore making it a poor choice in this project where the forces produced will be in tension. Capacitive load cells are also a common version with applications in both compression and tension. The working principle is around the ability of a material to store a charge. Two parallel plates are held in place, with a small gap between. An electric current is then applied, making one side positively charged and the other side negatively charged. As the plates move closer, a stored charge is created which then creates an output voltage, equating to applied load. The benefits of these load cells include high sensitivity meaning a wide range of forces can be measured and a simple design making the load cells more cost effective (Tacuna Systems , 2023).

Overall, when comparing these different types of load cells, the simplest option would be to use a strain based load cell, as this can be easily installed on the rig, and use the same acquisition process as the strain gauges on the wishbones. A load cell such as the WIKA F3201, shown in Appendix C – Figure 38 would be suitable for our application as this allows for a range up to 1000 kg in compression and tension. Looking at the dimensions and mounting points this could easily fit between the trailer hitch and main frame of the rig, and at around £190, this is reasonably priced (RS Online, n.d.).

### 3.8 Data Acquisition

The strain gauges, load cells and Wheatstone bridge amplifiers will create the signal, however this signal needs to be processed so that it can be understood, and force or strain data compared to a simple voltage difference. Within the University, there is a strong Motorsport Department meaning that there is more access and knowledge surrounding the data loggers used. An example of this is

MoTeC (Appendix C – Figure 36). This is used in a number of their cars, including the Sports 2000 MCR race cars. MoTeC offers a wide range in sensors, such as temperature, speed, steering, throttle and braking. Channels are then created within the software, which then converts the input signal from any one of these sensors and converts it into readable data. This can then be used within this project, as the voltage change from the strain gauges and load cells can be read. We can then set up a channel within the software which can specify how the voltage equates to strain or load.

This can then be simply plotted as strain versus time within the MoTeC, but once multiple runs are completed and strain is converted to load, these results can then be exported as a CSV file to MATLAB or Excel and then compiled and converted into a lateral force versus slip angle curve.

However, we must also consider the possibility that during the data acquisition phase, that there is no access to a MoTeC system, and therefore would need to look at other options. Data loggers can be bought at various different price points depending on the features, ease of use and flexibility to use other sensors or multiple sensors at a time. For example, the OM-CP-BRIDGE101A Strain Gauge Data Logger from Omega which can be seen in Appendix C- Figure 39 and can be sourced for around £470 at the time of writing (Omega, n.d.). This is a stand alone system, which is battery powered and can measure and record voltage signals from strain gauges and strain based load cells. The recordings can then be transferred to a PC using a USB memory stick and then analysed using the accompanying windows software. This is a small system with a logging rate of 4Hz and offers a simple and cost-effective method for data acquisition. However, this also comes with limitations such as the ability to only record one sensor at a time meaning one test will need to be run at once or the need to use multiple loggers at a time. Looking at a more expensive and premium option, the KeySight DAQ970A Data Acquisition System offers a complete package with built-in Wheatstone bridge amplifier, the use of quarter, half and full bridge is then configured by the user (shown in Appendix C – Figure 40). Strain calculations are built into the system, where the user only needs to input the sensing type (quarter, half or full bridge), the gauge factor and the excitation voltage. Nine control plugs in modules can be

used along with four channel simultaneous sampling, compared to the Omega system which is limited to one. However, the clear limiting factor for the use of this data logger is the price, at around £1970 at the time of writing (KEYSIGHT, n.d.). Overall, it is clear that if there is an option to use a MoTeC system owned by the University, then this would be the most cost effective and simplest solution, with the need to source the Wheatstone amplifier suggested above. However, if this is not an option then the Omega Data Logger will be adequate for the project, especially if two or more could be acquired.

After the data has been processed by the amplifier and recorded, it needs to be filtered to remove any noise which will distort the data, creating a smoother and clearer data curve. Typically a Butterworth filter is used, which can create the flattest frequency responses over a pass band region (Yadav, Yadav, & Mouli, 2022). When filtering the data, different passes such as low or high passes can be done to filter out certain frequencies, and the quickest way to achieve this is by using the MATLAB Signal Processing Toolbox (MathWorks, n.d.).

Once the data has been amplified, filtered and recorded, the wishbone forces need to be converted to lateral forces. This can be done in MATLAB or Excel, using the Equations 4, 5 and 6. Equations 4 and 5 can be rearranged to calculate TB, and then using Equation 6, we can calculate the force ( $F_b$ ) since we know the slip angle that the data has been collected at. This will then produce lateral force graphs for certain slip angles, where the peaks of each test can be compiled to produce a lateral force versus slip angle sweep curve, replicating the data produced by Avon Tyres.

## 4. Results

### 4.1 Finite Element Analysis

Finite Element Analysis (FEA) can be used to understand how a component will react when certain loads and forces are applied. During this project, all the components were designed within SolidWorks, which also has an FEA study option. This can then be used on my components. In general, FEA will break down a component into thousands of smaller chunks (finite elements), and then use mathematical equations to determine how those elements will behave depending on the parameters set which are then totalled to predict how the overall component will behave (Autodesk, n.d.). FEA for buckling can then be run as a linear or a non-linear study where essentially a linear analysis provides quantitative results, compared to a non-linear analysis, which provides detailed understanding of the displacements and stresses (Kurowski & Kurowski, 2011).

For these simulations, a material must be defined, from the selection within SolidWorks the AISI 1015 Cold Drawn steel was the most complete match, with similar elastic modulus and tensile strength values of 205GPa and 625MPa. Similarly, to create an accurate representation of the buckling within the tubes, the fixed geometry points need to be carefully selected. For these simulations, the tubes have been fixed at the ends where the rose joints fit which are the mounting points for the wishbone to the subframe. Therefore, movement of the wishbone can occur. However, using this method, we can accurately determine the force which the tubes can withstand before buckling, which is similar to the calculations run previously, allowing for accurate validation of both the calculations, the geometry and composition. Similarly, in these simulations, the outer bushing has not been restrained, meaning that the simulation is more representative with the theoretical calculations. However, it should be

noted that there will be some restraint in that direction due to the force applied by the struts and the vertical load, which would prevent the arm from buckling upwards as seen in Figure 26.

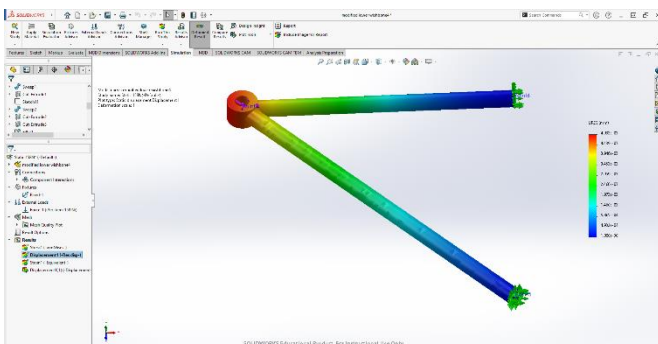


Figure 26: 158N Along Lower Arm (static)

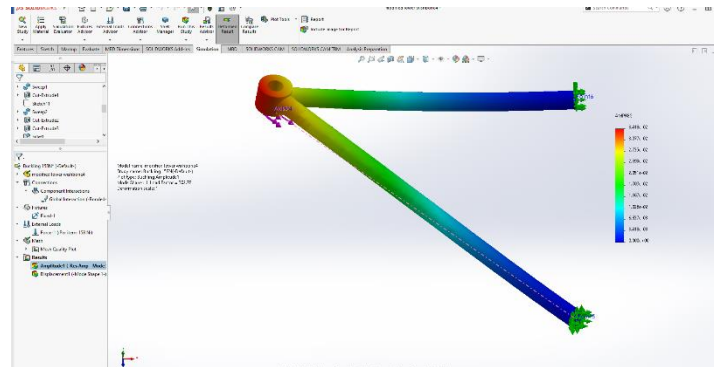


Figure 27: 158N Along Lower Arm (buckling)

Looking at Figures 26 and 27, these show FEA simulations produced within SolidWorks on the wishbone component. Based on the calculations from the Avon tyre data, a load of 158N would be loaded through these wishbones if we used the same testing parameters, and therefore this is the baseline for the design of new components. Within these FEA simulations, 158N was first loaded through the lower arm, with the force applied from the inner of the outer bushing, which is where the wheel hub would mount and therefore where the forces would be applied.

Figure 26 shows a static simulation, where the displacement which occurs. This simulation suggests that most of the displacement will occur around the outer bushing, however with limited deformation throughout the lower arm. However, when looking at the scale, the maximum displacement, shown in red is around 0.0045 mm and therefore suggesting that there will be no displacement on the physical component. Comparing this to the buckling load (Figure 27) of the same component with the same parameters, a displacement of amplitude can be seen, known as AMPRES. This is an arbitrary unit of resultant relative vibrational amplitude, meaning this shows the relative vibration for the different components of the part (Ningfeng & John, 2021). Very limited buckling can be seen, with the major point being outer bushing where the forces are loaded through.

This buckling study also calculates the minimum load required to cause buckling, known as a 'Load Factor', which has been calculated as 302. There  $302 \times 158\text{N}$  will be the required applied force to buckle this component in that direction, which equals 47716N. Comparing this to the theoretical

calculations, which has been calculated to take 57395N show that there is a clear difference of around 20% between the FEA and theoretical calculations. There are multiple reasons that could cause the discrepancy between the hand calculations and FEA studies. For example, the hand calculations are a simplified version of the problem where stresses are only calculated at certain points, compared to FEA where the stresses throughout the whole structure are considered (FEA Solutions, 2021). Similarly, the material properties used will not be identical, as for the hand calculations, the Young's Modulus is the only property considered. However, for the FEA, an entire Table of properties is used to understand the performance. Therefore, it would be reasonable to assume that the FEA simulations produce the more accurate results and should be followed when testing future tyre combinations.

However, by taking the worst case scenario of 47716N, this still provides a safety factor of 302. Initially, this number seems drastically too large and out of proportion. However, it must be considered that the tubing used was a standard size which must fit other components such as the outer bushing, threaded inserts and rose joints, and therefore shows that the design was dictated by geometry and not safety factors. Static simulations can also show the strain and stress forces which act on the component and these results can be seen in the Appendix E.

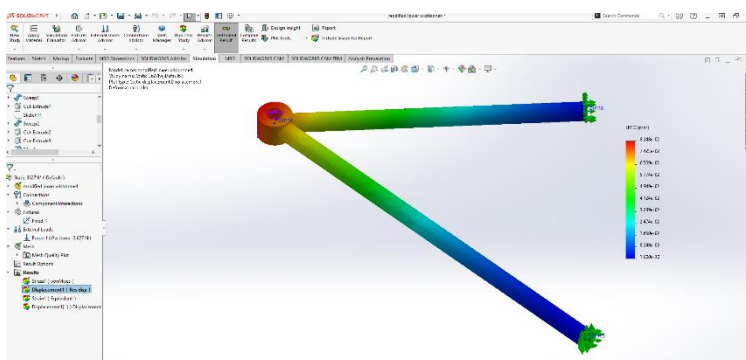


Figure 28: 3627N Upper Arm (static):

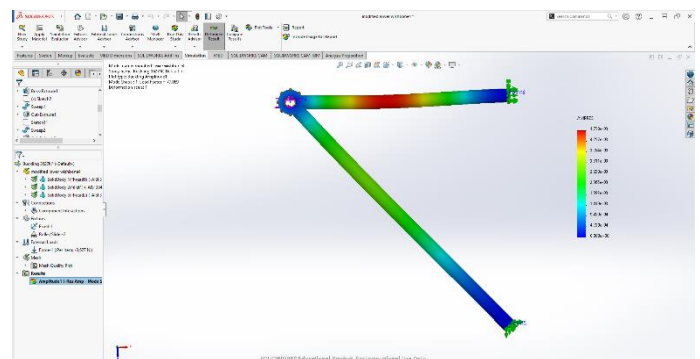


Figure 29: 3627N Upper Arm, (buckling)

Similarly, Figures 28 and 29 show the FEA simulations done on the upper arm of the wishbone. A load of 3627N has been calculated from data supplied by Avon Tyre. Figure 28 shows a static simulation, and Figure 29 shows a buckling simulation. Looking at Figure 28, it is very similar to Figure 26, where

the majority of the deformation occurs near outer bushing and then equally spread down both the arms. The displacement that occurs is around 0.075 mm, greater than in Figure 26, but still negligible. Figure 29 then shows the buckling along the upper arm, where failure would occur within the middle of that tube, buckling upwards, indicated by the red area. However, again this is a small amplitude and a load factor of 84 has been calculated by SolidWorks, meaning that 304kN would need to be applied in that direction to buckle the material.

Figure 30 shows an FEA of the combined loads, which suggests that this component has a safety factor of 11.813. This appears more realistic than the lower arm safety factor, suggesting that the material and geometry chosen matches the specification, along with providing overhead for when greater loads are applied in future testing.

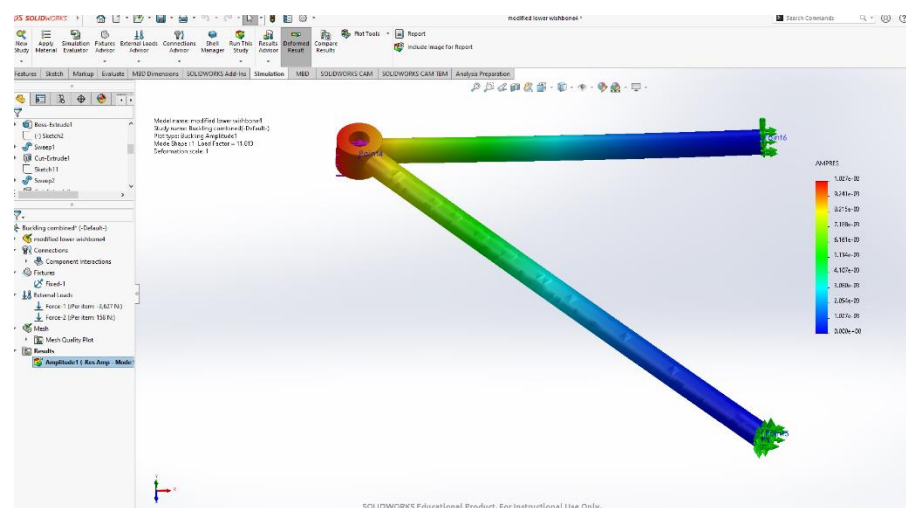


Figure 30: Combined Load

Figure 31 shows an FEA analysis run on the designed subframe and frame assembly. A force of 1000N has been applied to the frame whilst using the bottom surface of the subframe as a fixed location, which allows the full 1000N to be applied through that trailer mounting point. This has been done to simulate the towing forces required, mainly caused by the friction generated from the tyres when they are pointing at the certain slip angles inwards. As expected the simulation shows that all the displacement concentrates around the trailer hitch mounting location. However when looking at the scale, it is clear that this displacement is negligible with the largest measuring around 0.054 mm.

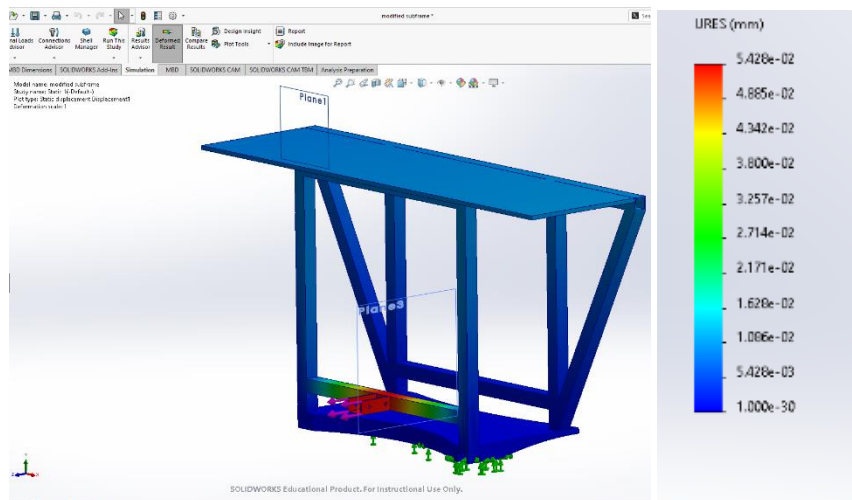


Figure 32: FEA Analysis of Trailer Mounting Point (1000N)

## 4.2 Full Assembly

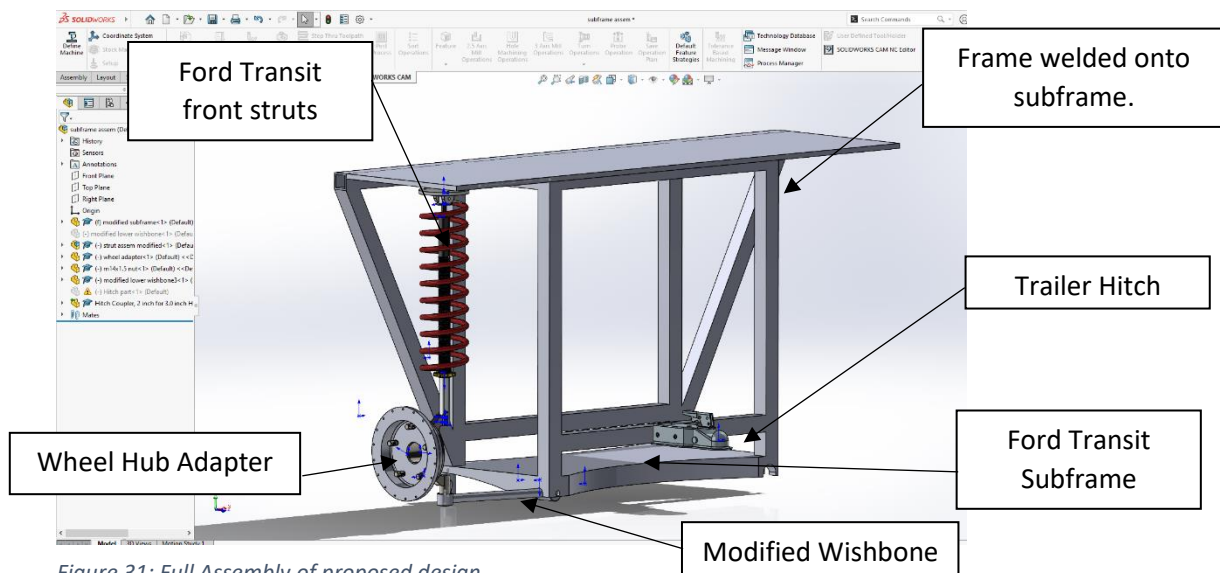


Figure 31: Full Assembly of proposed design

Figure 32 shows the full assembly of the proposed design. The subframe has been simplified as the specific geometry is not crucial, however the mounting points for the wishbone have been carefully measured and drawn. Looking at the drawing, the MacPherson strut and trailer hitch have been taken from GrabCAD; a popular website where individuals upload and share their drawings for public use, referenced as (Bisht, 2019) and (Hodder, 2018) respectively. The design clearly shows there are options on where the load cell could fit. Firstly, they can be mounted before the trailer hitch mounting point, meaning the longitudinal forces will act through that point. However, it would mean that some vertical support would be needed, potentially a plate which the hitch can rest on, without impeding on the longitudinal forces measured. Alternatively, the load cell could be mounted after the trailer

hitch, before the attachment point on the towing vehicle, by using a custom tow bar with the load cell mounted along that. An FEA simulation was done on the current design, where 4900N was loaded through the front struts. This roughly equates to 500 kg of force, and therefore simulating if 1000 kg was loaded through the centre of the subframe, which has been calculated to displace the plate at around 4.3 mm at each point. Therefore, it should be noted that this presents a point of flex, which could be mitigated with the use of an I-Beam of box section steel running across the top of the frame and improving rigidity.

### 4.3 Design Specifications

Looking at the SolidWorks FEA simulations that have been run, the original design requirements have been met as the wishbones with the combined load have a safety factor of around 12, meaning that 12 times this applied load can be applied before failure. Then when looking at the subframe assembly, very little deformation can be seen at an applied load of 1000N, meaning that this rig is suitable for higher loads, which may come when testing tyres with more grip or at greater slip angles. The original specification of the test rig was designed to match and validate tyre test data provided by Avon Tyres. The results of the testing have demonstrated that this specification has been met, as the test rig was able to withstand all the expected forces without failure.

#### 4.4 Final specifications

Figure 33 shows the final assembly of the wheel adapter and wishbone, mounted on the original subframe. Due to time constraints of the project, it was not possible to create the frame, as designed and shown in Figure 32. However, it is clear where the frame will be welded to the subframe, and how the MacPherson struts will mount to the top plate. It is also clear where strain gauges or load cells can be mounted on the wishbone arm. Whilst the main frame has not been constructed, this project has shown a clear proof of concept in the wishbone, wheel adapter and frame design, allowing for future work to begin exactly where this project has finished.

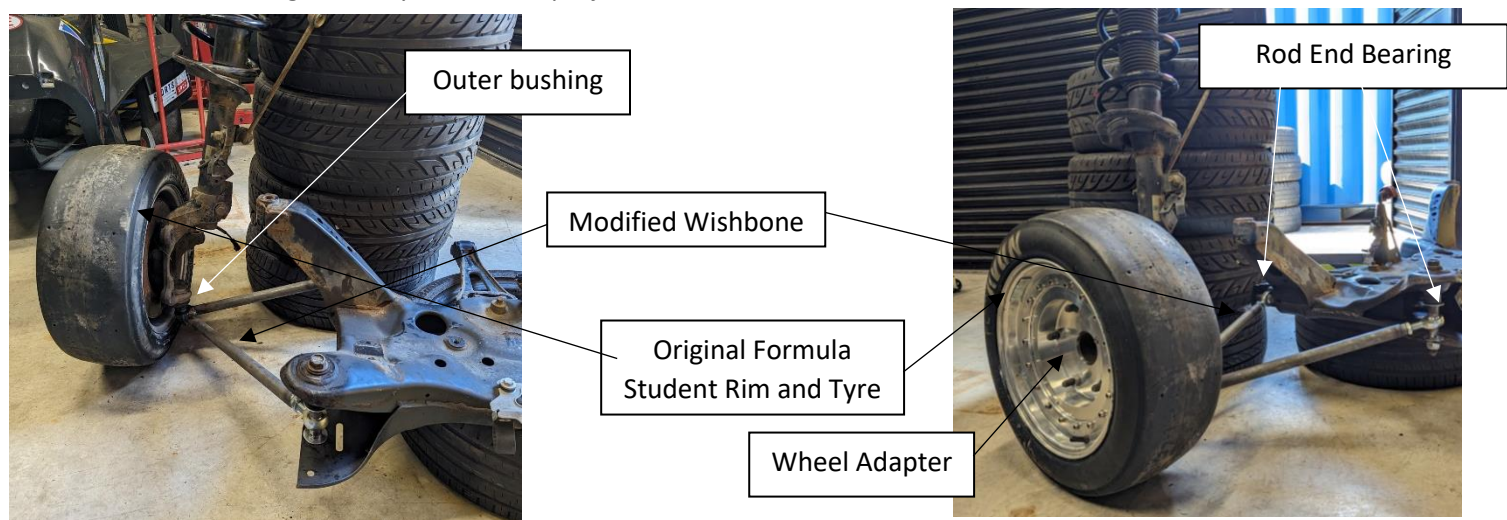


Figure 33: Final Assembly of wheel and wishbone on original subframe

Throughout the design process, several iterations were undertaken before finalising in preparation in for the manufacturing phase. The initial design phase involved the creation of a wheel adapter, initially conceived as a solid piece of aluminium. However, upon further analysis, it became clear that the design could be improved by hollowing the adapter's centre. This alteration served the dual purpose of reducing both material usage and mass, however at the expense of increased machining time. Utilising SolidWorks assembly modelling proved important in visualising the component integration and ensuring proper fitment. For instance, the assembly highlighted a critical issue during the second design iteration concerning the clearance for the socket required for securing the wheel nuts. As a result a revision was made during the subsequent third and final design iteration to rectify this constraint, thereby improving on the overall design's compatibility. Likewise, during the design phase

of the wishbone component, the initial approach involved using fixed bushings for the mounting points at the subframe. However, a thorough evaluation revealed that this approach had a major issue, as it would impede the range of motion required for the wishbone's functionality. Subsequently, adjustments were made to ensure the proper operation of this crucial component. Similarly, modifications were considered for the outer mounting point of the wheel hub, initially designed with reduced material usage in mind. During the assembly, it became clear that this design decision created limitations, particularly concerning the available surface area for securely welding the arms in place. Consequently, refinements were implemented to address these constraints and to ensure the structural integrity of the assembly.

## 5. Discussion

### 5.1 Effectiveness of research

The outcomes of the design project included several key achievements that will significantly contribute to our understanding in the field of tyre dynamics. Firstly, the major achievement was the successful design and development of a cost-effective tyre test rig, specifically engineered to accommodate a diverse range of tyre choices and setups. In addition, a wheel adapter was designed to allow a Formula Student wheel and tyre to fit onto the Ford Transit hub. This was the first phase of the design as the project is initially based around the use of the Formula Student tyres. Furthermore, the project involved the fabrication of two wishbones designed to fit onto the Ford Transit subframe. The specification of components such as strain gauges, load cells and data acquisition systems were outlined and we provided examples of this equipment. Furthermore, we developed a comprehensive data analysis program that outlines the procedures for data collection, processing and the subsequent utilisation of this data for future tyre research. Ultimately, this project has designed the foundations for a more cost-effective and comprehensive tyre testing rig, where the lateral forces can be understood for a wide range of tyre and vehicle combinations.

When comparing the design in this project to previous tyre testing projects and designs, there is not many which are available to directly compare to this research. The closest match would be the lateral and longitudinal study on ATV tyres across off-road surfaces, conducted by (McIntyre, 2015). This project used strain gauges and load cells in a similar manner to our project and produced lateral forces versus slip angle graphs to use in validation of computer produced tire models. Key differences would be the tyre choice, surface choice and motorising the wheels. An image of the complete rig can be seen in Appendix F. Similarly, a study has been conducted which does analyse road tyres, however this design was made to fit on a rolling road, rather than to be towed. This project also collected lateral force versus slip angle data, however this was used to create a finite element model of a tyre. This was

taken from (Korunović\*, Trajanović, Stojković, Mišić, & Milovanović, 2011) and can be seen in Figure 10.

Several challenges and issues were encountered throughout this research project. Firstly, the University's procedure for processing and ordering of essential materials resulted in time delays. For instance, the approval of the aluminium for the wheel hub took longer than expected, causing the machining of the wheel hub to have scheduling conflicts at CBM, as their workload was already occupied with prior commitments and delayed this process. Additionally, the scheduling conflicts of staff members furthered these delays in ordering of the materials and subsequent fabrication of the wishbones. These issues caused delays during the entire project that ultimately hindered the completion of the entire build and sensor calibration.

Several factors have been identified that can potentially impact the accuracy of the tyre testing results. Firstly, it is unlikely that tyres will reach their peak operating temperature during testing, a condition particularly relevant for motorsport tyres. To mitigate this issue, the use of tyre warmers before testing has been considered as a possible solution. Another consideration related to the forces measured during testing, which are transmitted through the subframe and wishbone, rather than being directly applied to the tyre itself. This complicates the assessment of whether all tyre forces have been accurately captured. Furthermore, the accuracy of results is determined on the quality of the road surface used for testing. In the case of motorsport tyres, which generally operate on smooth tarmac, therefore finding suitable public roads can be challenging. Ideally, a dedicated race track would be the most representative surface; however, this option creates significant expenses in terms of private track rental. Lastly, the sensors used in data acquisition systems may generate substantial noise due to the minimal voltages produced. To address this issue, certain data acquisition systems, such as the Keysight model, offer automated data filtering capabilities to enhance the accuracy of data analysis.

## 5.2 Next steps

In the context of future research, several recommendations emerge from this project. Firstly, the project should continue the collection of tyre data of Avon Formula Student Tyres utilising the testing rig established in this research. This data can be subsequently compared with existing data from Avon Tyres, offering a basis for comprehensive validation. Furthermore, the acquired tyre data can be integrated into the MATLAB Magic Formula Tyre Tool, generating a comparison of the results to a simulated tyre model. To expand the scope of the research, it is recommended to conduct similar data collection exercises for different tyre types, potentially including the University of Wales Trinity Saint David MCR Sports 2000 tyres. The data from these additional tyres can also be incorporated into the MATLAB tool to create tyre models. Ultimately, these models can be applied in future vehicle dynamic projects conducted within the University, enabling further and more accurate research within this field, as one of the main limitations of current vehicle dynamic projects is due to the tyre model which is being used, especially when looking at projects surrounding the Sports 2000 MCR Race Car.

## 6. Conclusion

Overall, it is clear that this project has successfully designed a system for testing the lateral forces produced by automotive tyres at certain slip angles. As proposed, this equipment provided a more cost effective method, with the major costs coming from the aluminium material and machining process. As this was a University based project, this did reduce the initial outlay for the components, such as the Formula Student wheels and tyres and the Ford Transit subframe and front strut assembly. By the end of this project, a clear design and testing procedure has been outlined, therefore making an ideal project for another University student to take on, whether as an Undergraduate or Master's dissertation. With the manufacturing of the wishbone and wheel adapters complete, the next step would be to fabricate and manufacture the main frame then test and validate the strain gauges and load cells. Once these are working correctly, data from the Formula Student tyres can be collected, which can then be validated again using the Avon Tyres or FSAE TTC data. Once this data has been validated, we know that the test rig is performing as expected, which means that we can then begin to create new tyre models, on tyres with little accessible data such as the Yokohama tyres used on the Sports 2000 MCR race car.

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## 8. Appendix

### 8.1 Appendix A – Wheel Adapter

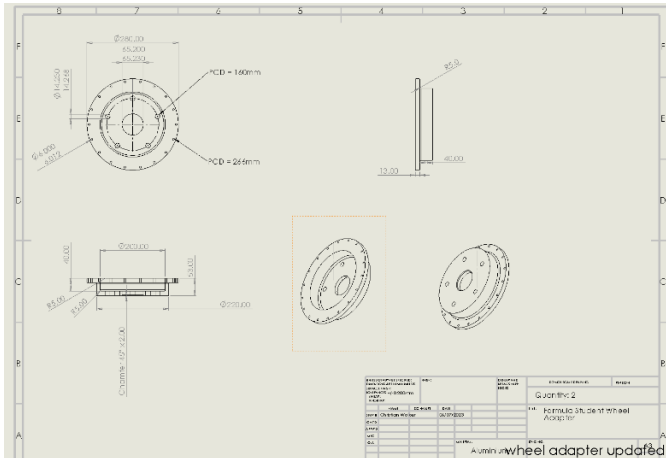


Figure 34: Mechanical Drawing of Adapter, used by the Machinists at CBM

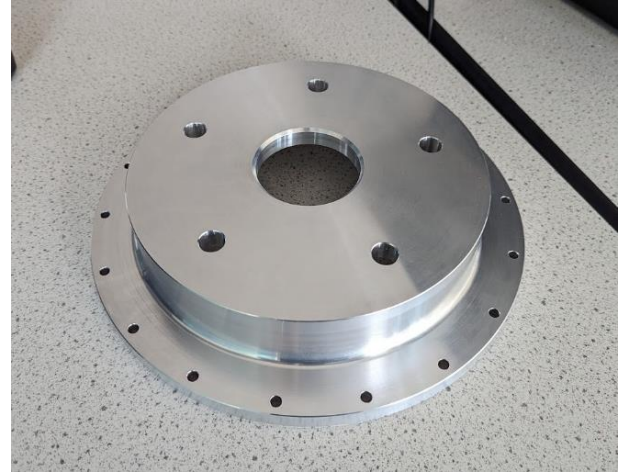


Figure 35: Completed Wheel Adapter

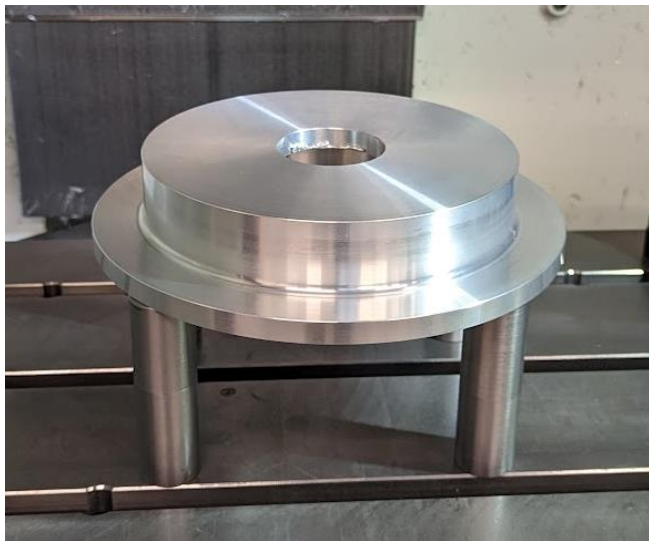


Figure 36: Wheel Adapter positioned for Milling.



Figure 37: Wheel Adapter Fitted to Rim

## 8.2 Appendix B – Wishbone

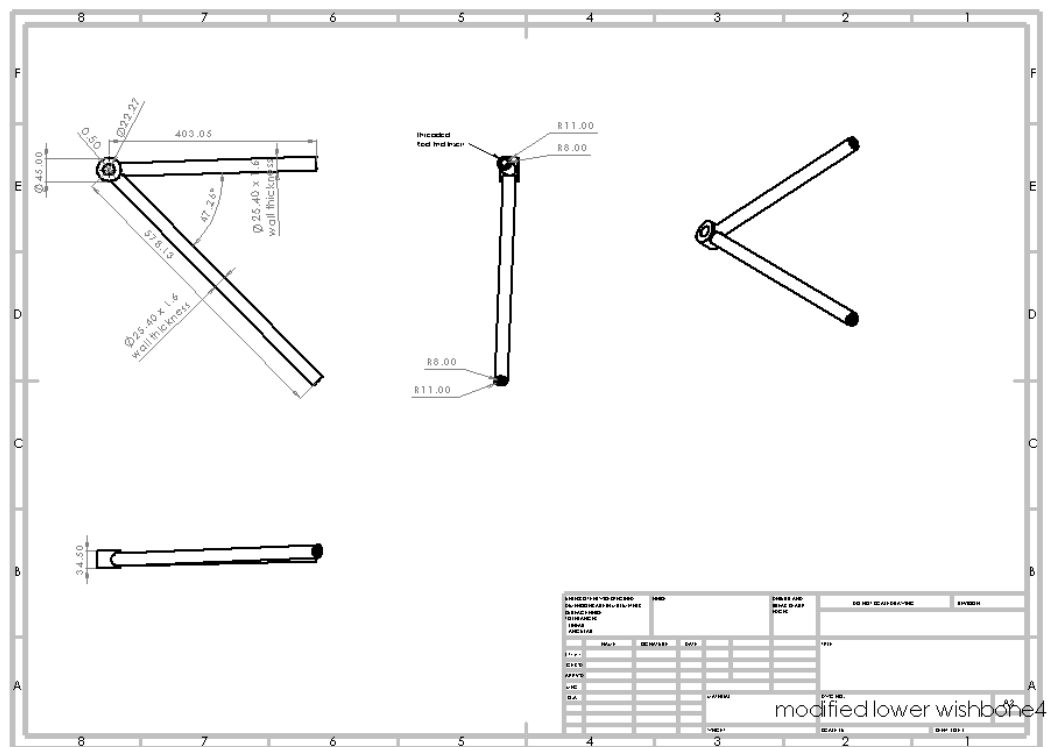


Figure 38: Mechanical Drawing of Wishbone used for Manufacturing.



*Figure 39: Completed Wishbone*

## 8.3 Appendix C – Strain Gauges and DAQ's

### Micro-Measurements Strain Gauge, $\pm 3\%$ Range, 350 $\Omega$

RS Stock No.: 223-6470 | Mfr. Part No.: MMF404144 | Brand: Micro-Measurements



Figure 41: Suggested Strain Gauge (RS: Strain Gauge, n.d.)

### Standalone Load Cell Amplifier



Figure 40: Suggested Amplifier (Leo Bodnar Electronics, n.d.)



Figure 45: MoTeC Data Logger (C185) (Race Data Systems, n.d.)

### RS PRO Load Cell, 500kg Range, Compression Measure

RS Stock No.: 204-2764 | Brand: RS PRO



Figure 44: Alternative Sensor for Wishbone (RS Pro, n.d.)

### WIKA F3201 Series Strain Gauge, 1000kg Range, Compression, Tension Measure

RS Stock No.: 268-9025 | Mfr. Part No.: 79102839 | Brand: WIKA

☐ Add to compare



Available to back order  
delivery within 1 working

1 Units

FREE delivery for on

Not available for guaranteed

Price Each  
£190.04  
(exc. VAT)

Figure 43: Suggested Load Cell (RS Online, n.d.)

OM-CP-BRIDGE101A

Currency:



load cell data logger



£470.69 OM-CP-BRIDGE101A-30MV

PLACE ORDER



- Strain gauge data logger with multiple Start/Stop Function
- Ultra High Speed Download
- 1 Million Reading Storage Capacity
- Memory Wrap
- Battery Life Indicator
- Optional Password Protection
- Field Upgradeable

Data Loggers - View related products

Figure 42: Cost Effective Data Logger (Omega, n.d.)



Figure 46: Expensive Alternative Data Logger (KEYSIGHT, n.d.)

#### 8.4 Appendix D – Final Rig



Figure 47: Images of Completed Assembly

## 8.5 Appendix E – SolidWorks FEA Results

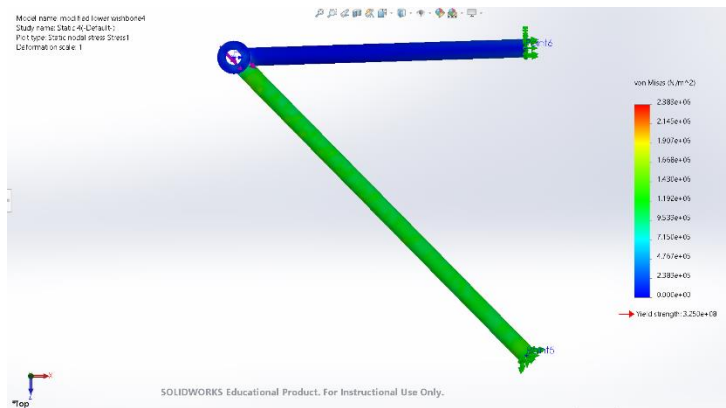


Figure 48: Upper Arm Stress Analysis

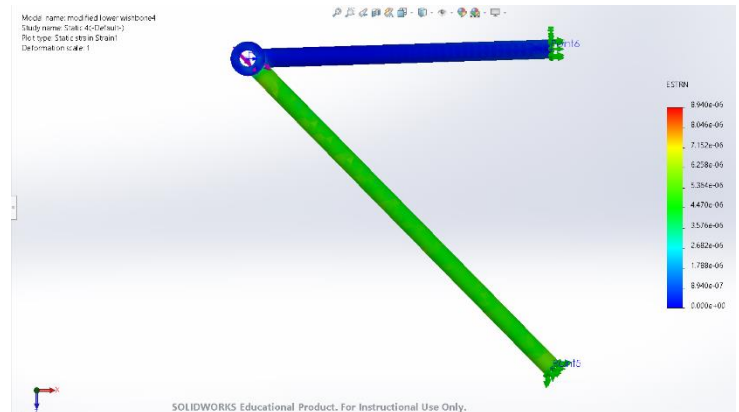


Figure 49: Upper Arm Strain Analysis

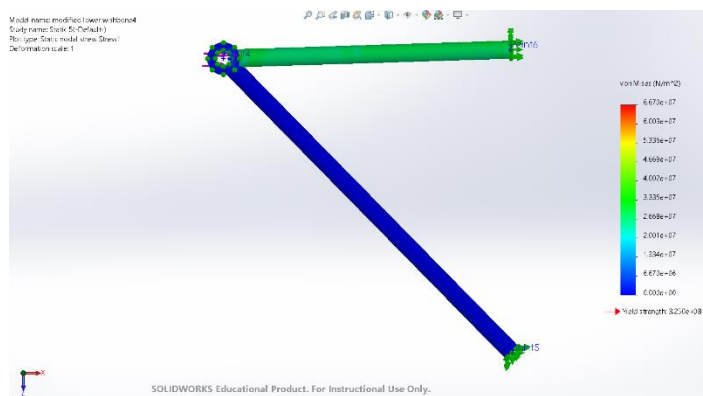


Figure 50: Lower Arm Stress Analysis

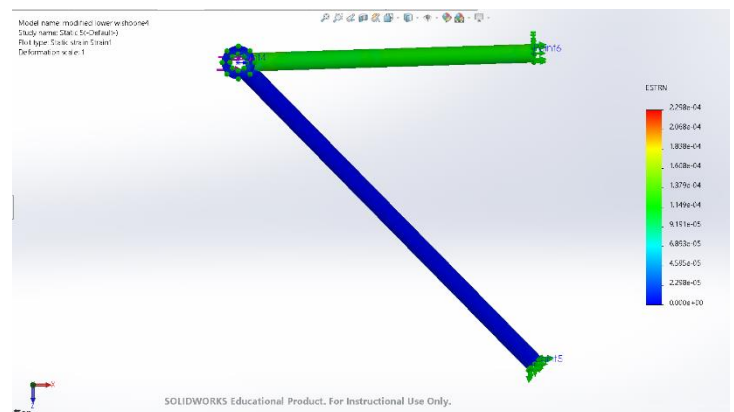


Figure 51: Lower Arm Strain Analysis

## 8.6 Appendix F – Previous Tyre Testing Designs



Figure 52: Imaged taken for a Tyre Testing Rig from (McIntyre, 2015)