Design of a Tire Test Rig

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The design and operation of a racing vehicle requires a thorough understanding of how the vehicle interacts with its operating environment. Tires are the only point of contact between the vehicle and the ground, this means that tires characteristics determine the forces and moments that can be exerted upon a vehicle. There is currently a lack of relevant tire data available to many Formula SAE teams with commercially available data being very expensive to obtain. The aim of this project was the design of a small, mobile and inexpensive testing machine that will allow Formula SAE teams to obtain relevant tire data.

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Nomenclature

\( S \) = longitudinal slip ratio

\( R_{\text{g}} \) = tires geometric and unloaded radius [m]

\( \omega_{\text{w}} \) = tires angular velocity [rad/s]

\( V_{\text{f}} \) = tires forward velocity [m/s]

\( \alpha \) = slip angle [deg]

\( \delta \) = steering angle [deg]

\( \theta_{\text{w}} \) = velocity angle of wheel [deg]

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I. Introduction

The design of any motor vehicle requires an understanding of the maximum forces that can be transmitted to the ground to determine the vehicles handling characteristics and also the safety of the vehicle [1 and 2]. For race cars the transmissions of forces and moments through the tires is one of the key factors in determining if the vehicle is safe to drive and if it is to be competitive [3 and 4]. This requires an understanding of the characteristics of the tires being used, which is gained through tire data.

When designing and testing any vehicle an accurate understanding of the loads exerted on the road is important. This understanding is gained through tire data and is used when analysing initial designs for loading and suspension characteristics [5 and 6]. If tire data is not used in the design of a vehicle, various components, such as the suspension, may be over engineered and have excessive weight making the vehicle to heavy to be competitive. The other likely scenario is the components are not strong enough and will fail during use. This endangers the lives of the driver, other competitors and spectators as well as having a large financial cost to the race team.

Tire data is also used to analyse the effect of changing parameters such as tire pressure, camber angle, normal force, etc. will have on the forces that the tire can generate. When trying to setup a race car to be competitive it is important to have accurate information about the tires characteristics, as it allows for quick and precise tuning. If tire data is not available, the driver must be relied upon to give their opinion of how the changes have affected the handling and a wide range of changes will need to be tested. This requires the driver to be highly skilled and able to repetitively drive at the same standard. Drivers with this level of skill are not common amongst Formula SAE teams.

Due to the importance of tire data in the design and operation of race car, it is vital that a race team that wishes to be competitive is able to obtain tire data continualy throughout their operation [7]. Due to the costs and limitations of tire data obtained commercially, it is vital that the Formula SAE team at ADFA have a means to generate tire data. This will allow for innovation in vehicle design as well as being competitive without having to conduct changes in vehicle design and setup through trial and error.

A. Aims

The aim of this project was to design a mobile tire test rig for the Formula SAE team at the Academy. The need for tire data would have to be established as well as the scope of the data needed. Through correspondence with team members at the start of the year it was clearly evident that they had a desire for tire data. In consultation with the team, namely Lorin Coutts-Smith, and the project supervisor, Mr Alan Fien, the initial aims of the design were developed. These aims are that the device:

- Measure longitudinal slip under both driving and braking conditions and the resulting longitudinal force
- Measure lateral slip angle and the resulting lateral force
- Have adjustable normal force on the test wheel
- Have variable camber on the test wheel
- Be capable of testing all tires that the team may wish to use in the future
- Be inexpensive to build
- Be able to have more sensors added to it in the future as the teams requirements grow
- Be easy to use to encourage the generation and use of tire data

II. Background Research

A. The Need for Tire Data

The transmission of driving forces from a motor vehicle to the environment is through the vehicles tires. As such tires are one of the most critical items on a race car. However to many race car teams and designers the properties of tires are overlooked as the theory of how a tire interacts with the road is very complex and hard to comprehend. The only effective way for tires to be taken into consideration is through physically testing them and recording their properties so that they can be referred to by designers and operators.

Many well funded professional race teams and race car designers rely heavily on commercially obtainable tire data when designing and adjusting their cars. This is especially true in the Formula One and Indy Car Series. It is often observed that the teams that are selected to help test and develop the tires with the manufacturers, such as Bridgestone and Dunlop, obtain better results in the races [8]. This is because the teams are given access to the tire data earlier and are able to suggest changes to the tires compound and characteristics that better suit their vehicle. This highlights the importance of tires and their characteristics in racing. Unfortunately in other codes of motorsport that do not have such high levels of funding, tire data is scarce and driver feedback is the main method of obtaining data on the tires characteristics.
This need for tire data by Formula SAE teams lead to the creation of the Formula SAE Tire Testing Consortium, where formula SAE teams pay an initial joining fee which is then put towards paying for a round of commercial tire testing at the CALSPAN Tire Testing Facility [9]. The CALSPAN Tire Testing Facility offers testing at a heavily discounted price for the consortium as it wishes to promote the use of tire data by university students, however the cost of using the facility at discounted rates is approximately $10,000 USD per day. Unfortunately the Tire Testing Consortium tests tires of interests to its main customer base which is Formula SAE teams in the USA. A result of this is that the tires tested are predominantly of US manufacture and mounted on 13” rims. Until February 2012, the consortium had not tested any tires on 10” rims. The consortium finally tested two tires on 10” rims and found in the process of doing so that the commercial facility being used could not test the full range of parameters due to the smaller size of the rims.

It was clear that the team needed their own method of obtaining tire test data without paying the large price that is required to obtain it commercially. Also the team needed to be able to obtain data on the tires that they use on their vehicles or may wish to investigate using. As such the team needs to be able to obtain data for tires on 8”, 10” and 13” rims.

B. Modern Tire Testing Machines and Sensors

The automotive industry as well as the aircraft industry uses numerous testing machines to generate the tire data they require. Research was conducted to find out what machines are used and the main types of machines were then investigated for their suitability to the teams needs.

The Institut für Kraftfahrwesen Aachen has a dynamic tire test rig that they developed in order to be able to produce their own tire data. This machine uses a small rotating drum to replicate the road surface. This drum is capable of producing a surface speed of up to 160 kph. This is because the machine mainly tests for transient tire characteristics. It also test camber angles from -50 to +25 degrees which is an excessively large range. The use of a small rotating drum distorts the contact patch of the tire and leads to inaccurate data when generating the types of tire data used for race cars. This machine is primarily aimed at investigations into tire properties to predict vehicle reactions in emergency situations as well as roll over’s [10]. This is typical of all the small rotating drum machines that where investigated.

The Politecnio di Milano in conjunction with the Laboratory for the Safety of Transport developed a large rotating drum tire testing device called the Ruota Via [11]. This machine used a large steel rotating drum to minimize the distortion in the contact patch due to the curved surface [12]. This causes other engineering problems due to the 2.6m diameter rotating steel drum, such as the manufacture of said drum which weighs 5,500kg as well as ensuring adequate stiffness in the drum. As a result the supporting structure is quite large and weighs approximately 140 tons and takes up over 140m$^3$ of space. Testing machine was designed to also test suspension and brake systems as well as conduct high speed tire testing. This style of tire test rig is too large and has more functions than the team requires.

Another tire testing device currently in use is the Flat Plank Tire Tester in Changchun Automobile Institute. This device is designed to test non-steady state properties of tires only and as such it not suitable. However the device does demonstrate that tire forces can be observed and calculated through the use of strain gauges. [4 and 13] It has been observed that an advantage of obtaining tire data through transient testing is reduced tire wear on the test tire as a comprehensive testing regime can lead to excessive tire wear[14].

The most commonly used style of testing machine in the industry is the stationary steel belt machine. The two most notable designs are the MTS Flat-Trac and the CALSPAN Tire Research Facility Flat Track machine. These style of machines provide the majority of tire data used in industry, especially the steady state data used when designing and tuning a race car. These machines use a belt rotating around two drums as the testing surface. The belt is usually made of stainless steel as they are capable of withstanding the forces generated as well as for manufacturing reasons. The use of a stainless steel belt as the testing surfaces poses multiple engineering challenges including the transmission and recording of forces from the tire. The layout of these machines has remained constant over the last 30 years with a steel belt running between two drums as the driven testing surface and an A frame structure above this which holds the tire being tested. The normal force, camber angle and slip angle are all varied by hydraulic rams that control the location of the wheel hub [14 and 15]. Due to this use of hydraulic rams the previously mentioned parameters can be varied to any value within their minimum and maximum operating range. This is a good feature of this design however the level of variability is
more than is needed to obtain tire data except for slip angle which requires a large number of data points in order to generate usable data plots.

The majority of these flat track tire testing machines use a six component strain gauge balance between the wheel hub and supporting structure to measure the forces exerted upon the tire. These are highly effective at recording the forces produced and would be well suited for use on any proposed tire testing machine, however their cost makes the use of an existing one unfeasible and the complexity means that he design of one would be outside of the scope of this thesis. The design and implementation of a strain gauge balance to the final tire test rig could be undertaken as a future upgrade to the machine. The CALSPAN Flat Track testing machine is capable of gathering wet weather tire data through the use of nozzles placed in front of the tire. Different water pressures and flow rates are than used to create a water film on the surface with a thickness that can be varied between 0.13 mm-10.24 mm [16]. This method of wet weather testing could be implemented on the proposed test rig to allow wet weather data to be gained without relying on the weather.

The desire of many professional racing teams to gain large amounts of operating data for their vehicles has lead to the creation of many commercially available sensor systems that can be used to generate tire data. These range from commonly available infra red tyre pyrometers, which the Formula SAE team at ADFA already use to more complex optical slip angle sensors. Many of these sensor systems are well suited to a mobile tire test rig.

The first system that was investigated was the commercially available wheel force transducers. These devices are very similar to the strain gauge balances used on commercial tire testing machines however they are mounted to a modified rim. This allows the forces at the spindle to be measured, however the resulting data must then be manipulated into usable data as it comes out in a sinusoidal wave form due to the rotation of the rim and transducer. This system provides a great advantage in that it can also be used on an existing vehicle to get an accurate description of the forces through the vehicles wheels when operating. The design and development of such a system is outside the scope of this thesis; however this would make a great project for the team or future thesis students as it could be used on the test rig as well as to instrument vehicles during testing.

If this option were to be pursued for the final design of the tire test rig, an existing sensor would need to be bought. The ideal wheel force transducer to use would be the MTS Spinning Wheel Force Transducer 10 (SWIFT 10). This system is ideal as of all the available transducers it has been specifically designed to test wheels on rims as small as 7 inches and is a well proven design, as the MTS SWIFT range is widely used in industry [17]. This sensor is classed as a low cost system by the manufacturer at $70,000 USD. This price is too high to make the use of a commercially available wheel force transducer feasible as one of the main aims of the project was for it to be low cost.

Another commercially available sensor system that could be used on the test rig is an optical slip angle sensor. These sensors are mounted parallel to the plane of the wheel being tested and are traditionally used to instrument a complete test vehicle, however they could be fitted to a mobile tire testing rig. The commercially available systems have an accuracy of $< \pm 0.5^\circ$ and can operate at velocities of 0.3-400 km/h [18]. These systems however cost approximately $20,000 USD for the lowest specification units. It may be possible to develop such a system at the university; however the scope of the project would require somebody else to develop it separately. These systems are accurate and would allow for the collection of data in numerous ways including varying the angle of the tire relative to the test rig, propelling the tire around circles of different radiuses or a race track. However due to the cost of commercially available systems and the complexity of building an optical sensor this method is not currently feasible.

C. Slip Ratio

Tire data used in the automotive industry shows recorded longitudinal force and its relationship to the longitudinal slip ratio of a tire as shown in Figure 3 [9]. As such any tire testing device that measures the longitudinal forces produced by a tire must also measure the slip ratio of the tire if the data is to be of any use. According to the Vehicle Dynamics Terminology standard SAE J670 the longitudinal slip ratio is the difference between the angular velocity of the driven (or braked) wheel and the angular velocity of the free rolling wheel.
This is also described by equation 1[19] that uses the forward velocity of the tire as well as its radius and rotational velocity

\[ s = \frac{R \omega_{\text{tire}}}{V_{\text{tire}}} - 1 \]  

(1)

This means that to accurately record the slip ratio of a tire being tested the rotational velocity of the test tire must be recorded as well as the rotational velocity of an equal size free rolling wheel. The use of an identical tire can be avoided if the forward velocity of the tire testing device is recorded. This could be obtained from the test vehicle, however to allow for ease of use the forward velocity should be obtained from a free rolling wheel attached to the tire testing device. This would be easy to design into the device as it could be as simple as a wheel speed sensor mounted on the hub of the wheel. These sensors are already used by the Formula SAE team and are cheap, readily available and easy to implement. The free rolling wheel could be used to support a portion of the devices weight. This method would require no modification or instrumentation of whatever vehicle is used to propel the tire testing device, making the use of the final system easier.

D. Slip Angle

Tire data is often presented in a graph of lateral force versus slip angle with multiple data sets representing the different normal loads, tire pressure or camber angles that the tire being tested was exposed to [9]. This data is very useful when adjusting a race car as it shows the lateral forces that a tire should produce under different suspension setups. As such the production of this data has been identified as one of the main functions of this project. The slip angle of a tire is defined as the angle between the velocity vector of the tire and the x axis (or plane) of the tire. This is represented mathematically in equation 2[20]. The difference between the velocity vector of the tire and the plane of the tire produces a lateral force that is equal to the slip angle times the cornering stiffness of the tire, as shown in Figure 4.

\[ \alpha = \delta - \theta_v \]  

(2)

The slip angle of a tire can be changed and recorded on a mobile test rig in three ways. The first is to propel the test rig along a straight line and change the angle of the tire in relation to the test rig. This method uses the same principles as those used in the large stationary testing machines that have been previously discussed. This method would make the system more complex as it requires the wheel to be both driven and steered and would limit the number of pre existing components that could be used in the construction of the system. This system, if appropriately constructed, would allow a large range of slip angles to be ‘swept’ through quickly with minimal variations in tire properties such as temperature and pressure. This method would produce less tire wear as the tire data would be obtained quicker [9]. The slip angle could be measured through the use of either a rotary or linear potentiometer appropriately mounted. These sensors would be easy to mount and integrate into a data acquisition system such as the Motec ACL that is currently used by the Formula SAE team.

The second method of changing the slip angle of the tire being tested is to connect the tire test rig to the vehicle providing the propulsive force in such a way that the x plane of the test tire is always parallel to the chassis fore and aft centreline. The vehicle and test rig are shown in Figure 3. Typical Longitudinal Force vs. Slip Ratio Data. This data is typical of what is obtained when testing the properties of racing tires. [9]

Figure 3. Typical Longitudinal Force vs. Slip Ratio Data. This data is typical of what is obtained when testing the properties of racing tires. [9]

Figure 4. Tyre Lateral Force Generation. This shows how lateral force is produced due to slip angle.[20]
would then be driven around circles of different radii as this would expose the test tire to different slip angles. The slip angle could be measured by placing a rotary potentiometer or some other device on an unloaded castering wheel. If the wheel is unloaded there will be no difference between the wheels velocity vector and x plane, allowing it to give a true indication of the tire test rigs velocity vector angle [20]. This method could be used to sweep through a range of slip angles by driving around a spiral shape of increasing or decreasing radius. This requires a wider testing space than the previous method though it avoids the complexities of trying to dynamically change the position of the tire relative to the testing rig that the previous method presents. This method will be cheaper and simpler to implement making it better suited to the team’s requirements.

III. Design Specification

After conducting the background research, the next step was the creation of a design specification for the mobile tire test rig. Some of the design specifications were initially outlined when the project was established; however they were investigated during the research phase to ensure that they were correct. The design specification also ensures that the finalized design will meet all of the aims that were described previously.

A. Mobile Test Rig

The most notable initial requirement that was validated was the need for the test rig to be mobile. It was found during the research that the creation of a stationary test rig would be outside of the scope of this thesis as well as outside of the team’s resources. It was also found that a mobile test rig that could be transported to different locations could test the effect of various surfaces on the tires characteristics. This would be greatly beneficial as it has been noted by many race teams that some tires have different characteristics at different tracks due to the tracks surface. The most notable example of this was when many Indy Car teams tested their cars at Laguna Seca immediately after the surfaced had been refinished, when the teams came back later in the season for the race that was held there, they found that their previous setup was not effective as the surface had changed due to wear and aging [8]. The requirement for the machine to be mobile meant that an investigation into suitable propulsion vehicles and mounting arrangements would also need to be conducted at a later stage.

As the test rig is to be mobile it will require a means of transporting it around and propelling it that the team has ready access too. This means that the final design will need to be compatible with a vehicle that is obtained through the defence white fleet, a university vehicle or other possible options. These options needed to be explored and a vehicle specified before the final design could be created.

B. Testing Speed and Slip Ratio

It was found during the background research that the main tire characteristics which are to be found do not vary greatly at different testing speeds. As such the specified tire data can be gathered at lower operating speeds. This combined with speeds of approximately 40kmh of many vehicles in the skid pad test, lead to the maximum operating speed of the test rig being 40kmh [21]. The slip ratio range was determined through an investigation of existing tire data and the practices of commercial tire testing; it was found that the slip ratio ranges used are generally ±0.2 [9]. As such the slip ratio was specified as ±0.3 to ensure that the design would be able to expose tires to their maximum longitudinal force. The slip ratio, combined with the maximum velocity of the complete rig being 40kmh led to the maximum speed of the tire being 52kmh. The rotational speed of a shaft to drive an 8” tire at 52kmh was calculated as 4400 rpm. These values could then be used in the design and selection of various driveline components.

C. Slip Angle

The literature review found that the vast majority of racing tires have a lateral force that peaks at an approximate slip angle of 6-7 degrees, with passenger vehicle tires peaking at around 15-20 degrees [8 and 9]. As the test rig is only to test race car tires, the maximum slip angle that needs to be developed was set at 15 degrees to ensure that the peak lateral force of race tires can be found. The final design may however be capable of exceeding this slip angle without any adverse consequences.

E. Camber

When researching camber and its effects on tire characteristics, it was observed for road racing vehicles that do not operate on an oval track, that they predominately used small positive camber angles. The distinction is made here for non oval track racing vehicles as oval track vehicles use stagger, to generate a maximum cornering force to one direction only at a detriment to the other direction. As such this application and its range of camber angles is not relevant to this project. It was further observed from race cars and commercially available performance tire data that the range of camber angles traditionally used is 0-4 degrees [8]. As such the parameters have been specified for the test rig to test from 0-5 degrees camber at one degree increments.
F. Tire Size

The Formula SAE rules specify that a team may use tires mounted on rims of 8” diameter or larger; this specified the minimum diameter that test rig should accommodate. The reason for wishing to investigate this smaller rim size is that currently motor racing tires for 10” rims are only used in Formula SAE, meaning that the market for them is quite small. However tires on 8” rims are used in other motorsport classes meaning that there is a wider market and therefore greater choice and potential performance gains due to the wider selection. From discussions with team members and the project supervisor, it was decided that the team would not wish to investigate tires on rims larger than 13” any time in the foreseeable future.

IV. Methodology

The first steps in this project have been previously covered in depth in this report and the initial report, being the background research and the creation of the design specifications. These steps both needed to be conducted in detail before any other major steps, due to their importance. An understanding of what tire data is, how it is gathered and what it is used for needed to be gained before the parameters of the system could be specified. Once this had been achieved, the parameters of the machine could then be defined. This section will now deal with the implementation of the defined parameters.

A. Upright Selection and Design

The design criteria posed many challenges that would need to be considered for the design of the upright to be used. The first challenge and the most significant in terms of impact was the requirement to test wheels on rims with diameter as small as 8 inches. This had an immediate impact on the mounting of brakes to the upright, after investigation and consideration the decision was made to have inboard brakes fitted to a drive shaft or some other device. This was to overcome the need for brakes mounted to the hub due to the inadequate volume available in which to package the brake rotor, caliper, upright and drive shaft [22]. The use of overhung brakes was investigated however they were deemed unsuitable as they added to the complexity of the upright and other options would be cheaper and easier to implement.

The initial stages of the upright development were focused on finding a joint that could be used in the driveshaft that could handle the necessary forces and had the smallest dimensions that where practical. After researching many manufacturers’ catalogues and looking into various possible designs, the decision was made to use the Constant Velocity (CV) joint and driveshaft from a Daihatsu Charade. The specific model chosen was the 1983-1992 G100 Daihatsu Charade. Research showed this to have the smallest maximum diameter of any CV joint that is used in a commonly available car. The maximum external dimension was 71mm. The advantage of this driveshaft and CV joint combination is that there are many Daihatsu Charades of this era still on the road today with spare parts for this vehicle being readily available and also cheap with second hand parts also being readily available from automotive dismantlers, this is where the parts that were used to generate dimensions where obtained from.

Once the Daihatsu Charades CV joint and driveshaft had been chosen for use, the exact dimensions of the parts needed to be obtained, so a CATIA model could be created. The parts were collected from an Auto Dismantlers locally and then cleaned and dismantled prior to being measured. The upright of the Daihatsu Charade was also obtained to allow for the bearing and housing dimensions specified in catalogues to be checked as some sources were contradictory. Once the drive shaft and CV joint had been cleaned they were taken to the student workshop where all the dimensions were recorded and then modelled in CATIA. This process took one to two days in total.

Once the CV joint and driveshaft had been modelled, work began on designing a new upright that would fit inside an 8” rim. A few initial designs were created in CATIA that would then be constructed out of aluminium, however upon further discussion with the project supervisor and reflection of the project aim of low cost, this option was not pursued. The reasons for this included the problems associated with the interference fit required for the wheel bearing and the problems this would have if the upright was made out of aluminium. When investigating the possibility of a steel upright it was decided to use the existing Daihatsu Charade upright and
make an adaptor for it and its stud pattern. This allowed the design to be greatly simplified from a manufacturing point of view as these parts could be machined out of 25mm thick aluminium plate. This option also had the great advantage of not having to create and specify the construction of a hub instead only an adaptor.

The use of the Charade upright simplified the construction of the machine however it added unseen complexity to the design process. This was due to the complex shape of the upright as well as its geometric relationship of the mounting holes in it. There were no existing CAD models of a charade upright that could be found and a method had to be devised to obtain its dimensions. The method chosen was to machine up adaptor pieces that would fit in the holes perfectly and then use Digital Read Out systems, fitted to the milling machines and lathes in the student workshop, to find the geometry of the part in a Cartesian co-ordinate system. This proved quite difficult and took approximately 3-4 full days in the student workshop to ensure that the values obtained were correct and accurate. This would not have been possible without the assistance of Marcos de Almeida, the student workshop supervisor, who helped greatly and organised the use of a traditional milling machine edge finder as well as an optical edge finder which he obtained for this procedure.

Once the coordinates of the holes had been ascertained as well as the external dimensions of the upright it was then modelled in CATIA, as can be seen in figure 5. An adaptor plate and other fittings were then designed, as shown in figure 6. The design called for the use of commonly available material sizes and the minimum amount of machining operations where ever possible. This was to ensure that the final product would meet the aims of being low cost and easy to manufacture

**B. Suspension and Adjustable Normal Force**

One of the many challenging aspects of this design was the suspension of the test wheel. As the wheel would be tested on surfaces of different qualities and the surfaces would not be perfectly smooth, as found in laboratory conditions, the wheel would need to be damped. The design of a conventional suspension system does not normally pose many challenges [22]. However the requirement to test tires at different normal forces as well as needing to be able to instrument the suspension, to find the forces being produced, posed multiple challenges.

The first main problem that was investigated was the need to be able to instrument the suspension components to provide data on the forces being produced. Whilst the design of the sensor system for this rig is outside the scope of the project, as it is being conducted by Mathew Trewick, it still needed to be considered throughout the project. A preliminary design decision was made to use strain gauges on suspension components to detect the forces being produced. It was determined that the number of suspension components should be minimised to allow for easier force calculations. It was determined that if there was only four suspension components, using the resulting forces found from the four components the forces in the lateral, longitudinal and normal direction could all be calculated as well as the self aligning torque of the tire. These are the four main values that are recorded when testing a tire.

Due to the large amount of information available on suspension design and upon further discussion with the project supervisor it was deemed not feasible to use a suspension system with only four members. The reasons for this was that no solution could be developed that would allow for the successful transmission of the normal force and the self aligning torque.

It was found that using an upper and lower A-arm suspension system where the lower arm also had a drag link to deal with the self aligning torque could be made to work. The top A-arm would need to have the spring and damper unit attached to it on the inboard side of where ever the strain gauges would be mounted to ensure that only five members were instrumented. This proved challenging as the suspension components are to be manufactured out of aluminium square hollow section. This decision was made as aluminium’s properties are better suited to the detection of strain than steel. The selection of square hollow section was to allow for the use of strain gauges designed for flat surfaces, as they would be easier for the formula SAE team to apply and use then strain gauges for round tube. The square hollow section that was selected was 6061-T61 in 19mm x 19mm x 1.6mm. This material was assessed to have suitable properties as well as being readily available through one of the team’s sponsors, Performance Metals Australia.
When incorporating a drag link in to the suspension multiple locations were investigated. Mounting it in the vicinity of the original steering arm location was investigated; however this idea was not adopted due to possible bump steer that would be created when the suspension was compressed [23]. For this reason it was decided to mount the drag link in the traditional location of either the top or lower A arm. The lower A arm was chosen for the location as it would make the top A arm less complex, which would help with the implementation of it having a non standard pivoting motion to provide the mounting for the spring and damper.

The adjustable normal force on the tire is achieved by changing the mounting location of the spring damper unit on the upper control arm. This changes the leverage effect of the unit on the arm and hence the force it applies through the suspension to the tire. Other methods were investigated including lowering the entire supporting frame or raising the supporting castering wheels relative to the testing surface to cause the tire to support more of the weight. These methods were deemed unsuitable as achieving correct implementation would create difficulties in repeatability or make the system hard to use when combined with the adjustable camber.

The advantage of the moveable spring and damper is that it simplified the design and requires only minimal machining operations to achieve. Also with minor modifications different spring and damper combinations can be used instead of the Ohlin’s Cane Creek double barrel unit that was selected. This unit was selected as the team currently posses them as well as information describing their characteristics. Another advantage of this is that they can be instrumented with load eyelets that were developed at UNSW@ADFA.

C. Camber Adjustment

The Camber adjustment is achieved through the rotation of the entire sub frame, supporting the engine and tire, about the centre of the contact patch of the tire being tested. This is achieved through mounting holes that reflect the discreet camber angles previously specified of 0-5 degrees. The exact geometry of these mounting holes was calculated in CATIA by initially modelling the mounting holes for zero camber, taking into consideration where they will be located on the frame relative to the centre of the tires contact patch. Once the zero camber holes had been established, the holes and their relations to the contact patch were simply rotated about the contact patch at one degree increments. It was found that due to the small increments used that there would be overlap between the holes. This problem was overcome by having the holes separated to lie on one of either two lines that had 25mm separation, this allowed the holes to be staggered and avoid interference with each other. Due to the offset of the test wheel from the centreline of the driving vehicle, it was found that one end of the mounting holes is in excess of a metre away from the centre of the contact patch. It was also found that the other end cannot be further away than 200mm. This was caused by the use of the Daihatsu Charade drive shaft and uptight. This started to cause many problems with mounting holes overlapping, especially on the side closer to the tire. It was than observed that there was a common point through which lines between the mounting holes for different camber all passed. This point was offset from the centre of the contact patch by 17.5mm. It was decided to use this location as the mounting hole for that side. The use of this hole as a common mounting point for different camber angles greatly simplifies the operation of the test rig as changing the camber is now effectively done by raising or lowering one end of the sub frame instead of both ends.

Whilst designing the camber adjustment, the ability to test tires of rims on different diameters was also dealt with. This had many similarities to the adjustable camber in the ways in which it could be achieved. After investigating the multiple options available it was found that repeatability would be difficult to achieve with many of them. It was decided that the same solution would be used as that found for the adjustable camber. Mounting holes at different heights would be used to raise or lower the sub frame to pre determined heights above the surface, allowing for different size tires to be tested.

The use of multiple mounting holes for both the wheel size and the camber caused the layout of the holes to start becoming very crowded and complicated. This was simplified by having the multiple sets of holes for the adjustable height/wheel size located on the sub frame and the holes for adjustable camber located on the main supporting frame. Having the adjustable camber mounting holes on the supporting frame was chosen as this ensured that the geometry of the adjustable camber mounting holes about the contact patch of the tire was not changed and therefore the changes in camber would still be about the contact patch. This would not be the case if they were located on the sub frame that is lowered and raised.

D. Propulsion Method

The propulsion section of the test rig was split into three sub categories consisting of the propulsion vehicle selection, the driving force selection and the braking force selection. These sub categories were investigated in isolation and then brought together when assembling all the items into a complete system and building the test rigs frame around them.

The first part to be investigated was the propulsion vehicle. With two of the aims of the system being easy to use and low cost, this meant that the propulsion vehicle would need to be one that the team already had easy access to and would remain so into the future at minimal expense. This lead to the decision that the propulsion
vehicle would need to come from the defence white fleet which consists of normal passenger vehicles that military members can request through their local transport yard, in this case located at Duntroon.

Once the decision had been made to use defence white fleet vehicles an analysis of the mounting points on the available vehicles would need to be conducted. This involved liaising with the local transport yard and then going down and measuring up the mounting points of the available vehicles. It was soon discovered that the majority of vehicles only had towing loops to attach to and that they were not suitable. However it was found that the Toyota Land Cruiser also had two welded plates with machined slots that would be ideal to attach the test rig too. The Toyota Land Cruisers Mounting points were then modelled in CATIA to allow for the frames attachment mechanism to be designed.

To generate a positive slip ratio the test frame would not only need to be pushed, as was examined above, but the tire being test would also need to be driven at a different speed [22]. There were three main options to achieve this being the use of a generator and electric motor, the use of a hydraulic pump and hydraulic motor or the use of an internal combustion engine and gearbox. The first two options were investigated; however the team did not currently posses any of the components and there would be packaging issues due to the split nature of the systems. This left the use of the internal combustion engine. It was desired that the engine chosen would have similar power to the engine of a Formula SAE vehicle to ensure that the correct slip ratios could be obtained. When combined with the desire to be low cost and easy to operate, this lead to the selection of a motorcycle engine that the team already posses. This meant that a selection had to be made out of the Suzuki GSX-R 600 engine and the Yamaha WR 450F engine. The GSX-R 600 engine provides more power, however it is also heavier and larger. It was decided to use the WR 450F motor as it would allow for a lighter and smaller system making it easier to transport, use and store.

Once the WR 450F motor was selected a suitable frame and mounting attachments had to be designed. This required taking multiple measurements from the engine scan and the engine and dyno frame that the team is currently working on. Once the engine mounts and its own supporting frame had been designed it was than incorporated into the sub frame to ensure that the engine sprocket and the final drive sprocket lined up.

The means of providing braking force was taken into consideration earlier in the report when designing an upright suitable for an 8” rim. It was found that traditional breaks that fit inside the hub would be very small and would not be suitable for the sustained braking that is conducted when testing for negative slip ratios [22]. The use of overhung brakes would also be challenging. When the use of inboard brakes was considered, it was found that these would not only be the easiest to implement but also the cheapest as the team has many suitable brake components from previous vehicles. This method would also allow for the use of a second calliper and rotor in the future if the team wished to test at higher negative slip ratios.

It was found that the team had multiple Wilwood Dynalite Callipers that could be used on the system. These brake callipers have been used on SAE cars with 13” rims and can provide the required braking force. The next step was designing or selecting a rotor. An unused rotor from a WS08 was found and it was decided to use this as it would only require the fabrication of a rotor mount for the drive shaft instead of a rotor mount and the rotor itself. Once the mount had been modelled and added to the driveshaft the calliper mount was then modelled to ensure correct fit. Once again the mount was designed with ease of construction in mind so the part has limited machining operations.

E. Possible Design Changes

Some aspects of the design may be changed without affecting the functionality of the test rig. These changes can only be made if they are well thought out and made with regards to the many design decisions discussed previously in this report. This section will detail the various aspects of the design that can be changed during the construction phase or as part of future modifications.

The most notable aspect that can be changed is the engine selection and the corresponding section of the sub frame. This design was created with the selection of a WR 450F motorcycle motor, however if the team does not wish to use one of their engines in this capacity, they are able to modify the engine mounts to suit whatever motorcycle engine they choose. It is recommend that the motor used is of similar weight and size to the WR 450F however larger and heavier engines can be used if a suitable analysis is conducted. The test rig could also be initially constructed and used without a motorcycle motor being mounted. This arrangement would not allow for the gathering of data on positive slip ratios however lateral force and slip angle could still be tested.

The dimensions and design of the frame could be modified prior to construction. Unfortunately Doug Collier was not able to be consulted during the design of the frame, as was initially intended. This lead to the frame design not being reviewed by Doug for his input on the welding aspects. The frames dimensions and construction material can be modified as long as the relationships between the mounting holes for adjustable height and camber, the suspension mounting points, driveshaft attachment and engine mounts are observed. Once again any modifications to the design should have a proper assessment done in which the impact on the properties previously mentioned are assessed.
The brake system can also be modified to suit the availability of parts. If different components are to be used then the mounting arrangements for the parts will need to be analysed, as the calliper mounts and rotor mounts designed as part of this project will likely be unsuitable. Other braking components such as the master cylinder can be readily changed as the machine has been designed with ample space in which to mount ancillary systems and possible future modifications. The engine dyno rig in use by the team and its ancillary systems were taken into consideration when designing the test rig. As the test rig is to be mobile it was made a priority to ensure that any ancillary systems could be easily mounted within the frame to avoid them being exposed on the outside whilst transporting or using the rig.

The castering wheels and their supporting structure on the main support frame can be modified if the team wishes to change to different supporting wheels. These changes are possible as long as the height of the supporting frame above the test surface remains the same and the supporting structure is modified to ensure that the forces are safely transmitted. However the aircraft tail wheels that were selected for this design are readily available and relatively cheap.

The mounting supports of the support frame to the propulsion vehicle can be changed if the team wishes to use a different vehicle other than the defence white fleet Toyota Land Cruiser. This will require new mounts to be designed and possible modifications to the supporting structure.

In the future, a new upright could be designed that incorporates a strain gauge balance. This would allow for more accurate readings of the forces and moments produced. This would be a large project and the designers would need to ensure that the centre of the tires contact patch is not changed or they would need to make suitable modifications to the camber adjustment system and suspension system if it is.

V. Conclusions

This thesis has outlined the design process that was used to develop a tire test rig that can obtain longitudinal and lateral force data for the Formula SAE team at ADFA. The thesis explained the need for tire data by the team and what tire data the team should be able to generate themselves. The parameters of a system that could achieve this were then defined and justified.

The final design that was developed for this thesis meets all of the aims that were established in the introduction as well as satisfying all of the design parameters that were established. The emphasis on the machine being low cost and easy to use proved challenging to meet however through research and hard work the use of many pre existing components were incorporated into the design, to ensure the system remained low cost and easy to use.

The final design provides the Formula SAE team with a device that will allow them to gather data to help with future designs of vehicles as well as the tuning of vehicles handling. Whilst the design has a large scope for future developments to improve the quality and quantity of data, this thesis has provided a capability that does not currently exist and shall continue to grow with use into the future.

VI. Recommendations

The main recommendation is that the team first build and start to operate the tire testing machine before any substantial changes are made to the design. The team can modify the design prior to and during construction to best suit the parts available to them, however at the time of design all parts specified were deemed the most likely to be used due to their availability and low cost.

Once the team has gained experience in the collection and use of tire data, research can be conducted into potential modifications and upgrades. One upgrade that should be examined is the design and manufacture of a strain gauge balance similar to the ones used in commercial tire testing machines. The implementation of such a device could allow for tire data of higher quality to be produced, as well as an increase in the number of resultant forces and moments that are recorded. Such a modification would however require a new suspension system and upright to be designed. The team does not currently have a need for such high quality tire data or the extra characteristics that this would provide; however over time the team will likely grow to need this capability.

A future modification that the team should investigate once they become familiar with the devices operation is the incorporation of a wet weather testing capability. This could take many forms however it will require the test surface to be dampened to a specified amount. There is currently a lack of wet weather tire data for Formula SAE and this modification would help to rectify this. Once again the team should gain experience in the machines operation before considering this modification.

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