CHAPTER 1
INTRODUCTION

1.1 Background of Study

Cornering stiffness greatly assist the design of suspension and steering systems, which taking into practical application in Universiti Teknologi Petronas, is the Shell Eco-Marathon event. Although the Shell Eco-Marathon event aims for the best fuel saving, however, “The lesser you turn the steering wheel, the faster you’ll be” [1], applies to fuel saving as well especially when vehicle is easily manageable around the corners without braking or slowing the vehicle [2]. Hence, this project can be used to assist the UTP team to better suspension and steering system by reducing the unknown variables before designing for the upcoming Shell Eco-Marathon 2013. As the first contact of a vehicle is its tire [3], the characteristics of the tires are needed to be known before design takes place for both material and time saving.

A static tire testing apparatus was designed, fabricated and tested on a VIVA FT 390 80/90-17 tire which was also used on the competed vehicle of UTP 2012 team. Loads are applied onto the tire to simulate real life situation, and force are applied on the steer beam to rotate the tire. This apparatus is expected to determine the lateral forces, cornering stiffness and sideslip angle. These results will later be verified by the UTP 2012 team vehicle with the GPS Data Logger mounted and calculated for the cornering stiffness.

Recommendations will be suggested for optimization and improvement for further research of this apparatus for low cost testing. Finally, conclusion will be done according to the comparison and result verification.

1.2 Problem Statement

Tire properties are kept private from consumers which limit the capability to design a better suspension and steering system. Heavy handling and unexpected vehicle behavior may surprise the driver which leads to unwanted accident as what happened in 2010 Shell Eco-Marathon. Hence, a tire testing apparatus is needed to estimate the characteristics of the chosen tire for the competition to reduce the unknown parameters.

1.3 Objective

The objective of this project is to obtain the cornering stiffness of the tire similar to the ones used in the vehicle of UTP 2012 team using static method. Moreover, the project aims to design, build and test the tire testing apparatus. Upon successful of obtaining the data, it will ease the designing of suspension and steering system for UTP 2013 team.

1.4 Scope of Study

The tire testing apparatus was built and tested only on the tire used by the vehicle of UTP 2012 team, which is the VIVA FT390 80/90-17 tube type. The project aims only to obtain cornering stiffness from this apparatus and will be verified by calculations from the results from Satellite Data Logger DL2 mounted on the vehicle of UTP 2012 team.

CHAPTER 2
LITERATURE REVIEW

2.1 Sideslip Estimation

In order to calculate the understeer or oversteer of the vehicle during cornering, the sideslip of the vehicle has to be known. Sideslip is as shown:

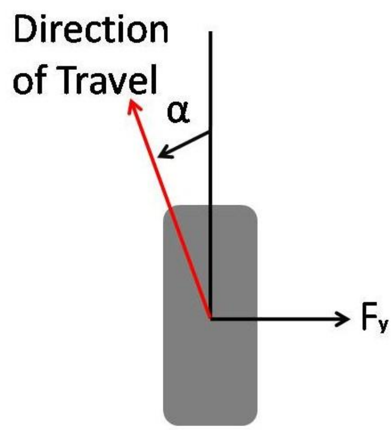


FIGURE 1. Sideslip

Fig. 1 shows that the direction of travel and intended is having very slight difference which is manipulated by the lateral force, F_y. Since the understeer and oversteer is determine by the sideslip angle, hence, it is one of the variable that will determine the system performance [4]. The group of researchers from Aisin Seiki co., Ltd and Toyota Central R&D Lab has suggested that the estimation be done using the pair of vehicle model observer and pseudo integral. The estimation method will be done using a full-scale vehicle tests which results in the confirmation of the system performance and robustness. Besides that, vehicle sideslip angle estimation can also be done using sensors with the estimation processed using two blocks in series [5]. The tire force and sideslip angle is able to be found even without some variables. Finally, the other alternative to estimate the sideslip angle is to use the Global Positioning System (GPS) pairing up with Inertial Navigation System (INS) sensor managements [6]. This method is able to obtain also the rolling and pitching of the vehicle from the motion since the system is attached on the vehicle body. This method of estimation was proposed for the high update accuracy for the vehicle states.

2.1.1 Hypothesis 1 Statement

The method using GPS used for the sideslip estimation is the best and most practical for the project's vehicle sideslip estimation.

2.2 Cornering Stiffness Estimation

Nocholas D. Smith had suggested the importance of tire characteristic such as cornering stiffness to a vehicle performance in his 2004 paper [**7**]. Binh Minh Nguyen and team from University of Tokyo proposed a new method of measuring the cornering stiffness which is without the need of sideslip angle, instead using the difference in lateral force between the left and right of the steered tires [8].

Hence, it is more than useful for a vehicle handling designer to know the tire curves characteristics in order to design a proper suspension and steering system. A group of students from Padova University of Italy also suggested that tire properties plays important role in two wheeled vehicle dynamics, which led them to come up with an identification of cornering stiffness of scooter tires using impedance measurements [9]. Experiments were done in lab and on road, concluding that cornering stiffness values at low rolling speeds come in agreement with those by static measurements. Besides that, Bryan G. Joseph et al. in as recent as 2012, had conducted experimental testing for cornering stiffness of bike tires [10]. They concluded that the higher the cornering stiffness, the better the vehicle handles, however, as the vertical load increases, the cornering stiffness increases to a maximum then decreases like a parabolic function. Lastly, the common Lateral Acceleration formula:

$$-\left(\frac{Cf + Cr}{Vx}\right)Vy + \left(\frac{bCr - aCf}{Vx} - mVx\right)\Omega + Cf\delta = m\dot{V}y$$

The equation was common and was found in Lecture Notes of Ir. Dr. Masri [11] on the topic Advanced Vehicle Dynamics. This equation is used to calculate the cornering stiffness of the front (C_f) and rear (C_r) of a four wheeled vehicle.

2.2.1 Hypothesis 2 Statement

Testing of cornering stiffness of the tire can be done for static measurement since the results agrees with low rolling speed.

2.2.2 Hypothesis 3 Statement

Tire deflection by the road while cornering equals to the tire deflection caused by rotating the wheel statically.

2.3 Critical Analysis of Literature

Through the many papers on the different ways on estimating the sideslip, the most practical for this project is using global positioning system (GPS). Judging it base on the technology Universiti Teknologi Petronas has, with the DL2 Data Satellite Logger pairing with Race Technology V7 software, many data can be obtained with high refreshing rate. By borrowing this gadget, it has reduced most of the budget from the project. In addition to that, the cornering stiffness of the tire of the vehicle will also be taken using the paired gadget and software. The results obtained from the software will be used to verify the experimental result.

Besides that, students from the Padova University concluded that cornering stiffness low rolling speed agrees with static cornering stiffness which encourages this project idea.

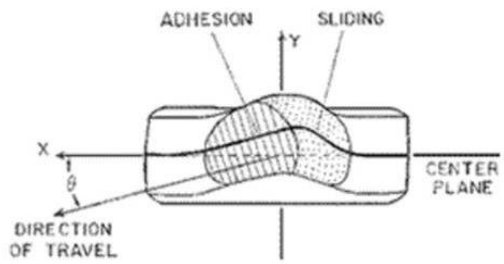


FIGURE 2. Tire deflect during cornering

Fig. 2 [12] shows the tire from the bottom view, the black patch as the contact patch of the tire to the ground which is slightly deflected due to the cornering. The project goes on with the concept of the deflection done by the road on the rotating tire while cornering is equal to the static tire deflection caused by steering the wheel which is treated as slip angle in order to proceed for the results.

2.4 Research Model

The model in Fig. 3 below illustrates the direction of research of this project.

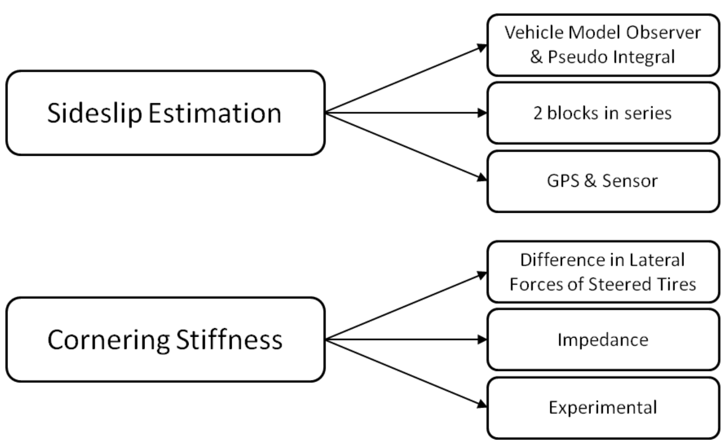


FIGURE 3. Research model

CHAPTER 3
METHODOLOGY

The method used is phased Rapid Application Development (RAD) method since a prototype is needed to be fabricated and tested. And lastly, the results obtained from the apparatus are verified in order to confirm it is usable and functional. This section will show what has been done throughout the project period.

The project is being planned as shown in Fig. 4. The Phase 1 (those in the orange doted box) is planned for FYP 1 whereas Phase 2 with the jobs in the blue doted box is for FYP 2. The arrows indicate the flow of the project with planning in the Phase 1 as the beginning of the project. Planning in every project is very important for the time, financial and research to be used effectively.

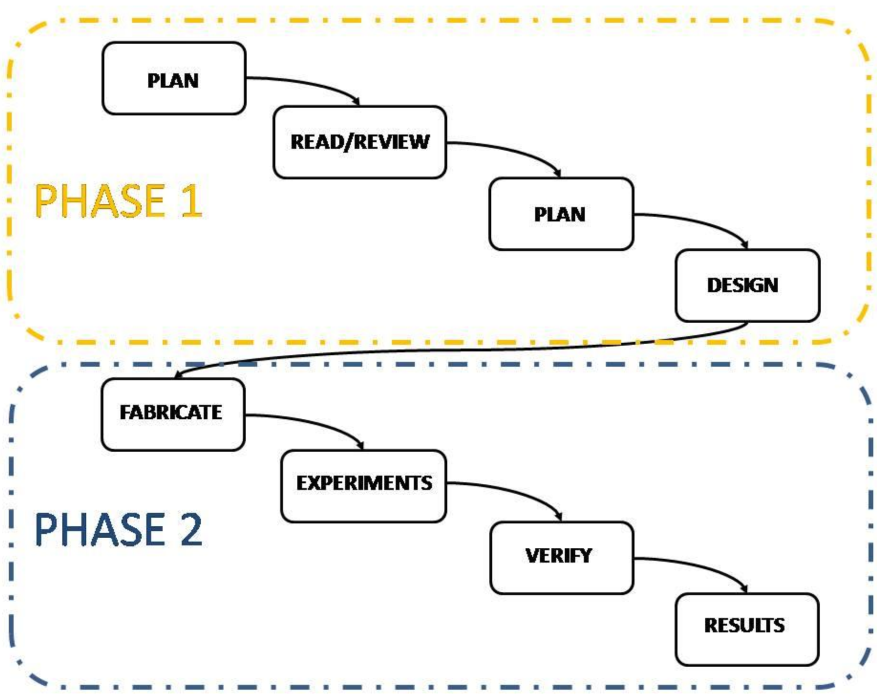


FIGURE 4. Methodology

3.1 Project Phase 1

In this section, there are four main jobs or items to be done which are boxed in the doted orange. The planning takes place in the beginning for the whole project flow in order to save time and resources. Researching and reviews on papers and existing technology have taken up quite a large amount of time. After reviewing on the literature, another planning stage takes place to decide on what technology or method to obtain the result, namely cornering stiffness of the tire similarly to the one used by the vehicle of UTP 2012 team, VIVA FT390 80/90-17 tube type. The design in this phase is the design of the tire testing apparatus done in Catia as shown in Fig. 5 below.

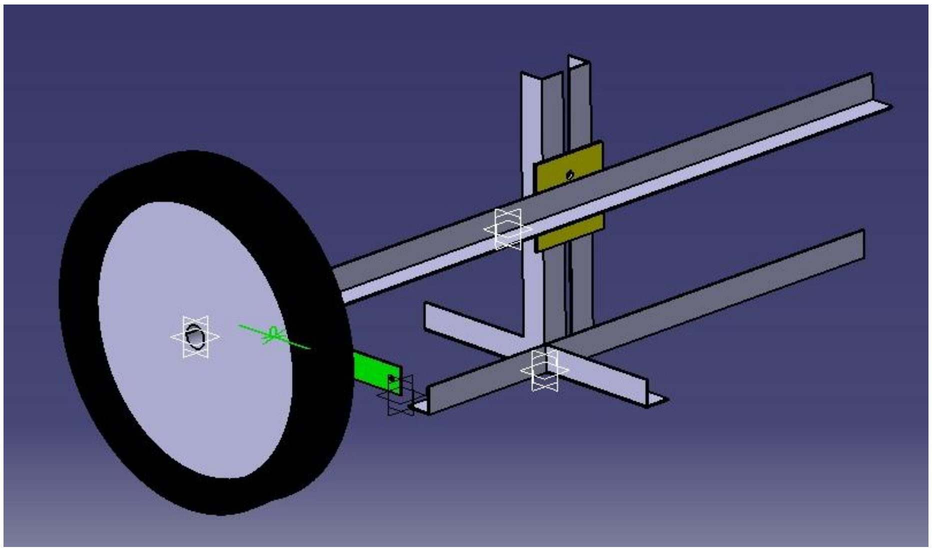


FIGURE 5. Tire testing apparatus in Catia

3.2 Project Phase 2

Similar to the Phase 1, this phase has four main jobs to be done. The beginning of Phase 2 marks the beginning of FYP 2 which starts off with the fabrication of the designed tire testing apparatus. Fig. 6 on the following page shows the assembly of the apparatus.

FIGURE 6. Assembled tire testing apparatus

There were two experiments done in the second stage of this phase, which is experiments on the tire were done using this apparatus and the simulation done on the vehicle built by the UTP 2012 team for Shell Eco-Marathon. The results obtained will be shown in the result and discussion section. The experiment of the vehicle is done with the Data Satellite Logger DL2 and hanging scale.

The Satellite Data Logger DL2 in Fig. 7 on the following page is mounted onto the vehicle and drove in a few circle of different radius to obtain the yaw rate and later the cornering stiffness. The data is processed by software called Race Technology V7 where graphs and location can be read. Results obtain from this high technology gadget will be used to compare with the results obtained from the tire testing apparatus for verification purposes. Everything that could be done as similar as possible are done, which includes testing with the same type of tires, the same zero degree kingpin angle, and even the same approximate weight on the wheel.

FIGURE 7. Data Satellite Logger DL2

3.3 Gantt Chart

A Gantt chart is shown in Fig. 8 on the following page to show the whole process of the report flow and timeline by month. The chart show both Phase 1 and Phase 2 of the project. The orange shows the current process which is at the final stage whereas the blue ones show the past done job.

No.	Details	Jan	Feb	Mac	April	May	June	July	Aug.	Sept.
1	Plan 1									
2	Review									
3	Plan 2									
4	Design									
5	Fabricate									
6	Experiments									
7	Verify									
8	Results									

FIGURE 8. Gantt chart

3.4 Key Milestones

The key milestones can be seen in Fig. 9 below which are (1) research and review, (2) design of the tire apparatus, (3) experiments of both tire and vehicle, and finally (4) the verification respectively - each taking up to a two-month period.

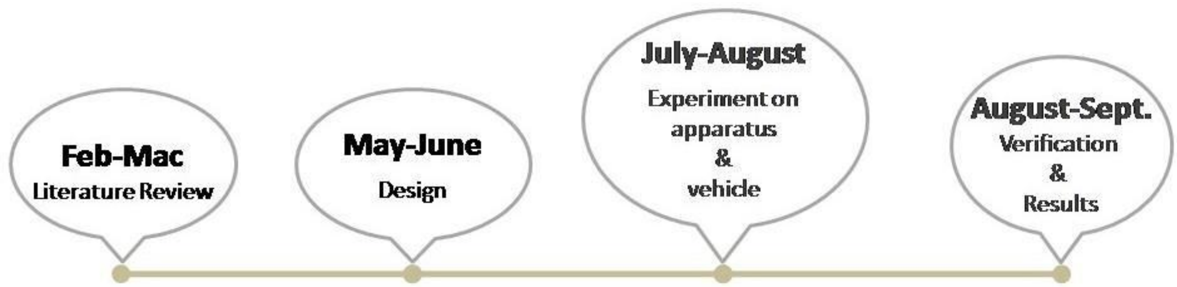


FIGURE 9. Key milestones

3.5 Tools

In the Phase 1 of the project, only simple sketches, reading and reviews are done through computer. Catia CAD software was used to design the tire testing apparatus. On the other hand, in Phase 2, fabricating and drawing tools are needed to fabricate the tire testing apparatus. Besides that, tools needed for the experiment is the weighing scale, hanging scale and a largely printed protractor. Finally, the paired up Data Satellite Logger DL2 and Race Technology V7 is used to verify the results.

3.6 Procedure of Using Apparatus

The apparatus shown earlier in Fig. 9 can be set up according to the following instruction, illustrated with the following Fig. 10:

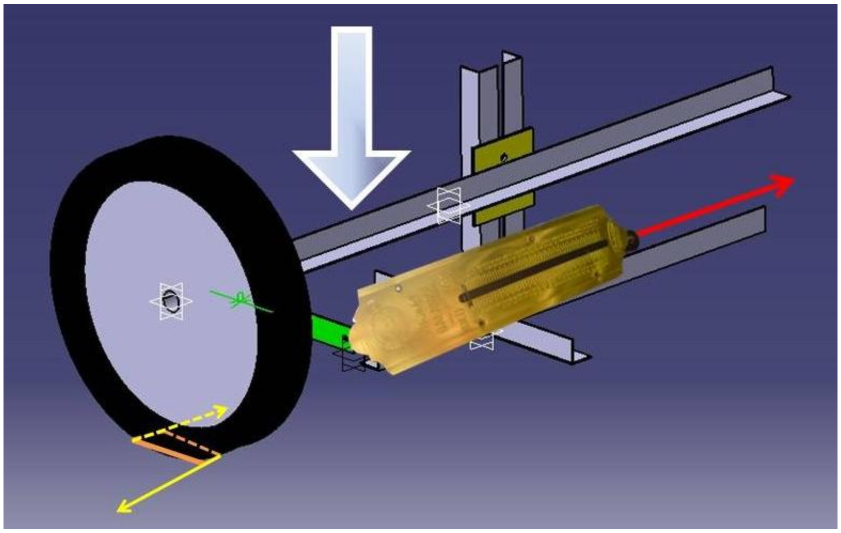


FIGURE 10. Apparatus diagram with force

1. Mount the desired or chosen tire for testing on the ball joint securely.
2. The apparatus is placed on tar road or any desired surface to be tested on.
3. Yellow plat which is welded together with the link will NOT be bolted tightly on the stand in order move freely horizontally.
4. The white arrow ↓ shows where the load is to be placed.
5. A scale is put under the wheel while increasing the load at white arrow until it reaches 45kg in this test.
6. After acquiring the desired load on wheel, put a piece of white paper under the wheel to obtain then ‘chop’ of the contact patch and have it measured.
7. Put the largely printed protractor near the wheel with the 0^o positioned at the axis of rotation of the wheel.
8. As of the figure, pull the hanging scale up to 0.5kg (indicated) in the red color direction with it hooked on the steer beam (green) and then letting the tire bring back to the original position.
9. Make sure the reading of degree (^{o}) is measured and recorded when the beam is pulled.
10. Repeat step 8 and 9 with increasing of 0.5kg until the wheel does not return to the original position which shows the maximum deflection has reached.
11. Finally, the result is recorded into a table for ease of view.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Results from the Tire Testing Apparatus (Static method)

The results shown below in Table 1 are tested on VIVA FT390 80/90-17. The weight on wheel is loaded up to 45 kg. The force (kg) is applied on the steering beam on the wheel which is at approximately 0.29 m from the centre of the wheel. The torque is equaled to lateral forces times the distance of the side of the contact patch to the centre.

TABLE 1. Test apparatus results

Force (kg)	**Slip Angle (◦)**	**Lateral Force (N)**	**Cornering Stiffness (N/◦)**
0.5	0.75	8.57	11.43
1.0	1.75	17.14	9.79
1.5	2.75	25.71	9.35
2.0	3.50	34.28	9.79

The red color arrow in Fig. 11 on the following page shows the force used to steer the tire, where in the first case is 0.5 kg (4.905N). Whereas the yellow arrows indicate the lateral forces which is found from the total length of the contact patch shown in Fig. 12 that follows.

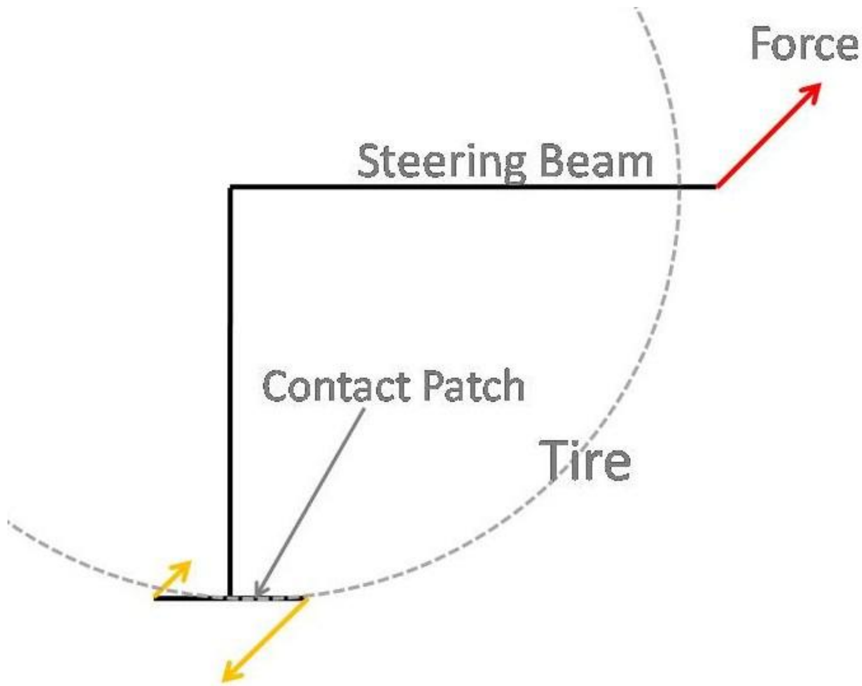


FIGURE 11. Free body diagram of apparatus

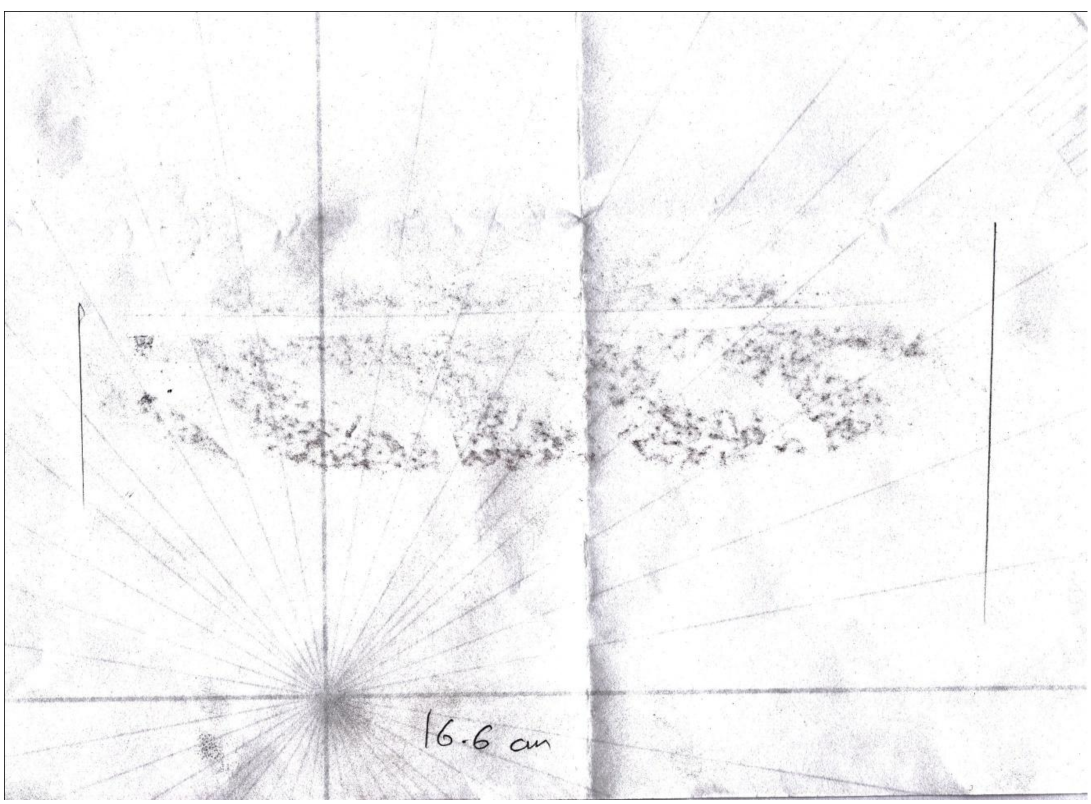


FIGURE 12. Contact patch of 16.6 cm

The maximum length of the contact patch is measured to be 16.6 cm. By equaling the force done onto the tire and countered by the tire, it is possible to calculate the lateral forces, calculation is shown below for the first reading as example:

Force (N) x Steer beam Length (m) = 2 x L.F (N) x Half of Contact patch (m)

4.905 N x 0.29 m = 2 x L.F (N) x 0.083

Solving for L.F – Lateral Force,

L.F (N) = 8.56898 N

Next by using the formula:

$$F_y = C_\alpha \alpha \qquad [13]$$

Where F_y = Lateral force

C_α= Cornering stiffness

α = Slip angle

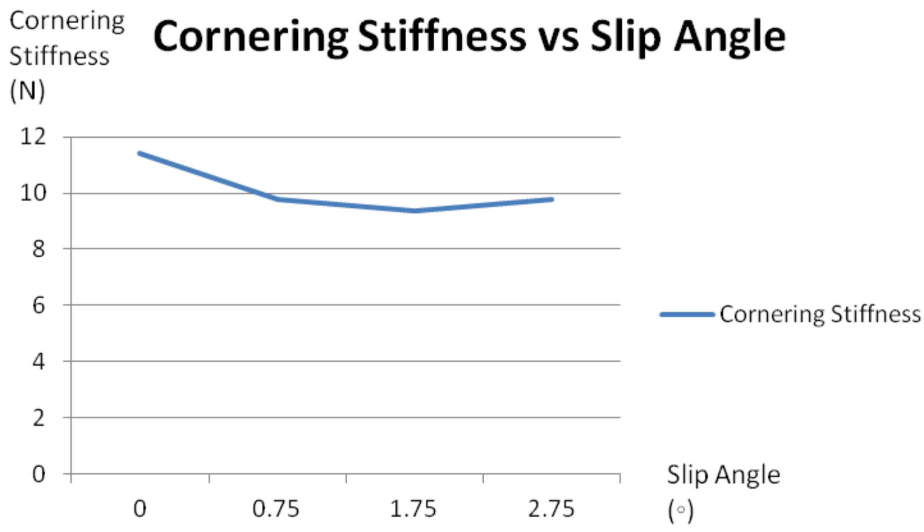
Substituting the lateral forces and estimated slip angle,

$8.57 = C_\alpha (0.75^o)$

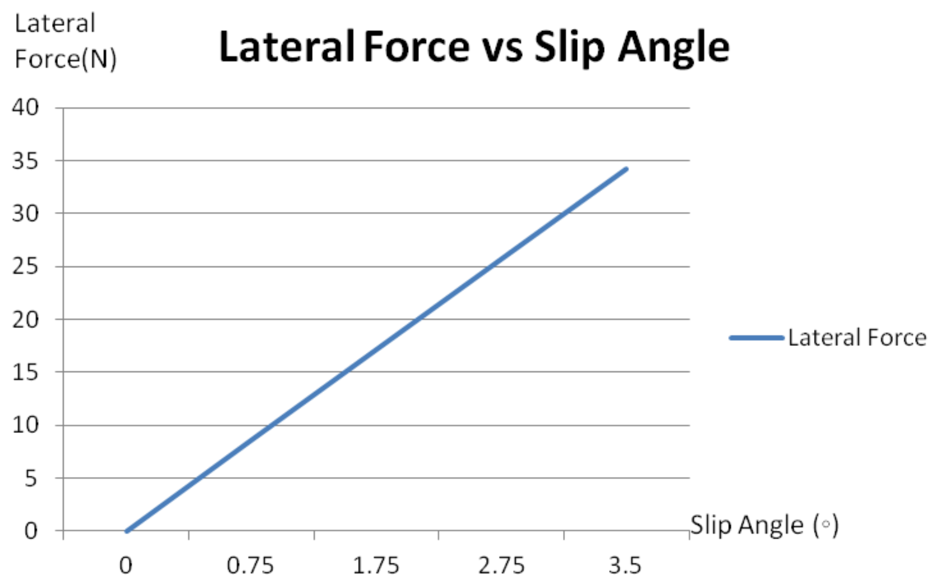
$C_\alpha = 8.57 / (0.75^o)$

$\mathbf{C_\alpha = 11.43\ N/^o}$

The cornering stiffness is 11.43 $N/^o$ as found in the above calculation example. Graphs for cornering stiffness vs slip angle and lateral force vs slip angle are plotted using Mircrosoft Excel as in Graph 1 and Graph 2 shown on the following page.



GRAPH 1. Cornering Stiffness vs Slip Angle



GRAPH 2. Lateral Force vs Slip Angle

According to Graph 1 above, the cornering stiffness is highest at the slip angle of 0.75◦ and remains constantly throughout the graph until the tire starts turning, and from Graph 2 shows the increment of Lateral Force is directly proportionate to the Slip Angle.

4.2 Result from the Data Satellite Logger DL2 (Dynamic Method)

Table 2 below shows the results of data extracted from Satellite Logger DL2.

TABLE 2. Data Satellite Logger DL2 Results

Corners	Cornering Radius (m)	Steering Angle, δ (◦)	C_r (N/◦)
Wide	62.28	10	7.12
Medium	45.00	15	6.40
Tight	19.62	30	7.68

Values obtained above are taken from Race Technology V7 software which gives accurate speed of vehicle and cornering radius. The operating speed of the vehicle is 4.44 m/s^2 constantly with three types of cornering radius.

Formula used to calculate the cornering stiffness is:

$$\delta = 57.3\,\frac{L}{R} + \left(\frac{Wf}{C\alpha f} - \frac{Wr}{C\alpha r}\right)\frac{V^2}{gR} \qquad [13]$$

Where δ = Steering angle
L = Wheelbase
R = Cornering radius
Wf = Weight on front wheel
Wr = Weight on rear wheel
Cαf = Cornering stiffness of front wheel
Cαr = Cornering stiffness of rear wheel
V = Velocity of vehicle
g = Gravitational acceleration

The calculation example for the first wide corner with 62.28m cornering radius is calculated according to the steps below.

First, we find the steering ratio of the tested vehicle, which is 0.574 in this case, the steered steering angle of 10^o is times with the steering ratio to find the steered angle on the wheel, δ:

$$\delta = 10^o \times 0.574$$

$$\boldsymbol{\delta = 5.74^o}$$

Secondly, the total weight of the vehicle with driver is at about 277 kg during the collection of these data with expectation of 90kg on front wheels and 187kg on the rear wheels as shown in Fig. 13.

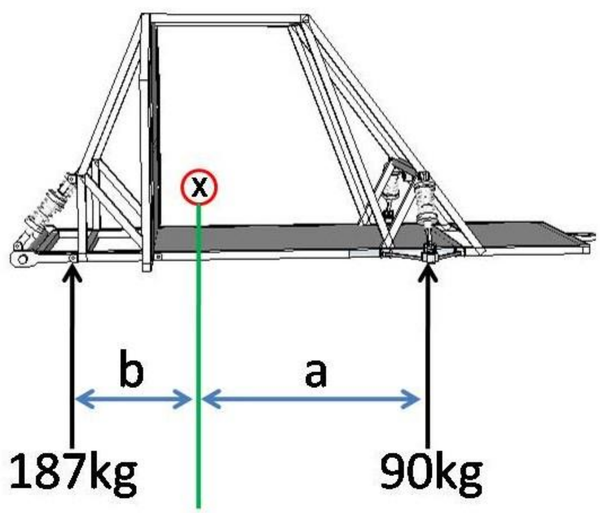


FIGURE 13. Centre of gravity

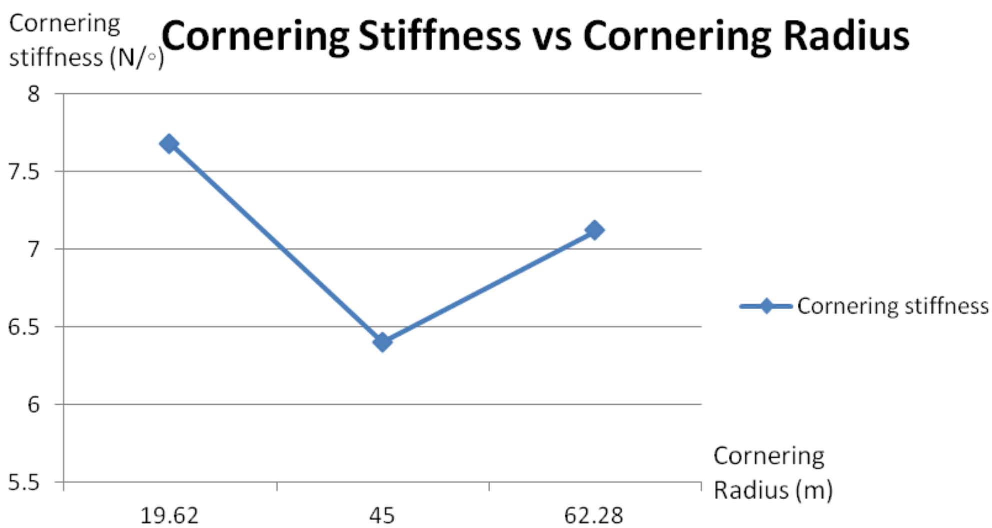
Next, the steered ratio on wheel is substituted into the formula above, shown below:

$$5.74 = 57.3\,\frac{1.55}{62.28} + \left(\frac{(90-187)\times 9.81}{Cr}\right)\frac{4.44^2}{9.81\times 62.28}$$

Finally, solve for the cornering stiffness, C_r:

$$\mathbf{C_r} \quad = \mathbf{7.12\ N/^o}$$

The calculation steps are repeated for the other entire cornering radius at different steered angle to confirm the cornering stiffness of the tested tire and plotted graph as in Graph 3 below.



GRAPH 3. Cornering Stiffness vs Cornering Radius

4.3 Verification of Result

The average cornering stiffness obtain from the tire testing apparatus is about 9.66 N/◦ excluding the odd test. On the other hand, the Data Satellite Logger DL2 plotted an average of 7.07 N/◦ of cornering stiffness.

$$\%\ \text{error} \quad = \frac{9.66-7.07}{7.07} \times 100\%$$

$$= 36.63\%$$

There are many possible causes to lead to errors as usual experiments. It is regret to be unable to produce the same graph parameters to compare with the tire testing graphs; however, the final result of the cornering can still be taken for verification.

For the tire testing graph, the Graph 1 shows a large reading which could be caused by two expected causes, which one is the error where the other three tests were producing consistent cornering stiffness since it is the same tire. The other possibility will be the force needed to start deflecting the tire initially. In the second graph, it shows that as the steer beam is pulled, lateral force on the tire develops increasingly which proportionally increases the slip angle. The tests on this was done trying to turn the wheel and letting it turn back to the original position in order to obtain the maximum deflection of the tire just before the tire starts to rotate. On the other hand, Graph 3 shows the cornering stiffness vs cornering radius of the vehicle at constant speed. The graph may seem to produce big difference in cornering stiffness value, but it was very consistent if ignoring the zoomed scale of the graph. Cornering stiffness for either test should be rather consistent since it is the tire that gives the cornering stiffness.

4.4 Cost

Since the testing gadget of the Data Satellite Logger DL2 is available in the University, this cost section here would only cover the fabrication of material for the tire testing apparatus. Labour cost for fabrication is not included as well since it is fabricated in the Universiti Teknologi Petronas Lab of Building 21 with the tools and drill bits available. The cost could be cut down much more on the angle iron since it has slight some left over, which was bought extra just in case of any error. The cost of materials needed are:

Angle Iron	RM 60.00
Ball Joint	RM 48.00
Scales	RM 94.90
Bolt and Nuts	RM 5.00
TOTAL	**RM 207.90**

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study set out to determine the alternative way of estimating cornering stiffness at a very low cost at about RM200 with self fabrication. It can be concluded that the tire testing apparatus built achieve the expected results. The second major finding from this project was also that the hypothesis made where the tire deflection done by the road while the wheel is rotating is the same as the tire deflection done by steering the wheel while the tire is static. Also, this tire testing apparatus is able to test the tire on any road surfaces provided the tire apparatus can be properly mounted on the grown.

In addition to that, this dissertation has shown that the result from tire testing apparatus was verified by the result obtained from the Data Satellite Logger DL2. The result of verification as discussed showing 36% difference. This show the many rooms for improvement and optimization which can be done and will be mentioned in the recommendation section.

5.2 Recommendations

Judging by the large percentage of errors, there are many rooms for improvement. In order to narrow down the difference in the results, more work has to be done. The works are measuring to be done accurately on the vehicle of the UTP 2012 team, while able to come up with a steering ratio graph which would assist the calculation more accurately. It is also suggested that weighing scales be put under all four tires of the vehicle in order to accurately measure the weight distribution and identifying the position of the centre of gravity.

Other than that, a heavier apparatus and a more solid steering beam is ideal for testing, not to mention the tediousness of carrying it, but it will surely give better accurate results. Proper mounting on the apparatus for load addition will also help to produce better results. Lastly, it is highly recommended that the force used to pull the steer beam is being done by a slow start/stop pulling machine which will give chance to take picture of the deflected tire.

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