PERFORMANCE ANALYSIS ON THE INFLUENT OF FRONT TYRES MOVEMENT TO THE STEERING WHEEL SYSTEM FOR STEADY AND RIDE ROAD CONDITIONS

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I certify that the project entitled "*Performance Analysis on the Influent of Front Tyres Movement to the Steering Wheel System for Steady and Ride Road Condition*" is written by *Engku Izyan Munirah binti Engku Afandi*. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

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Examiner	Signature

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Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

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DECEMBER 2010

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this project and in our opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

....

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Dedicated to my family and friends

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ABSTRACT

This thesis concerns with the experimental analysis of the influent of front tyre movement to the steering system. The objective of this thesis is to analyse the relationship between steering wheel and tyres direction and also with speed while cornering for steady and ride road condition. The thesis describes the method to collect the on road performance data between steering wheel and tyre movement. Two different driving maneuver had been evaluate for this study purpose which are steady state cornering with constant radius and zigzag cone test. The test is perform in Universiti Malaysia PAHANG (UMP) and the data used for the analysis is obtained by using UMP Test Car which has been installed with wheel steering sensor and DEWESOFT software for data acquisition purpose. The post processing method was performed by using FlexPro and Microsoft Office Excel. The post processing method in FlexPro to determine the steering and wheel steer angle is being done by using FPScript function. The results of analysis were represented in spline curve graph of steering angle and wheel steer angle versus time. Comparisons between steering angle and wheel steer angle profile are made. The post processing method in Microsoft Office Excel is to determine the graph of steering angle versus tire direction and also steering angle versus speed. From the graph represented, some discussions are made to analyse each relationships. Comparisons between all the tests are made in achieving the conclusion. It has been observed that the vehicle is in understeer condition in all tests. The result concluded that the understeer condition is dependant on the slip angles and forces acting on the tires.

ABSTRAK

Tesis ini mempertimbangkan eksperiment tentang pengaruh gerakan roda hadapan terhadap sistem kemudi. Tujuan tesis ini adalah untuk menganalisis hubungan antara arah gerakan roda hadapan dan sistem kemudi untuk keadaan jalan stabil dan permukaan jalan yang kasar. Tesis ini menjelaskan kaedah untuk mengumpul data prestasi jalan antara sistem kemudi dan gerakan roda. Dua manuver pemanduan berbeza telah dinilai untuk tujuan kajian iaitu steady state menikung dengan radius dan zigzag uji kon. Ujian ini dijalankan di Universiti Malaysia Pahang (UMP) dan data yang digunakan untuk analisis diperoleh dengan menggunakan Kereta Ujian UMP yang telah dipasang dengan sensor sistem kemudi dan perisian DEWESOFT untuk tujuan pengambilalihan data. Kaedah proses pasca dilakukan dengan menggunakan FlexPro dan Microsoft Office Excel. Pengolahan pasca kaedah FlexPro untuk menentukan sudut roda kemudi dan sudut gerakan roda hadapan dilakukan dengan menggunakan fungsi FPScript. Keputusan analisis diwakili dalam bentuk graf kurva spline untuk graf sudut kemudi dan sudut roda hadapan terhadap masa. Perbandingan antara profil sudut kemudi dan sudut roda hadapan dilakukan. Pengolahan pasca menggunakan kaedah Microsoft Office Excel adalah untuk menentukan graf sudut kemudi melawan arah roda hadapan dan juga sudut kemudi melawan kelajuan. Dari graf yang diperoleh, beberapa perbincangan telah dibuat untuk menganalisis setiap hubungan. Perbandingan antara semua ujian dilakukan dalam mencapai kesimpulan. Hal ini telah diamati bahawa kenderaan berada di dalam keadaan understeer dalam kesemua ujian. Hasilnya disimpulkan bahawa keadaan understeer bergantung pada sudut gelincir dan daya yang terhasil pada roda.

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LIST OF SYMBOLS

δ_o	Outer Ackerman angle
δ_i	Inner Ackerman angle
L	Wheelbase
t	Kingpin center to center
R	Turning radius
β	Sideslip angle
v	Constant velocity
ω	Angular velocity
m	Vehicle mass
F_{x1}	Longitudinal force at front axle
F_{x2}	Longitudinal force at rear axle
F_{y1}	Vertical force at front axle
F_{y2}	Vertical force at rear axle
F_D	Driving force
k	Different driving coefficient
R1	Radius 1
R2	Radius 2
R3	Radius 3
R4	Radius 4
V	velocity

LIST OF ABBREVIATIONS

UMP	Universiti Malaysia Pahang
SAI	Steering Axis Inclination
ABS	Anti-Lock Braking System

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

The steering system is the primer interface between the driver and the vehicle, through which the driver inputs his intentions to control the vehicle direction, and from which the driver receives important information about the vehicle state of motion and road condition from the steering torque. Consequently, the steering system characteristic has a great effect on the driver's, and vehicle response towards driver's input. The front wheels are reserved for the steering duties which it perform two functions, both the cornering forces and the engine acceleration/deceleration forces. So in a front drive the tires capacity can be easily exceeded. In a rear drive car the rear tires handle the engine acceleration/deceleration while the front only needs to handle the steering forces. Not only does this balance the load on the tires but it reserves the front tires exclusively for the all important steering duties.

1.2 PROBLEM STATEMENT

Steering of vehicles on a slippery highway is a difficult task for most passenger car drivers. The vehicles tend to slide outward with less lateral forces than on normal roads. When the drivers notice that their vehicles on a slippery highway start to depart from the cornering lane, most of them easily panic and make a sudden steering and/or braking, which in turn may induce spin-out and instability on their vehicles.

While driving, vehicle often bump into patholes and rocks and this will cause vibration at wheels. The vibration that occurs will somehow transmit to the steering wheel and cause the steering to vibrate. It will cause oversteer, understeer and neutral steer to the vehicle. The angle produce at the rear wheel is larger than front wheel, it will produce oversteer and make the vehicle turn into curve more than the driver intended.

While steering a vehicle, there is an effort has to be applied by driver at steering wheel to overcome frictional force that occurs between the wheels and the roads. By studying the function of steering gear, this effort can be reduces and steering wheels will turn easier.

In order to have better performance in wheel handling and while cornering, the relationship between steering wheel and tyre direction, speed and toe angle should be determined. The data between steering wheel and tyre movement in various driving manuever should be obtain to study the effect of driving maneuver to the on-road performance.

1.3 OBJECTIVES

i. To collect the on-road performance data between steering wheel and tyre movement in various driving maneuver.
ii. To analyse the relationship between steering wheel and tyres direction, and speed while cornering for steady and ride road condition.

1.4 WORK SCOPES

The scopes of the project as follow:

i. Literature review about steering system and front wheel movement
ii. Preparations on procedures for testing
iii. Run testing based on procedures for steady and ride road condition
iv. Analyse the results obtained for steering-tyre performance analysis
v. Discuss and conclude the project in the final report

1.5 PROCESS FLOW CHART

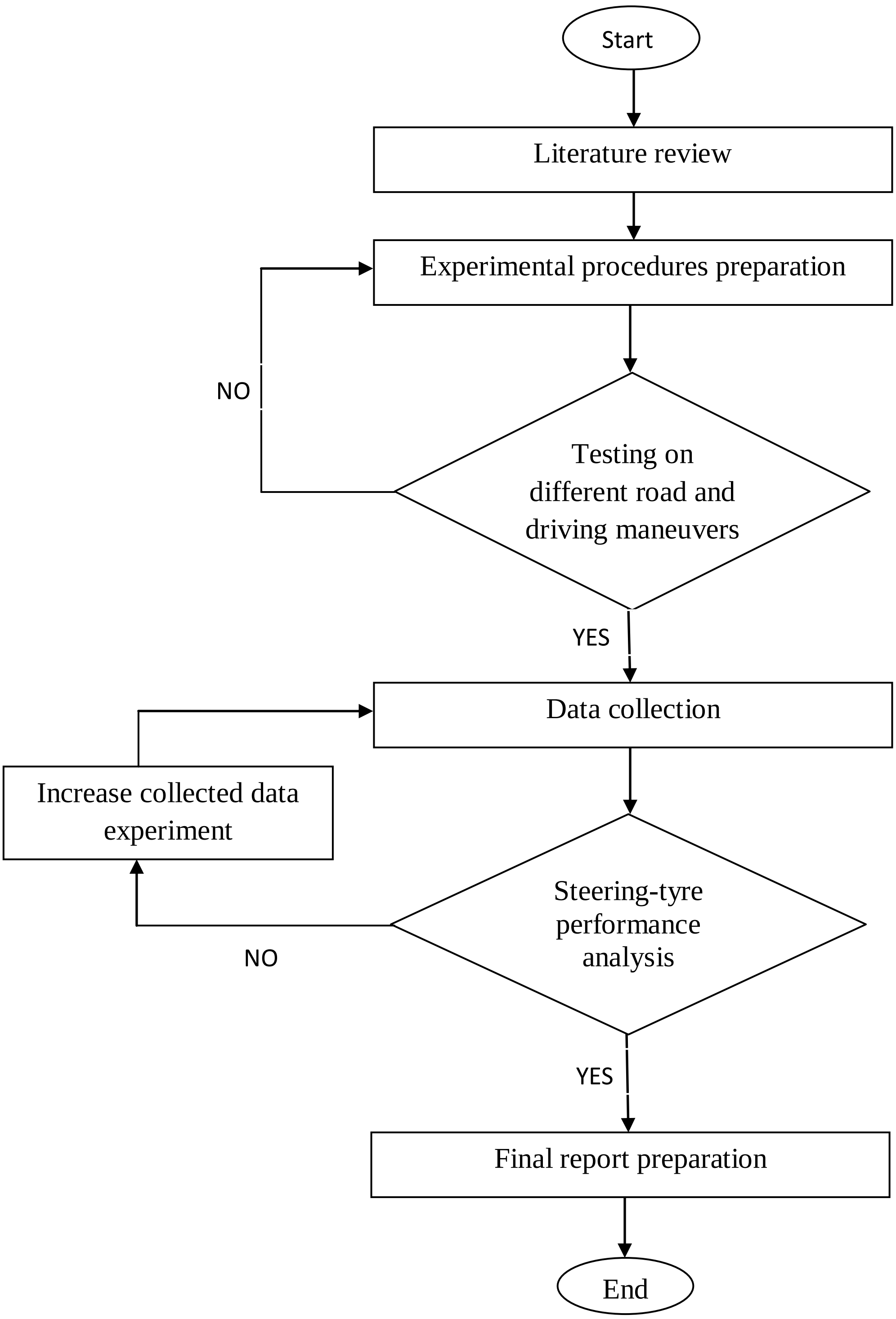


Figure 1.1: Project flow chart

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL FEATURES OF A STEERING SYSTEM

Steering is the term applied to the collection of components, linkages, etc. which allow a car or other vehicle to follow a course determined by its driver, except in the case of rail transport by which rail track combined together with railroad switches provide the steering function. The function of the steering system is to enable the driver to control the orientation of the front wheels and thereby control the overall direction of the vehicle (Gurgenci, 2001). The steering system will receives rotary or circular input from the driver at the steering wheel and changes it to lateral, or side-to-side, movement at the outer tie rod ends. This system will direct the wheels so that the vehicle can change direction in response to commands from the driver. The system provides directional change in the performance of an automobile which it converts rotary movements of the steering wheels into an angular movement of the front wheels.

2.2 MECHANISM OF STEERING WHEEL

When turning the steering wheel of our car, the wheels turn. There are causes and effect why do these things happen. From Figure 2.1, both of the front wheels are not pointing in the same direction when the car is steered. For a car to turn smoothly, each wheel must follow a different circle. Since the inside wheel is following a circle with a smaller radius, it is actually making a tighter turn than the outside wheel. When a perpendicular line is drawn to each wheel, the lines will intersect at the center point of the turn. The geometry of the steering linkage makes the inside wheel turn more than the outside wheel.

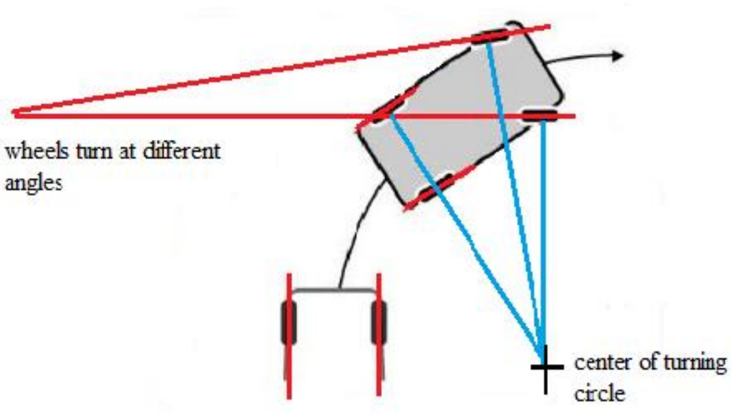


Figure 2.1: Turning the car

Source: How does car steering works, www.scribd.com

There are two most common types of car steering gear systems work, which is rack-and-pinion and recirculating-ball steering.

2.2.1 Rack-and-pinion steering

A rack-and-pinion gearset is enclosed in a metal tube, with each end of the rack protruding from the tube. A rod, called a tie rod, connects to each end of the rack. The pinion gear is attached to the steering shaft. When you turn the steering wheel, the gear spins, moving the rack. The tie rod at each end of the rack connects to the steering arm on the spindle as shown in Figure 2.2. The gearset does two things which are first, it converts the rotational motion of the steering wheel into the linear motion that is needed to turn the wheels and second, and it provides a gear reduction which makes it easier to turn the wheels.

In other words, rack and pinion system consists of a linearly moving rack and pinion, mounted on the firewall or a forward crossmember, which it steers the left and right wheels directly by a tie rod connection. The tie rod linkage connects to steering arms on the wheels and thereby controlling the steer angle (Gillespie, 2007).

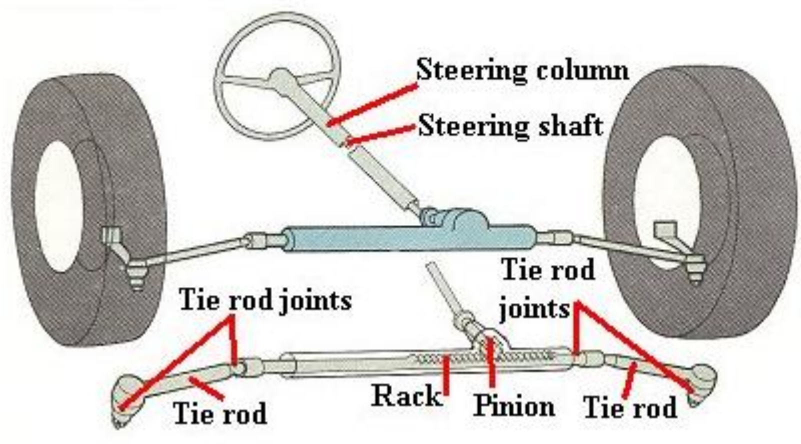


Figure 2.2: Rack and pinion steering

Source: www.motorera.com

2.2.2 Recirculating-ball steering

The linkage that turns the wheels is slightly different. The recirculating-ball steering gear contains a worm gear. The steering wheel connects to a threaded rod, similar to a bolt that sticks into the hole in the block. When the steering wheel turns, it turns the bolt. Instead of twisting further into the block the way a regular bolt would, this bolt is held fixed so that when it spins, it moves the block, which moves the gear that turns the wheels. Instead of the bolt directly engaging the threads in the block, all of the threads are filled with ball bearings that recirculate through the gear as it turns as shown in Figure 2.3. The balls actually serve two purposes: First, they reduce friction and wear in the gear; second, they reduce slop in the gear. Slop would be felt when you change the direction of the steering wheel, without the balls in the steering gear, the teeth would come out of contact with each other for a moment, making the steering wheel feel loose.

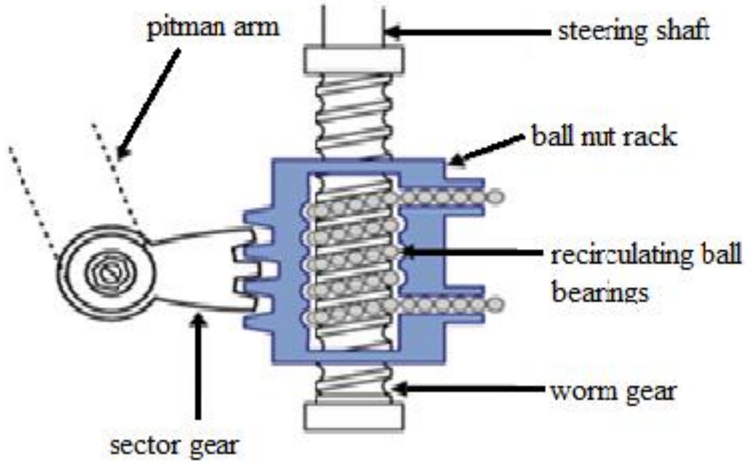


Figure 2.3: Recirculating ball steering

Source: How does car steering works, www.scribd.com

2.3 PRINCIPLES OF STEERING GEOMETRY

The safety, stability handling and performance of a vehicle depend on many factors and one of the most important aspects of these characteristics is the design of the steering system. There is several alignment geometry angles which relate to the steering linkages that will influence the easiness with which the vehicle can be steered, the steering stability and the tire wear. The angles relate includes:

2.3.1 Caster

Caster is the tilt of the steering axis of each front wheel as viewed from the side of the vehicle and it is measured in degrees of an angle (Layne, 2002). The caster angle is a directional control geometry angle that helps keep the vehicle moving straight ahead. If the steering axis is steered backward, the caster angle is positive and if it is tilts forward, the caster is negative.

Caster angle affects straight line stability and steering wheel return. High positive caster angle makes the front wheels want to go straight ahead and a normal positive caster angle provides stability and makes the steering wheel straighten out after turning. In other words, positive caster increases the effort needed to turn the wheel.

Too little caster angle can result in unstable steering and cause wheel shimmy. Extreme negative caster angle and the related shimmy can contribute to cupped wear of front tires.

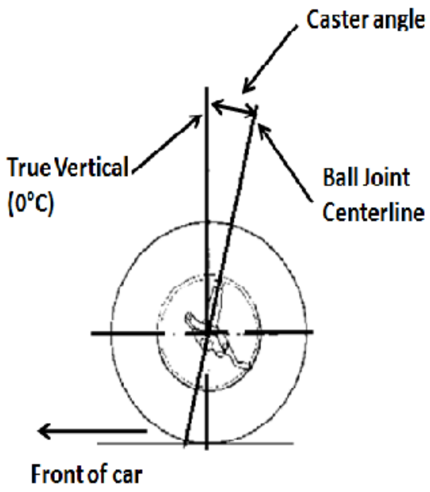


Figure 2.4: Caster Angle

Source: Layne, 2002

2.3.2 Camber

Camber is the inward or outward angle of the wheels when viewed from the front of the vehicle and is measured in degrees of an angle. When the tire appears to tilt outward at the top, the camber angle is positive while it is negative camber angle when the top of the tire is tilt inwards, as shown in Figure 2.6.

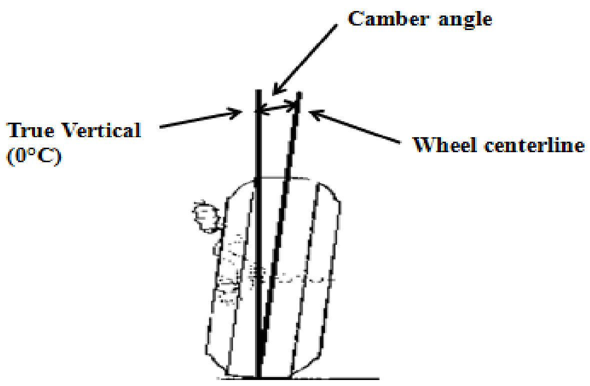


Figure 2.5: Camber angle

Source: Layne, 2002

Positive camber angle affects straight ahead stability and steering wheel return. As the vehicle turns, the outside suspension tends to rise on the wheel because of the positive camber. When the wheel returns to straight ahead position, the vehicles weight presses down on the steering axis and helps straighten the wheel.

Negative camber angle resists the tendency of the tire to slip sideways during cornering and also can increase steering effort. Most cars and light trucks designed to have positive chamber angle where as race cars and some high performance street vehicles have negative chamber angle.

Figure 2.6: Positive, Zero and Negative Camber Angle

Source: Layne, 2002

2.3.3 Toe

Toe is the difference in length of each axle is difference from each other, the front to the rear wheels in straight ahead position. Toe is measured at the center of the wheels from one wheel rim to the other.

Toe in is when the displacement is greater at the rear wheels and it is called toe out when the distance is greater at the front of the wheels. Rear wheel drive vehicles usually will have small amount of toe in at the front wheels so that it will allow the wheels to toe out when rolling to achieve zero running toes. Toe in, toe out and zero toe are shown in Figure 2.7.

Front wheels are usually toed in on rear drive vehicles and toed out on front drives to compensate for changes in the steering linkage and tires when the vehicle is moving (Layne, 2002). When the vehicle is moving, toe decreases because the wheels straighten out under acceleration and the steering linkages flexes slightly.

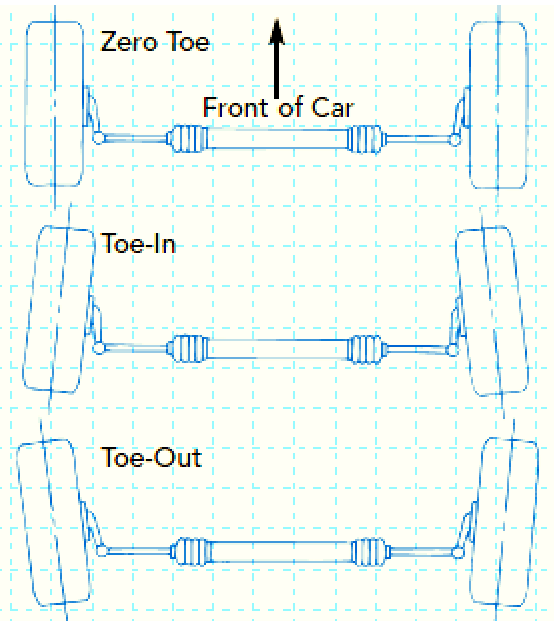


Figure 2.7: Zero toe, toe in and toe out

Source: Layne, 2002

2.3.4 Toe Out on Turns

Toe out on turns also referred as turning angle and it results from the different angles taken by the front wheels when driving through a corner. As vehicle turns, the outside front wheel turns at a lesser angle than the inside wheel as shown in Figure 2.8. This result in the front tires to toe out during cornering.

Some amount of toe out on turns is necessary because the outside wheel must turn on larger radius than the inside wheel (Layne, 2002). If the wheel turning angles are equal, the outside tire would scuff as it tried to turn on shorter radius.

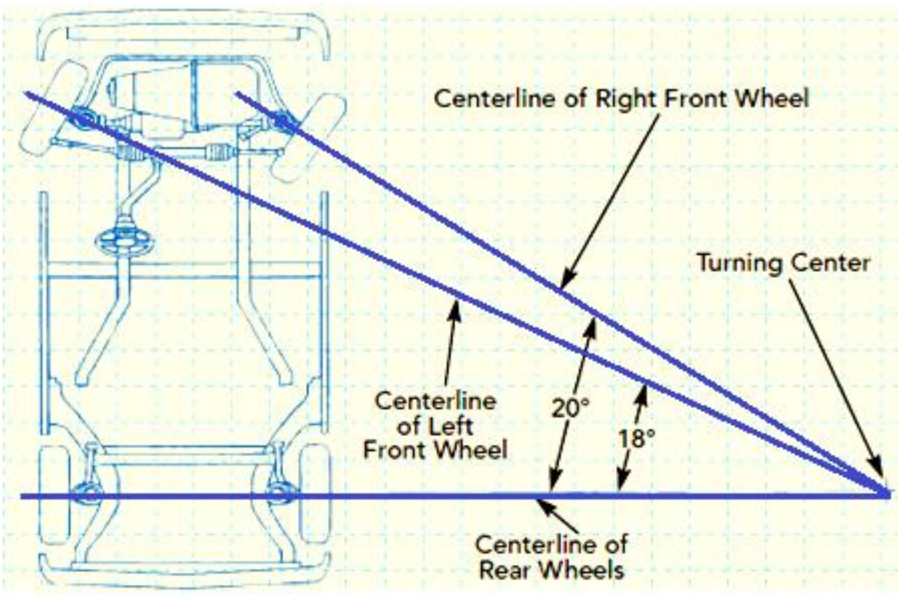


Figure 2.8: Toe Out on Turns

Source: Layne, 2002

2.3.5 Steering Axis Inclination (SAI)

Steering Axis Inclination is the tilt of steering axis from vertical as viewed from the front (Layne, 2002). It is an angle formed by a line through the centers of the lower and upper ball joints of the strut mount. Steering axis inclination affects steering feel and stability. SAI results in self-correcting forces that cause the front wheels and steering wheel to return to a straight ahead position after cornering.

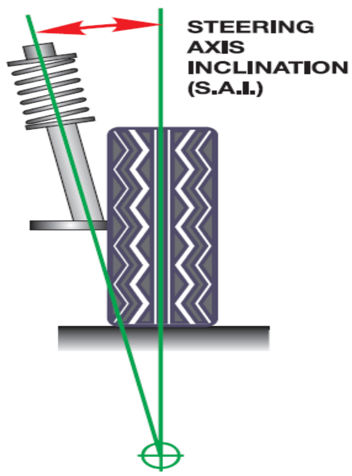


Figure 2.9: Steering Axis Inclination

Source: Layne, 2002

2.4 CORNERING DYNAMICS

According to Newton's First Law, a moving body will continue moving in a straight line until it is acted upon disturbing force. Newton's Second Law refers to the balance that exists between the disturbing force and the reaction of the moving body. In the case of automobiles, whether the disturbing force is in the form of an incline in the roadway or the cornering forces produced by the tires, the force causing the turn and the force resisting the turn will always be in balance.

2.4.1 Tires in a turn

At low speeds such as parking lot maneuvers, the vehicle turns according to the geometric alignment of the wheels. The wheels roll in the direction they are heading and the vehicle turns about the point establish by the projection of the front axles intersecting a projection of the rear axle (Riley, 2004). As the speed increases, the actual turn center moves forward due to slip angle of the tires.

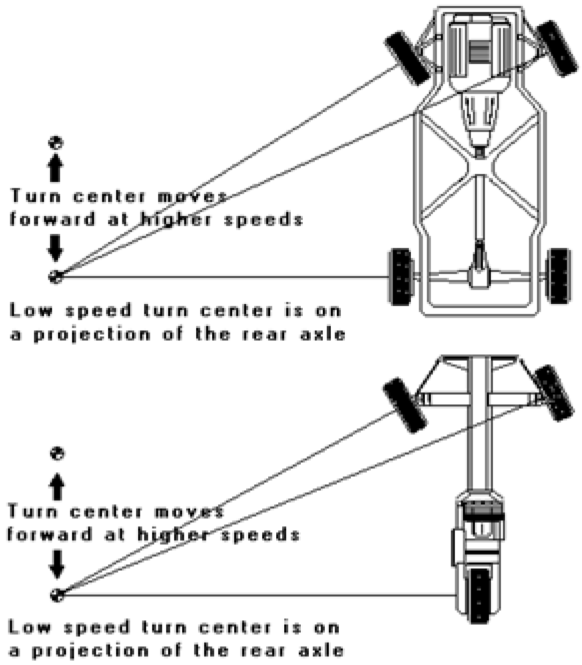


Figure 2.10: Vehicle Turn Center

Source: Riley, 2004

2.4.2 Slip Angle

Slip angle is related to the lateral load or cornering force of the tire. As lateral loads increase due to higher cornering speeds, tires creep to the outside of the turn and therefore move in a direction that is different from heading. The difference between the tires heading and the direction of travel is called the slip angle (Riley, 2004).

Vertical load on the tires has an effect on the lateral cornering force generated at a given slip angle. In general, the cornering force increases as the vertical load increases, but the increases are not proportional to the load. The tires ability is to develop cornering force, in relation to its vertical load and it is known as cornering coefficient.

Another cornering force comes from the tires camber angle. When the tire rolls at camber angle, it will generate a lateral force in the direction in which it is leaning. The lateral force is known as camber thrust. The thrust produced by camber angle is much less than the force produced by slip angle.

2.4.3 Oversteer and Understeer

The weight bias of the vehicle determines it's natural oversteer or understeer characteristic. A vehicle that is heavier at the front will tend to understeer and one that is heavier at the rear will oversteer (Riley, 2004). A vehicle in which weight is equally distributed between the front and rear axles tend to exhibit neutral steer characteristics, as shown in Figure 2.11. Although the neutral understeer or oversteer characteristics of a vehicle are determined by its weight distribution, the design of the suspension and the selection of wheel and tire size can enhance or moderate those characteristics.

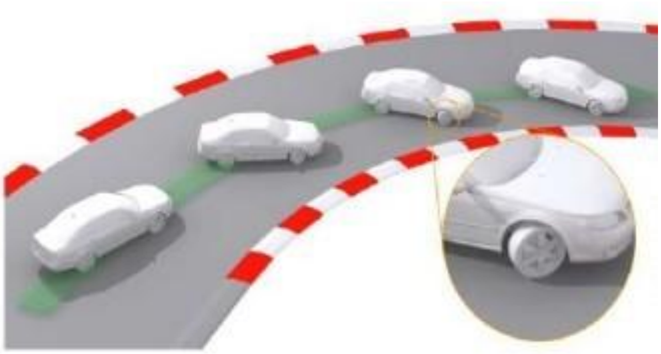


Figure 2.11: Neutral steer condition

Source: Riley, 2004

Understeer results when the slip angle of the front tires is greater than the slip angle of the rear tires. A greater steering angle is then required in order to maintain the turn (Riley, 2004). When the steering angle reaches full lock and the turn cannot be maintained, the vehicle drifts to the outside, as shown in Figure 2.12.

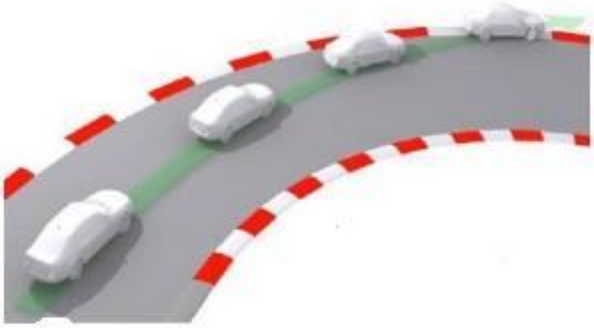


Figure 2.12: Understeer condition

Source: Riley, 2004

During oversteer condition; the slip angle of the rear tires is greater than the front (Riley, 2004). As a result, the turn rate increases on its own and the driver therefore reduces the steering angle to balance. During severe oversteer, the steering angle may reach full lock in the opposite direction while the vehicle continues on into the turn. The vehicle is then said to spin out, as shown in Figure 2.13.

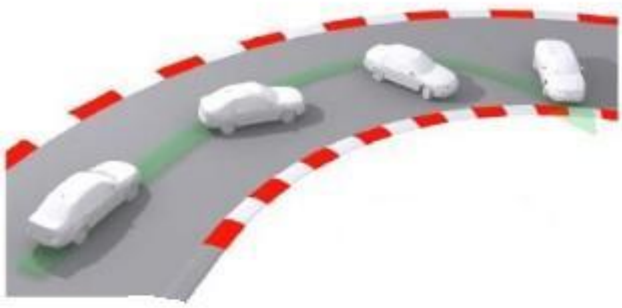


Figure 2.13: Oversteer condition

Source: Riley, 2004

2.5 ACKERMAN STEERING

Ackerman Steering is the relationship between front inside tire and front outside tire in a corner or curve. The principle defines the steering geometry where the inside tire needs to turn tighter than the outside tire. This allows both tires to roll around a common point in a corner or curve. By performing this principle, cornering ability and performance can be improved.

There are three types of Ackerman Steering which is True Ackerman, More Ackerman and Less Ackerman Angle. True Ackerman angle occur when a line drawn from the both kingpins and pillow balls through the steering arm mounting points intersect on the center line of the rear axle.

Having a high Ackerman factor is useful in taking tight corners at low speed. As a general rule, More Ackerman Angle will make the steering response smoother and vehicle will react smoothly to any steering input. For Less Ackerman angle, the initial steering response will be more direct and vehicle will react faster to any steering input.

All four wheels are rotating around the same centre as shown in Figure 2.14. This means none of them will slip. This can only be accomplished if the two front wheels are not parallel but there is an angle between them. This angle is called the Ackerman angle.

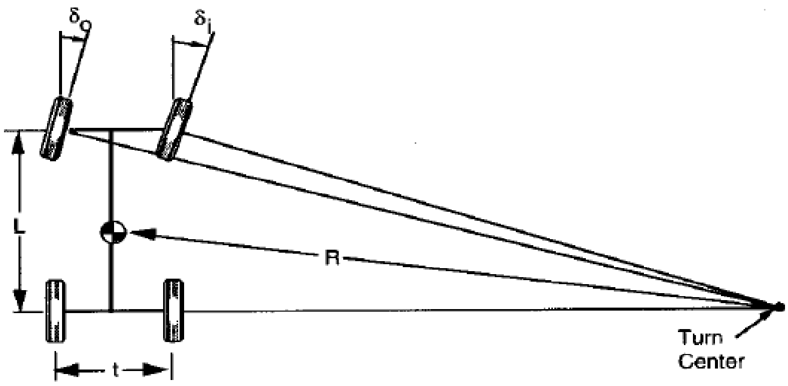


Figure 2.14: Ackerman Steering Geometry

Source: Gillespie, 2007

From analysis of the triangles in Figure 2.14, it shown that correct Ackerman geometry requires that;

$$\delta_o = \tan^{-1} \frac{L}{(R + t/2)} \approx \frac{L}{(R + t/2)} \quad (2.1)$$

$$\delta_i = \tan^{-1} \frac{L}{(R - t/2)} \approx \frac{L}{(R - t/2)} \quad (2.2)$$

$$\text{Ackerman Angle} = \delta_i - \delta_o \quad (2.3)$$

Where L is the wheelbase, t is the kingpin center to center and R is the turning radius.

For small angles, as for most turning, the arctangent of the angle is very nearly equal to the angle itself (in radians) (Gillespie, 2007).

2.6 FORCES AT TIRES

Driving dynamics deals with the mechanical laws that govern a vehicle’s motion with respect to the vehicle’s properties and the ones of the road. The description of the vehicle performance is very complex and mathematical models are required for the design and construction of the vehicles themselves (Pozuelo et al., 2007). The longitudinal force in a straight path causes a driving tractive or braking movement. During cornering, the front wheels are at an angle to the longitudinal axis of the vehicle, thereby causing the development of a lateral force.

The lateral tire force is the necessary force to hold a vehicle through a turn (Doumiati et al., 2010). It is generated by the lateral tire deformation in the contact patch as illustrated in Figure 2.15. The angle of deformation or the difference between the tires’s heading and velocity is known as tire slip angle. The tire lateral force is usually represented in function of its sideslip angle. The general characteristics of the lateral forces are it grows linearly for small slip angles and it ultimately levels off. This is due to the limits of tire adhesion.

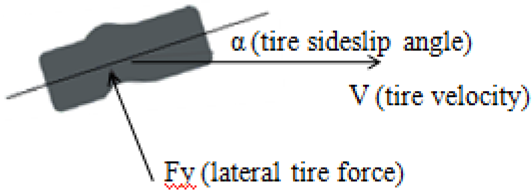


Figure 2.15: Lateral tire deformation

Source: Doumiati et al., 2010

In a body fixed reference frame B (Rill, 2009) as in Figure 2.16, the velocity state of the vehicle can be describe by

$$v_{0C,B} = \begin{bmatrix} v\cos\beta \\ v\sin\beta \\ 0 \end{bmatrix} \quad \text{and} \quad \omega_{0F,B} = \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \tag{2.4}$$

where β is the sideslip angle of the vehicle measured at the center of gravity. The angular velocity of a vehicle cornering with constant velocity v on a flat horizontal road is given by

$$\omega = v/R \tag{2.5}$$

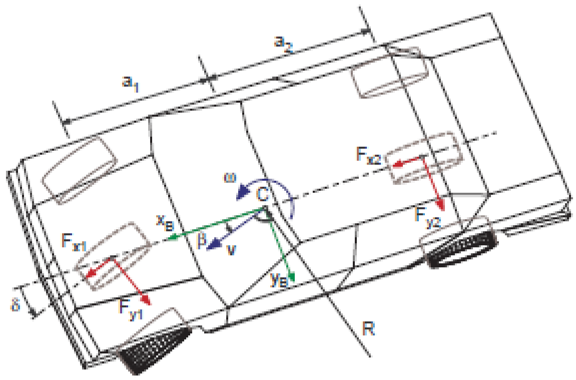


Figure 2.16: Cornering Resistance

Source: Rill, 2009

where R is the radius of curvature.

In the body fixed reference frame, linear and angular momentum result in

$$m\left(-\frac{v^2}{R}\sin\beta\right) = F_{x1}\cos\delta - F_{y1}\sin\delta + F_{x2} \tag{2.6}$$

$$m\left(-\frac{v^2}{R}\cos\beta\right) = F_{x1}\sin\delta + F_{y1}\cos\delta + F_{y2} \tag{2.7}$$

$$0 = a_1\left(F_{x1}\sin\delta + F_{y1}\cos\delta\right) - a_2 F_{y2} \tag{2.8}$$

where m is the mass of the vehicle, F_{x1}, F_{x2}, F_{y1}, F_{y2} are the resulting forces in longitudinal and vertical direction applied at the front and rear axle, and δ specifies the average steer angle at the front axle.

The engine torque is distributed by the center differential to the front and rear axle. Then, in steady state condition result in

$$F_{x1} = k\,F_D \quad \text{and} \quad F_{x2} = (1-k)F_D \tag{2.9}$$

where F_D is the driving force and by k different driving conditions, can be modeled as:

$k = 0$ rear wheel drive $F_{x1} = 0, F_{x2} = F_D$

$0 < k < 1$ all wheel drive $\frac{F_{x1}}{F_{x2}} = \frac{k}{1-k}$

$k = 1$ front wheel drive $F_{x1} = F_D, F_{x2} = 0$

Insert Eq.(2.9) into Eq. (2.6);

$$\begin{aligned} (k\cos\delta + (1-k))F_D - \sin\delta\, F_{y1} &= -\frac{mv^2}{R}\sin\beta, \\ k\sin\delta\, F_D + \cos\delta\, F_{y1} + F_{y2} &= \frac{mv^2}{R}\cos\beta, \\ a_1 k\, sin\delta\, F_D + a_1\cos\delta F_{y1} - a_2 F_{y2} &= 0 \end{aligned} \tag{2.10}$$

These equations can be resolved for the driving force

$$F_D = \frac{\frac{a_2}{a_1+a_2}\cos\beta\sin\delta - \sin\beta\cos\delta}{k+(1-k)cos\,\delta}\,\frac{mv^2}{R} \tag{2.11}$$

The driving force will vanish if

$$\frac{a_2}{a_1+a_2}\cos\beta\sin\delta = \sin\beta\cos\delta \qquad \text{or} \qquad \frac{a_2}{a_1+a_2}\tan\delta = \tan\beta \tag{2.12}$$

This is fully corresponds with the Ackerman geometry. But, the Ackerman geometry applies only for small lateral accelerations. In real driving situations, the sideslip angle of a vehicle at the center of gravity is always smaller than the Ackerman side slip angle. Then, due to $\tan\beta < \frac{a_2}{a_1+a_2}\tan\delta$ a driving force $F_D > 0$ is needed to overcome the cornering stiffness of the vehicle.

2.7 BACKLASH IN STEERING SYSTEM

Backlash is stated as a common fault that occurs in geared mechanisms, and this can produce inaccuracy or uncontrollability mechanism (Sarkar et al., 1997). In theory, backlash should be zero, but in actual practice some backlash should be allowed to prevent jamming.

The general purpose of backlash is to prevent gears from jamming, provide space for lubrication and also for differential expansion between the gear components and the housing as shown in Figure 2.16. Errors occur while machining the gear that leads to increasing possibility of jamming makes it necessary to increase the amount of backlash as same amount of cumulative errors. In other words, the smaller the amount of backlash, the more accurate must the machining of the gears. On the other hand, excessive backlash is objectionable, particularly if the drive is frequently reversing or if there is an overrunning load.

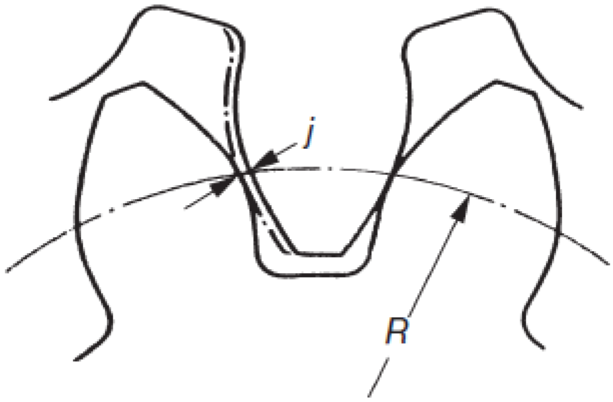


Figure 2.17: Backlash, j, between two gears

Source: Sarkar et al., 1997

2.8 ANTI-LOCK BRAKING SYSTEM

The four wheel ABS or Anti-lock Braking System is a safety system that prevents the wheels on a motor vehicle from locking up while braking (Sen, 2007). This system is designated to help the driver maintain steering control during hard braking, especially in slippery condition.

As an example, a driver drives a car without ABS on a slippery road, suddenly the driver notice something on the road and it hits the brake and try to turn aside. Despite of that, the car didn't turn because of the steering doesn't work and the car just skids out of control. This incident happens because all the wheels are locked up while the brake pedal is holding down. As a result, the driver loses the ability to steer the vehicle.

Under hard braking, an ideal braking system should provide the shortest stopping distances on all surfaces and maintain the vehicle stability and steerability. Thus, by using ABS, it can help much. It prevents the wheels from locking up, and help to maintain steering control during braking. In a similar situation as in the example, driving a car equipped with four wheels ABS, it would be easier to steer the vehicle while braking.

CHAPTER 3

METHODOLOGY

3.1 PROJECT GANTT CHART

The project gantt chart can be refer to Appendix A. The gantt chart shows the timeline for this project.

3.2 STEERING SENSOR

In this project, Hall Effect angle sensors with round case, as illustrated in Figure 3.1 is used. This sensor is applicable in automotive, agricultural, earth-moving machinery, industrial, railway and nautic fields. This sensor measures speed of the steering wheel and steering angle. This sensor cans measures angular range from $\pm15°$ to $\pm60°$. Dimensions and specifications of this sensor can be seen in Appendix B and C.

Figure 3.1: Hall Effect angle sensors with round case

Source: www.elenslr.it

3.3 DESIGN TESTING PROCEDURE

3.3.1 Purpose of SOP

SOP act as the guideline of the testing procedures when preparing for the car to be experimented in order to achieve the project objectives.

3.3.2 Scope of SOP

For this project, Proton Persona Sedan 1.6 Manual Transmission (MT) Base Line, as shown in Figure 3.2 is used.

Figure 3.2: Proton Persona Sedan 1.6 Manual Transmission (MT) Base Line (UMP Test Car)

Source: Faculty of Mechanical Engineering Universiti Malaysia Pahang

The speed for the car is limited on the SOP for the types of testing, refer Table 3.1. Types of testing on different types of road are listed in Table 3.2.

Table 3.1: Types of testing

No.	Test	Speed(km/h)
1.	• Roundabout test (Steady state cornering) Constant Radius and different speed	25, 30, 40,50
2.	• Cone Test (Rapid Cornering) Zigzag test(constant radius and different speed)	25, 30, 40, 50

Table 3.2: Types of roads

No	Types of roads	Purpose	Picture
1	Roundabout	Cornering test	 **Figure 3.3** : Roundabout radius 50m
3	Cone	Zigzag test and Lane Change	 **Figure 3.4** : Lane change

3.3.3 Safety Precaution

While conducting the testing, terms of safety are taken into considerations. In order to ensure the safety of the driver, passengers and vehicle, these precautions steps are taken:

i) The car condition needs to be checked. (i.e. wiper, signal, side and rear mirrors) and locked the door.

ii) The driver and passengers have to fasten the seat belt throughout the testing.

iii) The testing pathway ought to be clear and clean from unnecessary item and sand free.

iv) The traffic condition must be safe. If it is a necessary then placed the safety cones.

3.3.4 Experiment Statement

i) All the testing procedures have to begin by:

   a. All sensors placement and connection need to be checked and ensured to be attached correctly.
   b. The engine can be started.
   c. The power supply is switched on.
   d. The computer and the video camera are switched on.
   e. Starts the DEWESoft software and ensure all the sensors and camera are functional.

ii) The gear shifting for the experiment need to follow the maximum speed of each gear, refer Table 3.3.

Table 3.3: Maximum speed of gear.

Gear No.	**Speed of gear**
Gear 1	20km/j
Gear 2	40km/j
Gear 3	60km/j
Gear 4	80km/j
Gear 5	>80km/j

3.3.5 Testing Procedures

3.3.5.1 Steady State Cornering

The cornering testing took place at the roundabout 1 with outer diameter noted as R1 and inner diameter noted as R2 as illustrated in Figure 3.5. As before the beginning of the testing, the numbers of satellite reading have to be more than 8 and the steering angle is reset to be at 0 degrees. After that, the DEWESoft software system is ensured for a second time, to make sure all sensors are well functioned.

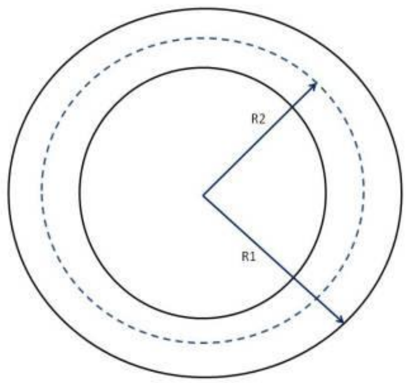


Figure 3.5: Roundabout 1 with inner and outer diameter

First, the car is drove at the inner diameter of the road until reached the speed of 25 km/h. The driver needs to follow the maximum velocity for each gear, refer Table 3.3 that has been set. When the velocity speed reached 25 km/h the recording started. It ended as the car finishes a complete circle of the roundabout which this can be referred on the GPS reading. This test is repeated for five times to ensure the reliability of data gained.

The test is repeated for 30 km/h and 40 km/h while at R1 is running the initial velocity at 25 km/h, 30km/h, 40 km/h and 50km/h. For inner diameter, R2 testing for 50 km/h is not done because of safety purpose which is already been considered.

After that, testing is proceed with roundabout 2 with outer diameter noted as R3 and inner diameter, R4 as illustrated in Figure 3.6. The test runs at same velocity 25 km/h, 30km/h and40 km/h.

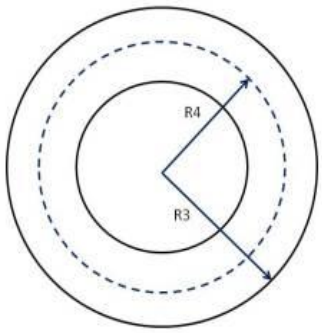


Figure 3.6: Roundabout 2 with inner and outer diameter

3.3.5.2 Zigzag test

The zigzag test followed the cone placement as set in Figure 3.7 for the guideline of the driver to maintain the speed. This zigzag test took place at the straight unpaved road that have rough surface. Before starts the recording, the numbers of satellite reading have to be more than eight and the steering angle need to be reset. Then the DEWESoft software system is confirmed again to be in well functioned.

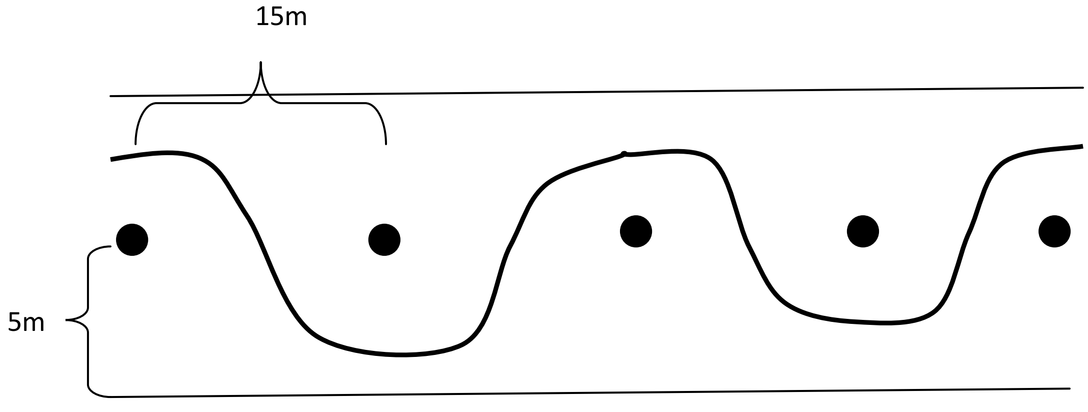


Figure 3.7: Cone placement for zigzag test

First, the car is drove until velocity 30 km/h is reached and maintained. The test is recorded when the front tire reached the first cone and ended when the rear tire passed by the last cone. This test is repeated five times and then followed by different constant velocity at 40 km/h and 60 km/h.

3.4 RESULTS AND ANALYSIS

3.4.1 DEWESoft

The data collected using steering sensor will then be transferred to DEWESoft software as shown in Figure 3.8. By using this software, data for steer angle, wheel steer angle and velocity is extracted. The data needed is transferred to FlexPro and Microsoft Office Excel to obtain several graphs.

Figure 3.8: DEWESoft Software

Source: Faculty of Mechanical Engineering, Universiti Malaysia Pahang

3.4.2 FlexPro

On every testing will be analyzed using the FlexPro such as shown in Figure 3.9. Whereby in this project will analyze on:

(a) The sensors respond to the velocity or direction of the car.
(b) The effects of road profile based on the analysis graphs that have been done.
(c) The influent of front tyre movement to steering wheel system.

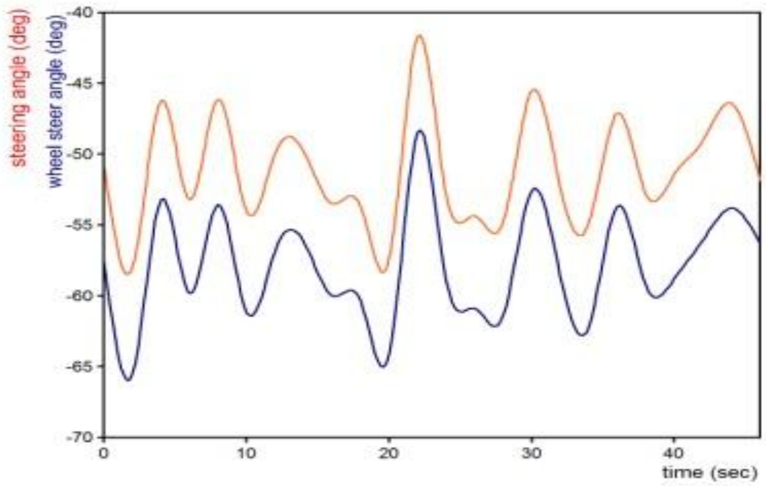


Figure 3.9: Graph of steering angle and steer wheel angle versus time

3.4.3 Microsoft Office Excel

To obtain several graphs, Microsoft Office Excel has been used. The data is before extracted and reduced from DEWESoft software. The average value for each data have been obtained to plot steering angle versus tire direction graph as shown in Figure 3.10 and also steering angle versus speed graph. The graph then had been analyse to find the relationship between each data.

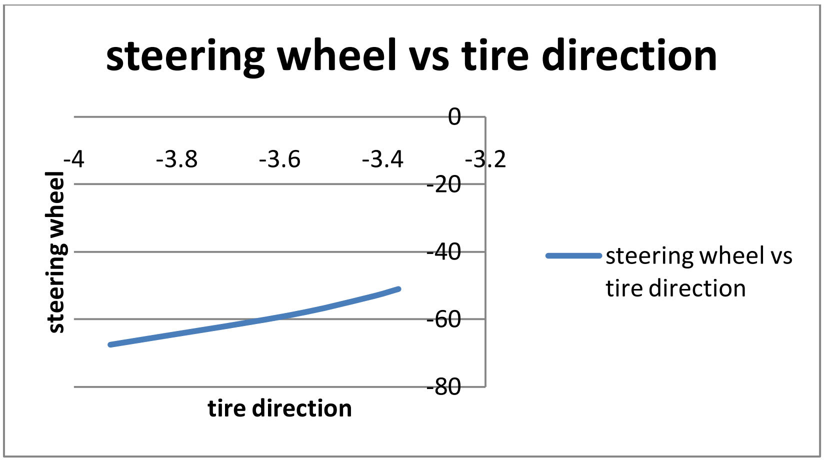


Figure 3.10: Graph of steering wheel versus tire direction

CHAPTER 4

RESULT AND DISCUSSION

4.1 STEADY STATE CORNERING

4.1.1 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 25 km/h

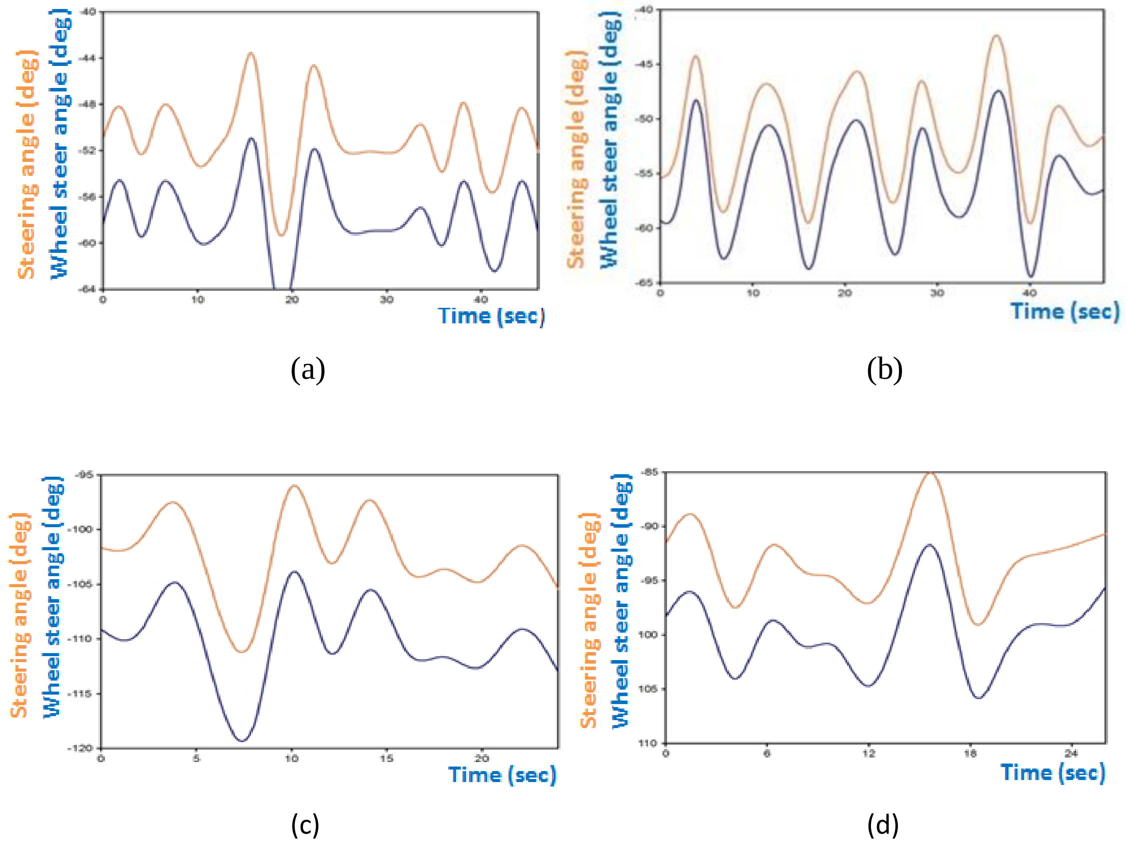
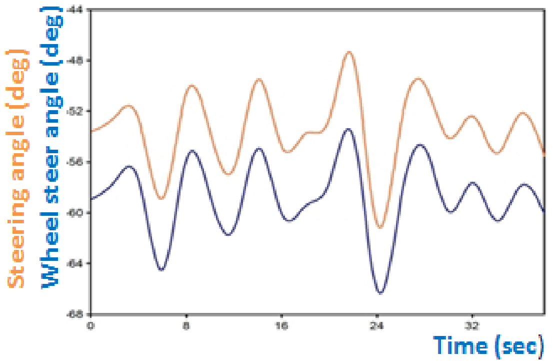


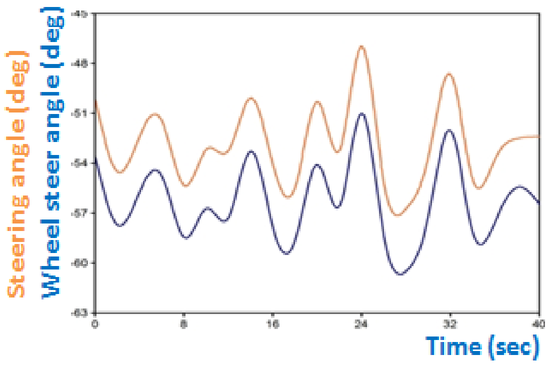
Figure 4.1: (a) Roundabout 1 inner diameter, (b) Roundabout 1 outer diameter, (c) Roundabout 2 inner diameter and (d) Roundabout 2 outer diameter

From Figure 4.1 (b), it shows that the steering angle and wheel steer angle produce have higher steering ratio compared to Figure 4.1 (a), (c) and (d). The higher the steering ratio produce, the easier it is to steer the vehicle. The higher the steering ratio produced, the more steering wheels have to be turned to achieve steering. In a rack-and-pinion steering system, the steering ratio is determined largely by the diameter of the pinion gear. From Figure 4.1 also, the relationship between steering angle and wheel steer angle can be determined. The profile graph for steering angle and wheel steer angle are the same. The difference between two graphs is large because at low speed, the wheel produce greater angle than steering wheel.

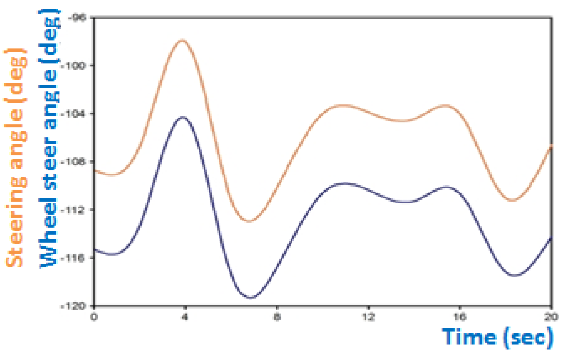
4.1.2 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 30 km/h



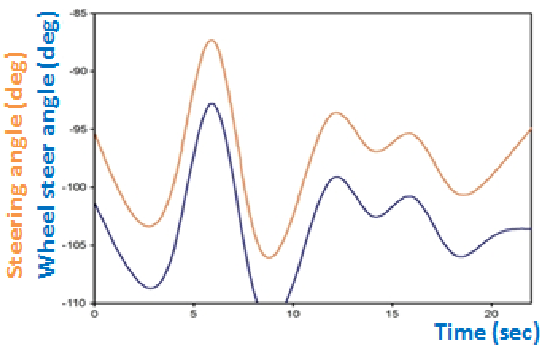
(a)



(b)



(c)



(d)

Figure 4.2: (a) Roundabout 1 inner diameter, (b) Roundabout 1 outer diameter, (c) Roundabout 2 inner diameter and (d) Roundabout 2 outer diameter

From Figure 4.2 (c), roundabout 2 inner diameter have the largest value of steering and wheel steer angle. Greater angle are required to maintain the turn to avoid vehicle from skidding. From Figure 4.2 also, the relationship between steering angle and wheel steer angle can be determined. The profile graph for steering angle and wheel steer angle are almost the same. The difference between two graphs is large because at low speed, the wheel produce greater angle than steering wheel.

4.1.3 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 40 km/h

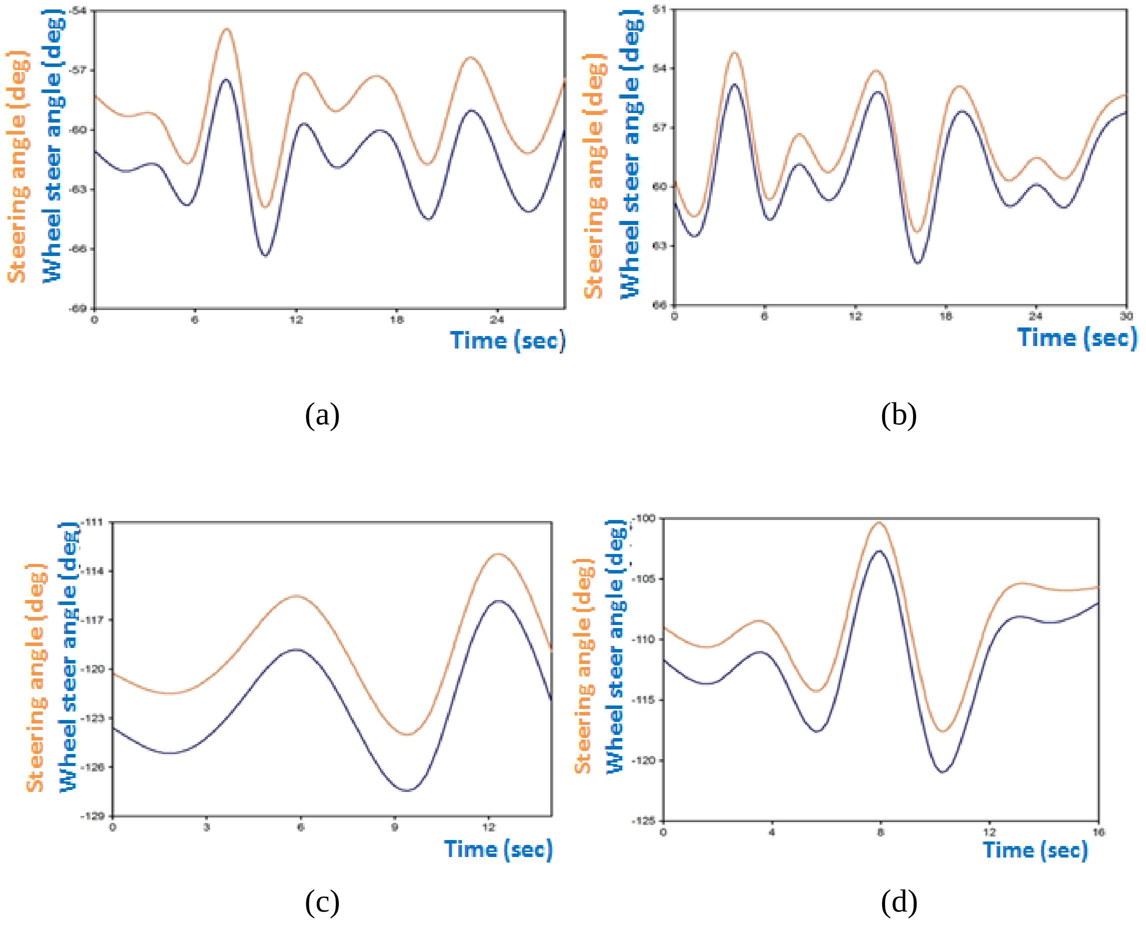
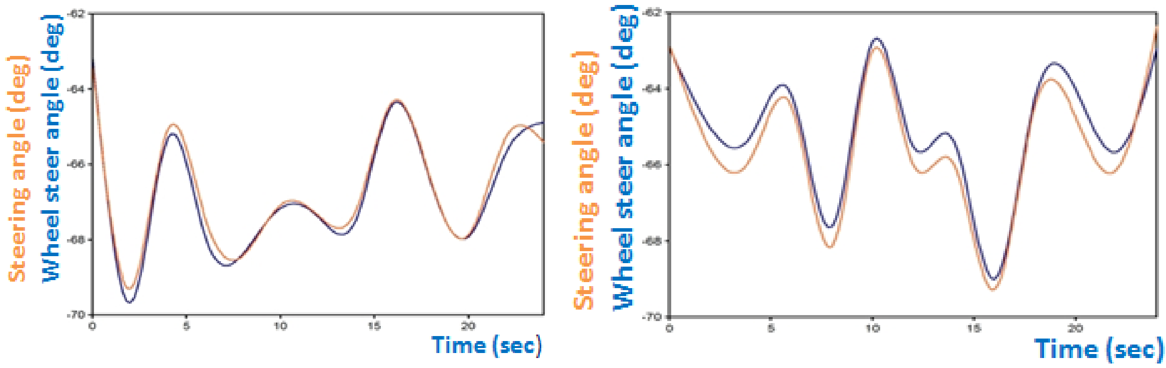


Figure 4.3: (a) Roundabout 1 inner diameter, (b) Roundabout 1 outer diameter, (c) Roundabout 2 inner diameter and (d) Roundabout 2 outer diameter

From Figure 4.3 (b), the steering angle and the wheel steer angle have almost the same value. This shows that at roundabout 1 outer diameter the wheel is acting as the same value of steering input. Thus, the vehicle can maintain the turn without skidding.

4.1.4 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 50 km/h



(a) (b)

Figure 4.4: (a) Roundabout 1 inner diameter, (b) Roundabout 1 outer diameter

For speed of 50 km/h, tests are run only at roundabout 1 inner and outer diameter due to safety precautions. Thus, at smaller radius of roundabout, higher speeds are not applicable.

From Figure 4.4 (a) and (b), it shows that the steering angle and wheel steer angle produce at high speed are almost equal. This means, the wheel producing an angle almost the same as steering angle input. As the speed increase, the steering angle and wheel steer angle is almost equal.

4.1.5 GRAPH OF STEERING ANGLE VERSUS TIRE DIRECTION

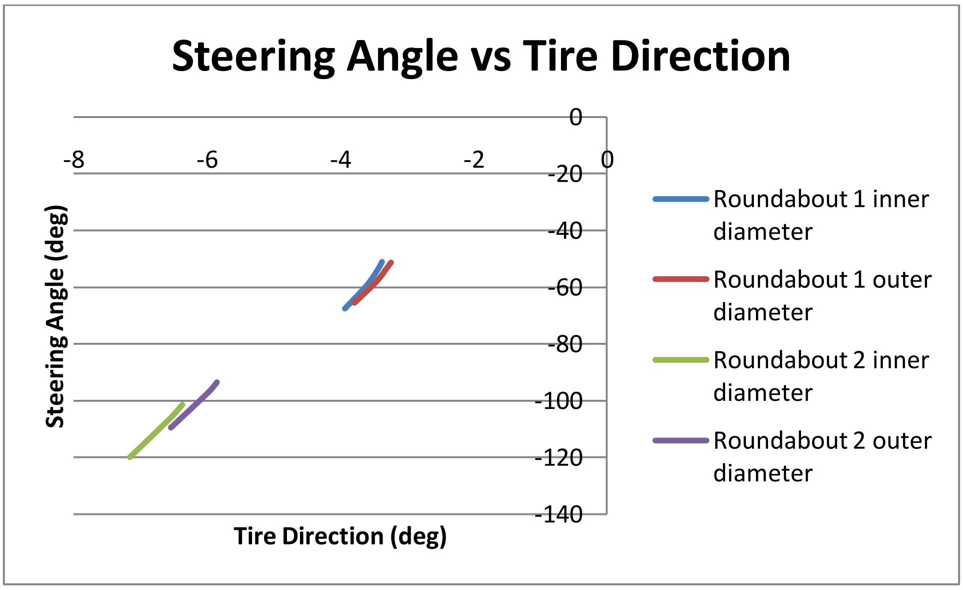


Figure 4.5: Graph of Steering Angle versus Tire Direction

Data form Appendix M is used to plot Figure 4.5 and for each figure plotted can be refer to Appendix E, F, G and H. From this graph, the steering wheel angle is increase with tire direction in negative value. The negative value shown the vehicle is moving to the right side.

As can be seen in Figure 4.5, all the tests produce similar profile which is it shows that the vehicle is in understeer condition. This shows that the slip angle produce at the front tires are greater than at the rear tires. Roundabout 2 inner diameter have greater steering and tire direction angle to maintain the turn while cornering. Lateral forces are getting higher to hold the vehicle through the turn.

4.1.5 GRAPH OF STEERING ANGLE VERSUS SPEED

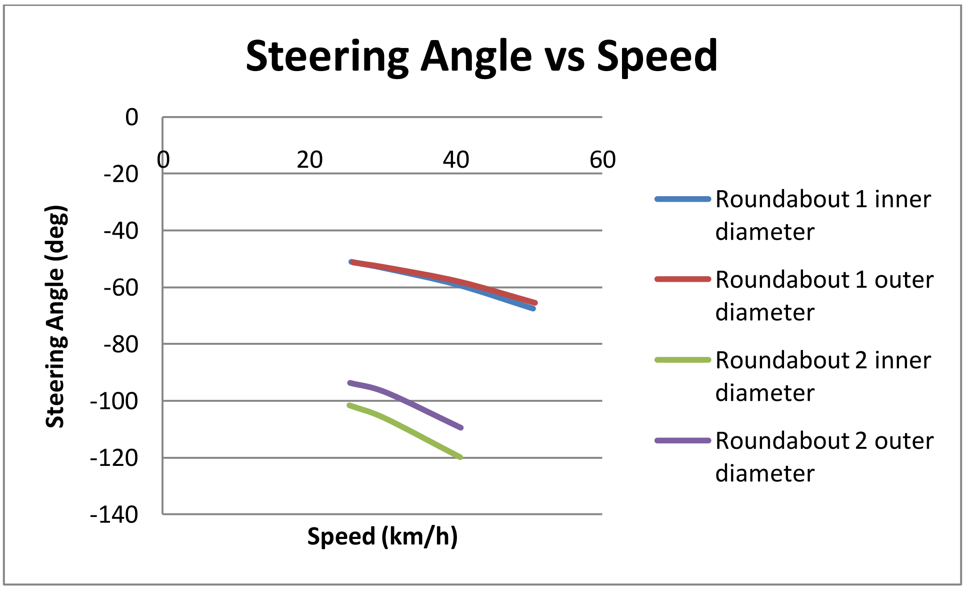


Figure 4.6: Graph of Steering Angle versus Speed

Data form Appendix M is used to plot Figure 4.6. Each figure plotted can be refer to Appendix E, F, G and H. From this graph, the steering wheel angle is increase with tire direction in negative value. The negative value shown the vehicle is moving to the right side.

As can be seen in Figure 4.6, all the tests produce similar profile which is it shows that the vehicle is in understeer condition. Front tires produced greater slip angles than the rear tires thus the vehicle can still maintain the turn without skidding.

4.2 ZIGZAG CONE TEST WITH 25 METER RADIUS

4.2.1 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 40 km/h

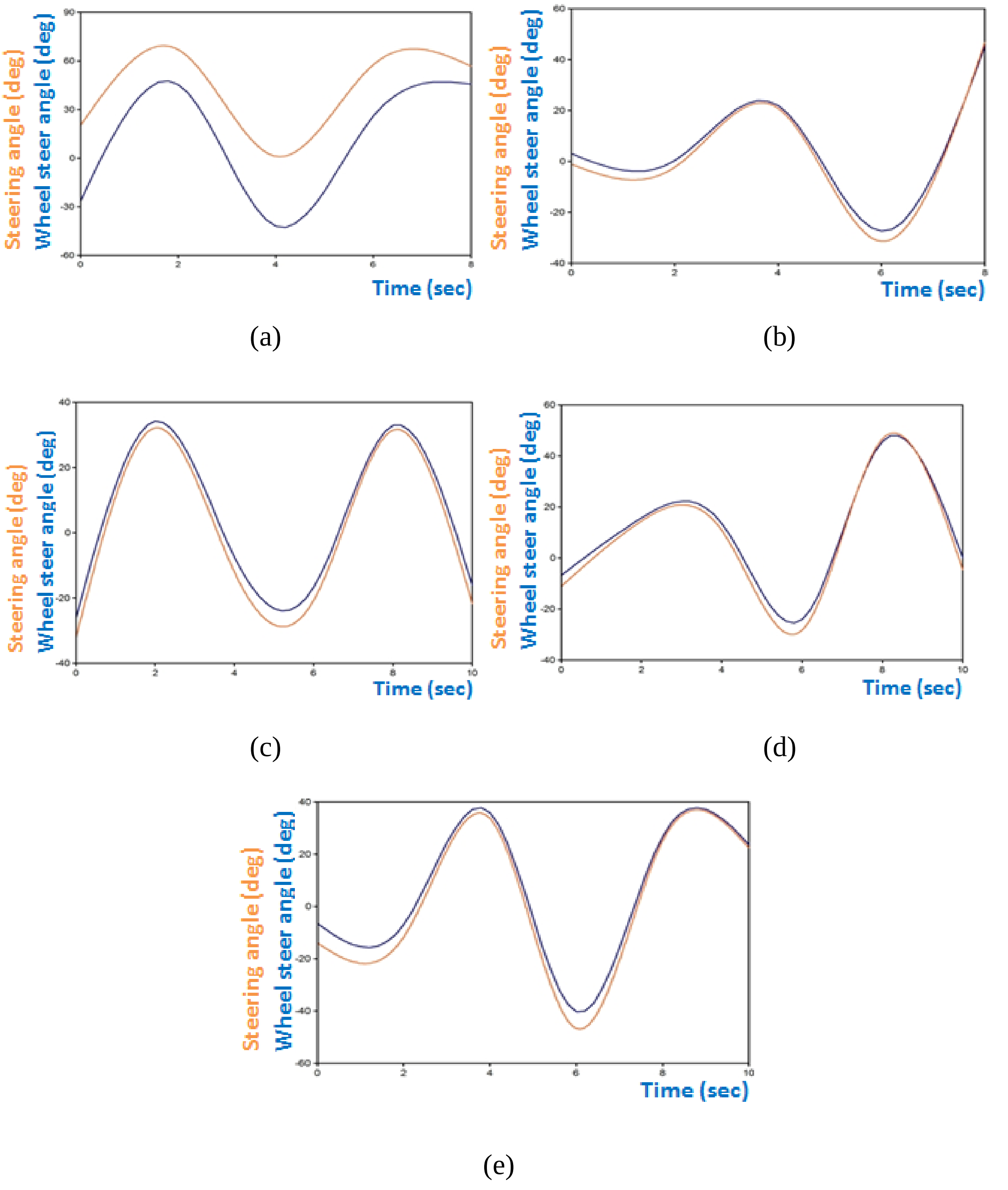
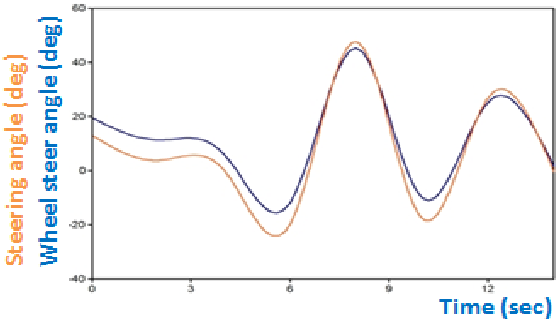


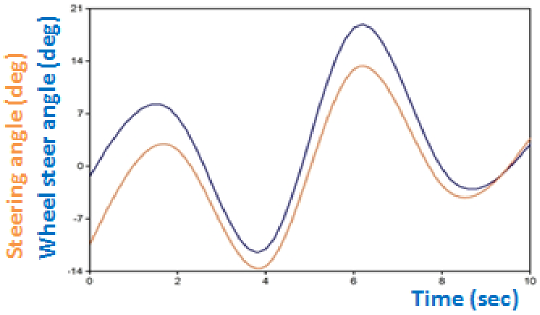
Figure 4.7: (a) First run, (b) Second run, (c) Third run, (d) Fourth run and (e) Fifth run

From Figure 4.7, the entire test produce almost equal value between steering angle and wheel steer angle. This shows that during this test, the tire direction followed the steering input. The vehicle moves according to the drivers input and it may prevent skidding.

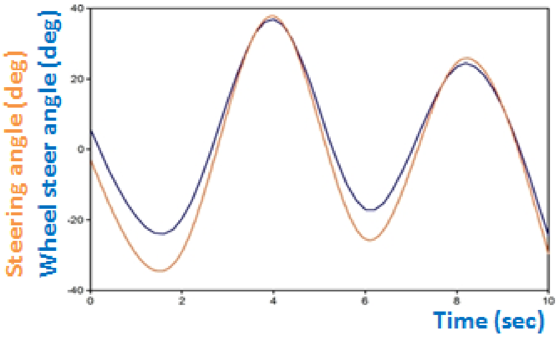
4.2.2 GRAPH OF STEERING ANGLE AND WHEEL STEER ANGLE VERSUS TIME FOR SPEED OF 50 km/h



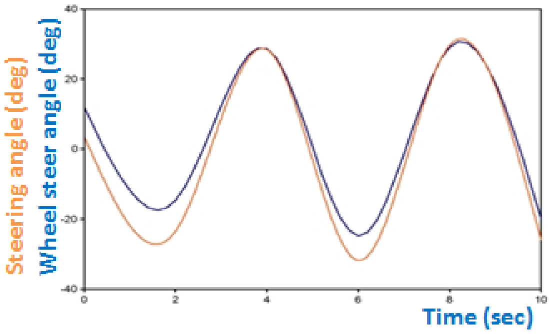
(a)



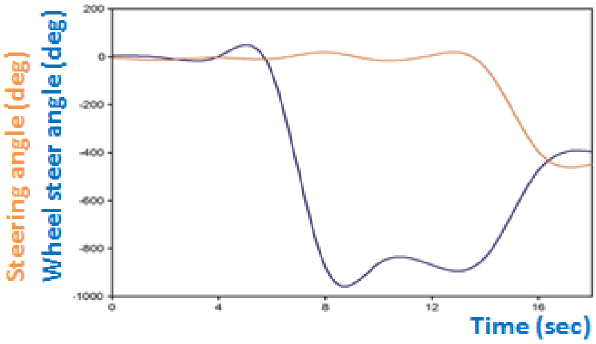
(b)



(c)



(d)



(e)

Figure 4.8: (a) First run, (b) Second run, (c) Third run, (d) Fourth run and (e) Fifth run

From Figure 4.8, the entire test produce almost equal value between steering angle and wheel steer angle. This shows that during this test, the tire direction followed the steering input. At higher speed, the steering angle and wheel steer angle becomes larger.

4.2.3 GRAPH OF STEERING ANGLE VERSUS TIRE DIRECTION

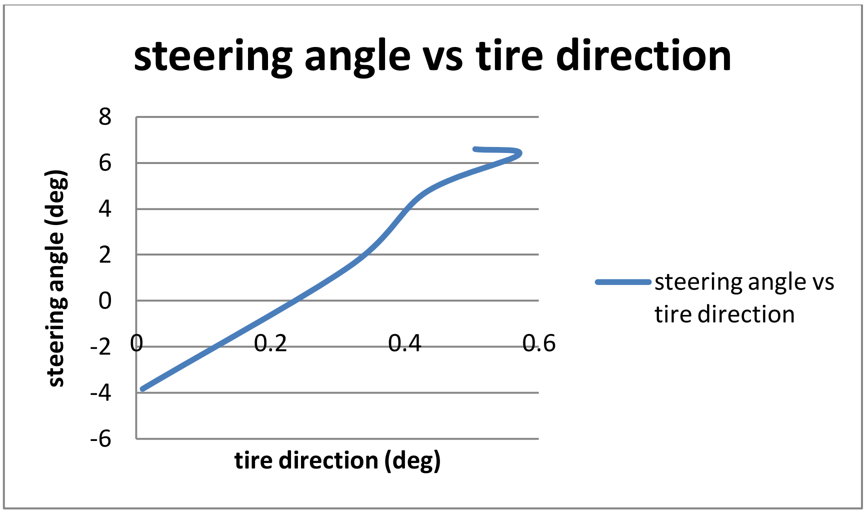


Figure 4.9: Graph of Steering Angle versus Tire Direction for 40 km/h

Data form Appendix N is used to plot Figure 4.9. From this graph, the steering wheel angle is increase with tire direction in positive value. The positive value shown the vehicle is tends to move to the left side.

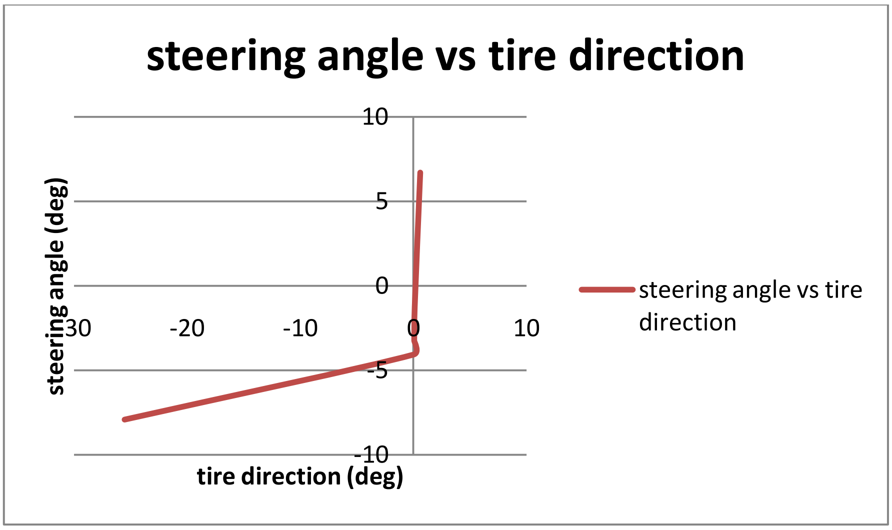


Figure 4.10: Graph of Steering Angle versus Tire Direction for 50 km/h

Data form Appendix N is used to plot Figure 4.10. From this graph, the steering angle is increasing with tire direction in negative value. The negative value shown the vehicle is moving to the right side.

4.2.4 GRAPH OF STEERING ANGLE VERSUS SPEED

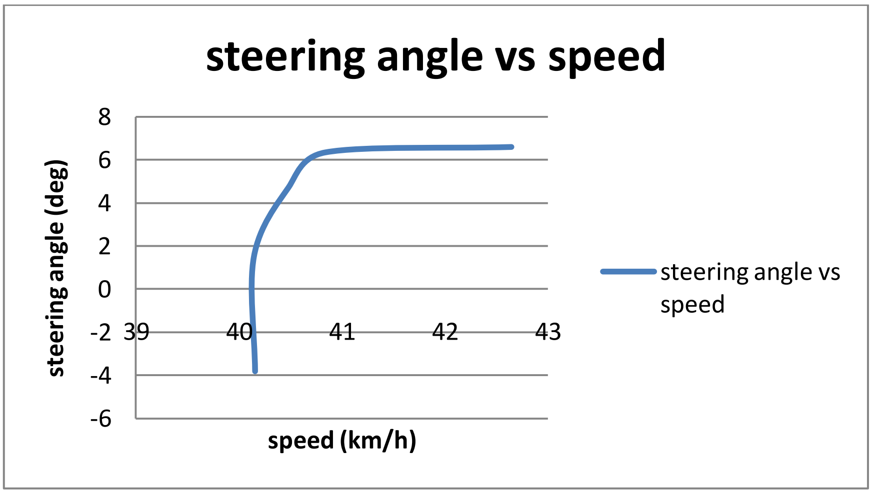


Figure 4.11: Graph of Steering Angle versus Speed for 40 km/h

Data form Appendix N is used to plot Figure 4.11. This graph shows that the steering wheel angle is increase with tire direction in positive value. The negative value shown the vehicle is moving to the left side.

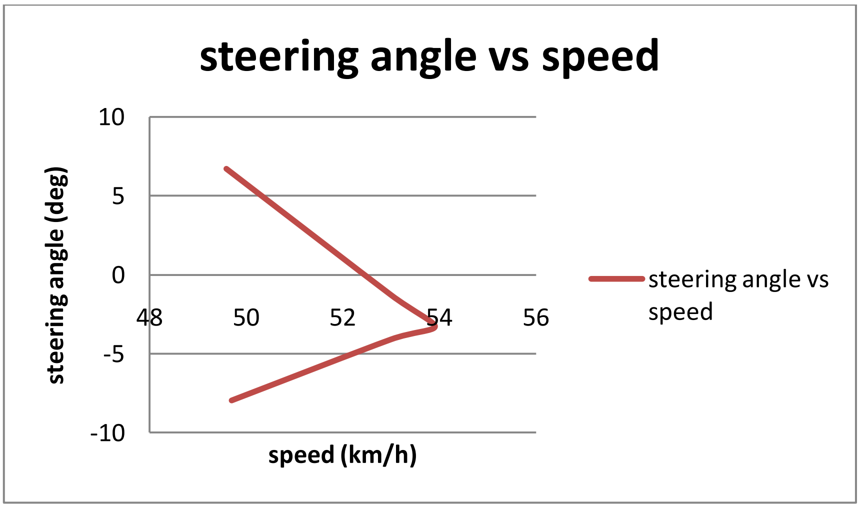


Figure 4.12: Graph of Steering Angle versus Speed for 50 km/h

Data form Appendix N is used to plot Figure 4.12. This figure shows that the steering wheel angle is decreasing with speed and then increasing in negative value. The negative value shown the vehicle is moving to the right side.

CHAPTER 5

RECOMMENDATION & CONCLUSION

5.1 Conclusion

Overall, the first objective of this study had been achieved by collecting the on road performance data between steering wheel and tyre movement in various driving maneuver. The data collected at steady state cornering and rapid cornering whereas the road condition is difference. The second objective is to analyse the relationship between steering wheel and tyre condition and speed while cornering. As can be seen from the results, the vehicle is in understeer condition while cornering. In this condition, the slip angle at front tyre is greater than the slip angle produce at the rear tyres. Thus, a greater steering angle is required to maintain the turn. From the results also, we can see that, the smaller radius of cornering, the greater steering angle produce in order to maintain the turn.

5.2 Recommendation

For future, this study can be compared by analyzing using simulation software that had been used by previous researchers. Software such as Car Sims and ADAMS will help a lot in simulates the dynamic behavior of passenger cars, light trucks, racecars and utility vehicles. Car Sims animates simulated tests and outputs over 800 calculated variables to plot and analyze, or export to other software such as MATLAB, Excel, and other optimization tools. Using such of this software, any types of vehicles can be analyzed with various maneuvers and condition without any limitation which can extend beyond the safety.

It is also recommended to the future researcher to continue this study by experimenting with other driving maneuver such as slalom test, single change maneuver and others. Other than performing test, this study can be continued also by varying the parameters such as variable driver.

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APPENDIX A

PROJECT GANTT CHART

FINAL YEAR PROJECT 1

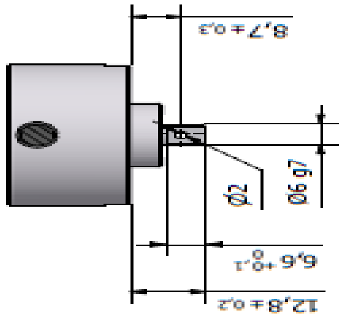
No	ITEM /WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	LITERATURE REVIEW																
2	STUDY ON STEERING GEAR SYSTEM																
3	GEOMETRY STEERING STUDY																
4	CORNERING DYNAMICS STUDY																
5	ACKERMAN STEERING STUDY																
6	FORCES IN TIRES STUDY																
7	STEERING SENSOR INSTALLATION PROCEDURE																
8	ROAD CONDITION EVALUATION																
9	VELOCITY RANGE SELECTION																
10	DESIGN OF EXPERIMENT																
11	FYP 1 PRESENTATION & PROJECT REPORT																

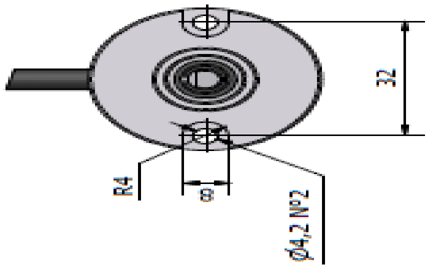
FINAL YEAR PROJECT 2

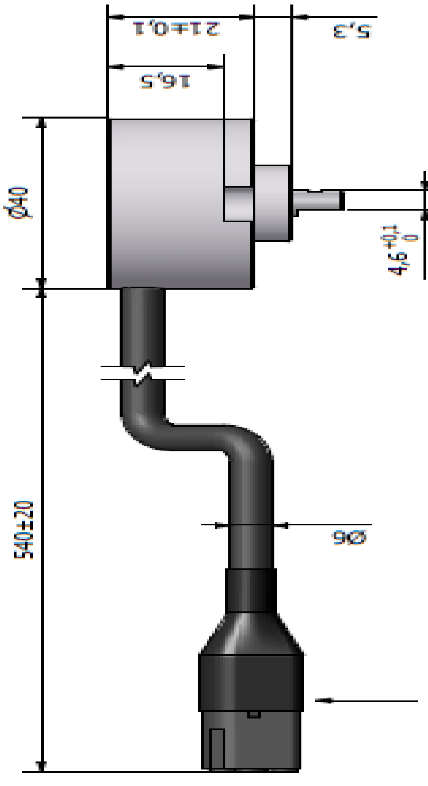
NO	ITEM / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	LITERATURE REVIEW																
2	EXPERIMENTAL SETUP																
3	STEADY STATE CORNERING TEST																
4	ZIGZAG TEST																
5	STEERING-TYRE PERFORMANCE ANALYSIS																
6	FINAL REPORT PREPARATION																
7	FYP2 PRESENTATION																

APPENDIX B

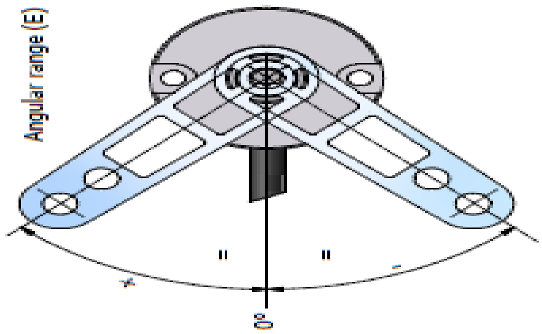
DIMENSIONS OF HALL EFFECT ANGLE SENSORS

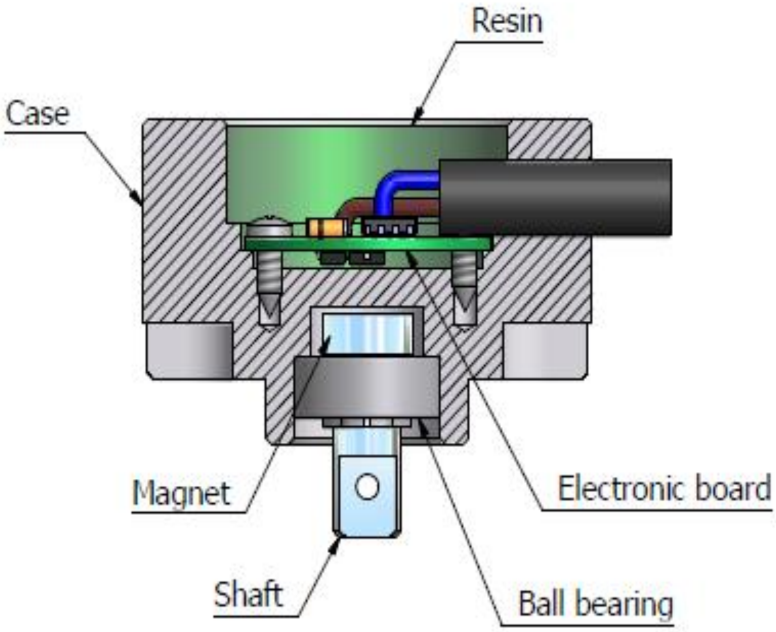






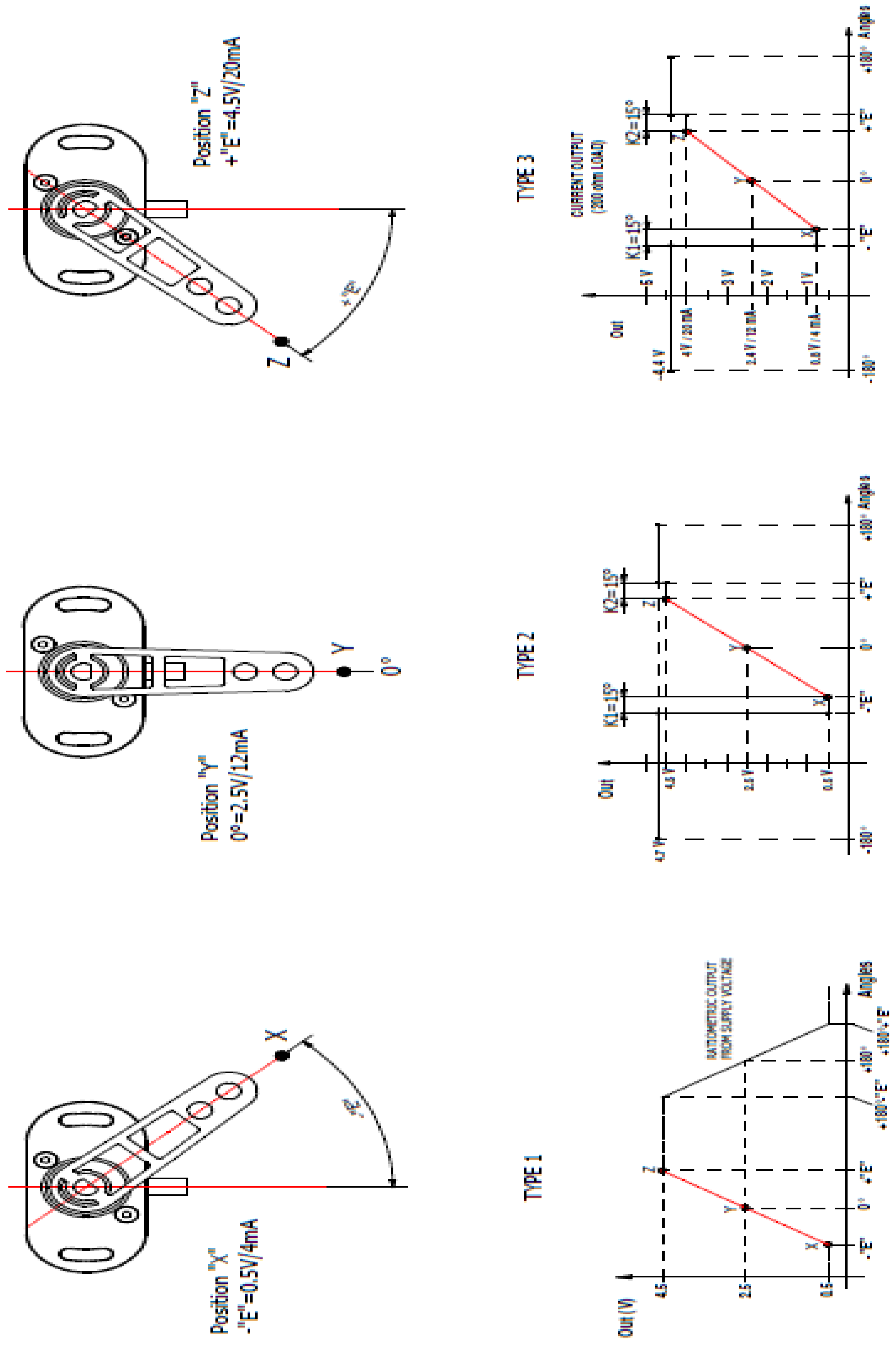
CONNECTOR - A	
TYPE	DESCRIPTION
1	Tyco superseal 3 pin contact
2	Deutsch 3 pin contact
3	G+H Type 17108
4	AMP 3 on 6 pin contact

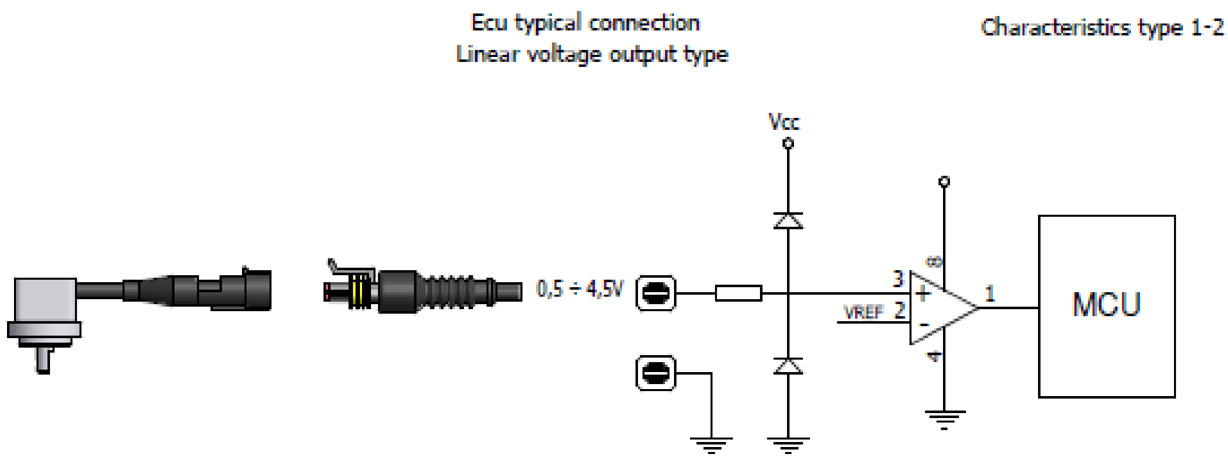


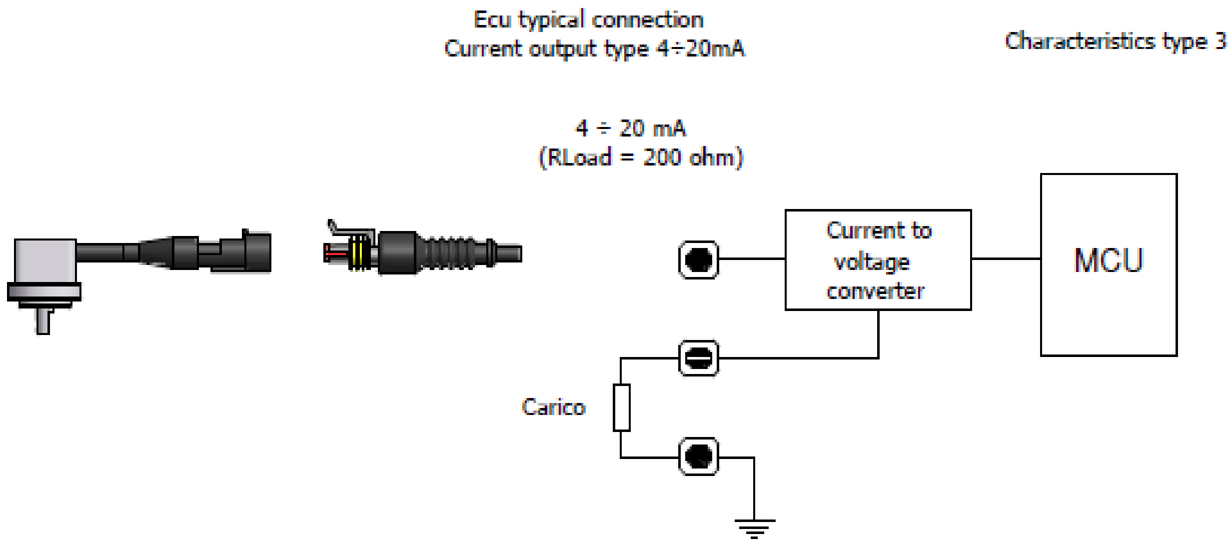

Resin
Case
Magnet
Electronic board
Shaft
Ball bearing

APPENDIX C

SPECIFICATIONS OF HALL EFFECT ANGLE SENSOR




Ecu typical connection
Linear voltage output type
Characteristics type 1-2
Vcc
0,5 ÷ 4,5V
VREF
3
2
1
8
4
+
-
MCU

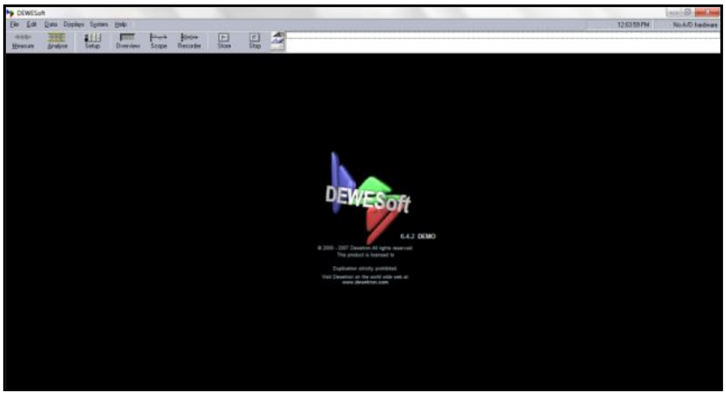

Ecu typical connection
Current output type 4÷20mA
Characteristics type 3
4 ÷ 20 mA
(RLoad = 200 ohm)
Current to
voltage
converter
MCU
Carico

APPENDIX D

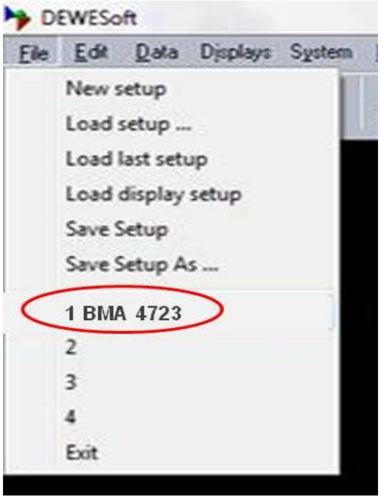
STEPS TO USE DEWESOFT

As for the data gained and results extracted is using the DEWESoft software. The steps are as followed:

1) The Data Acquisitions System of DEWESOft is turned on.



2) Test file setup entitle “BMA4723” is opened.

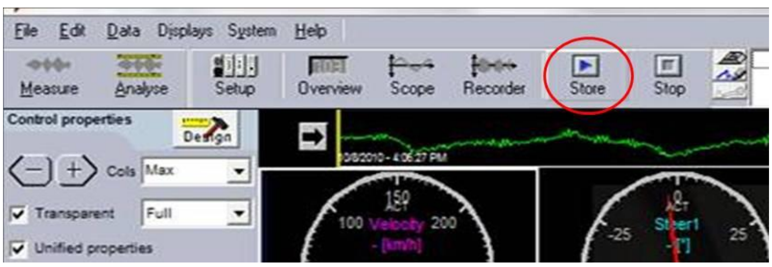


3) Before starts the testing the satellite signal is assured more than 8 by referring to GPS.

4) All the sensors signals are checked to be assured all are functioning well at clicked the OVERVIEW button.

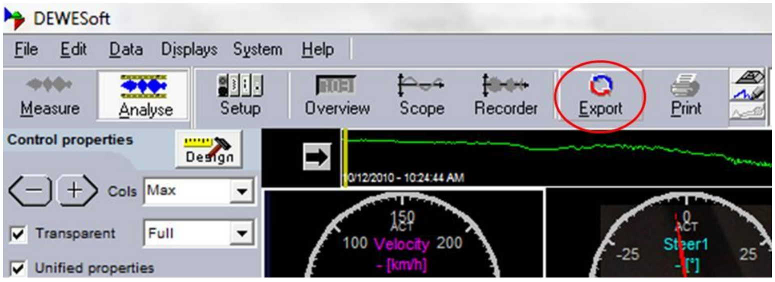
Figure 3.11: DEWESoft signals.

5) Begin to record the test by clicked the STORE button.

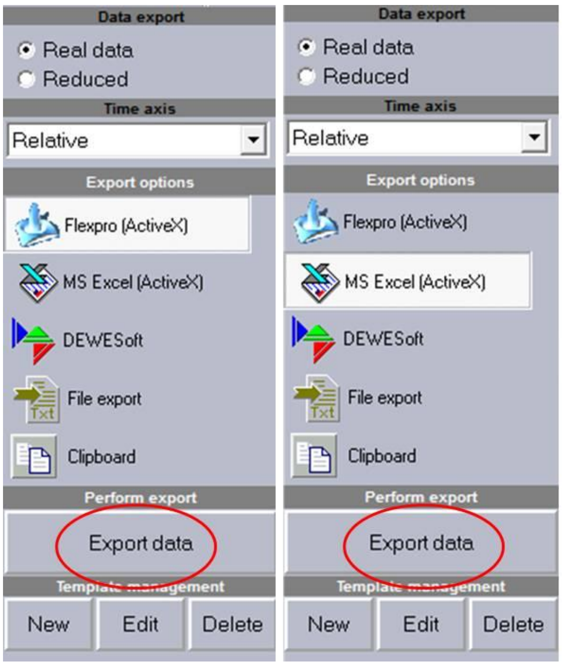


6) Ended the test record by clicked the STOP button.

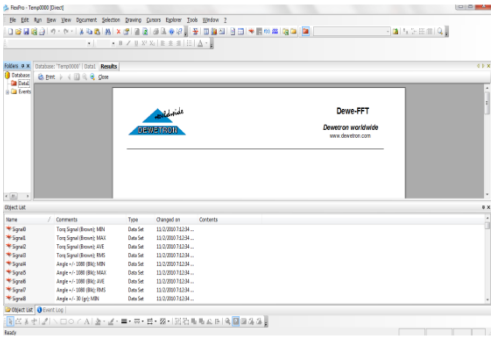
7) The data is extracted by clicked the EXPORT button.

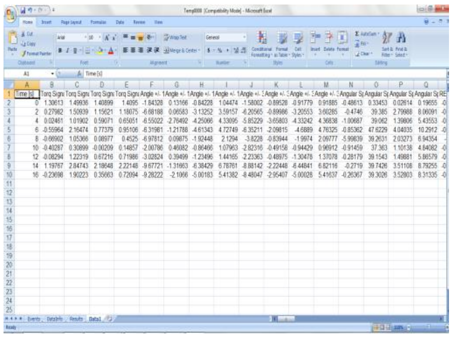


8) Then, users can choose to export the data to FlexPro or Microsoft Excel. After that clicked the EXPORT DATA button. User can export real data or reduced data.



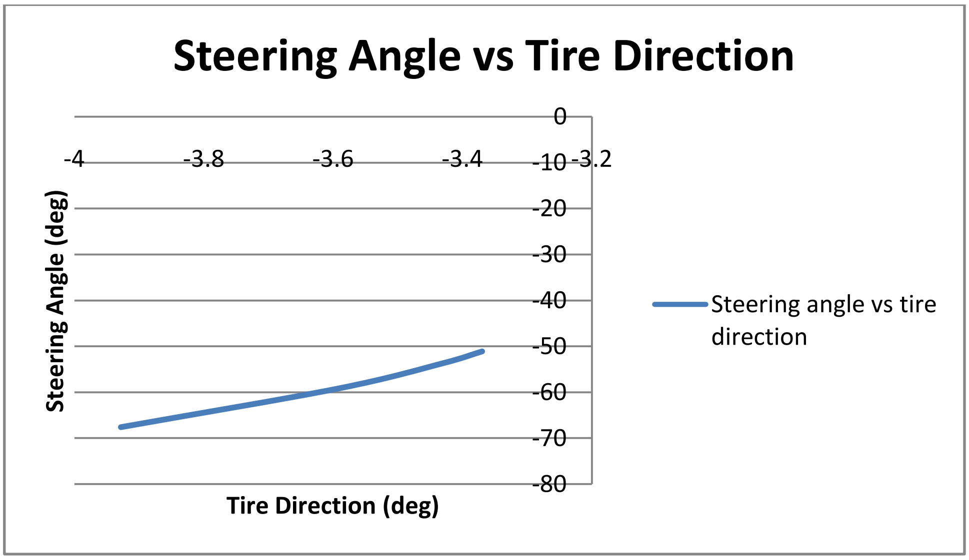
9) The data then is displayed as below in FlexPro and Microsoft Excel.



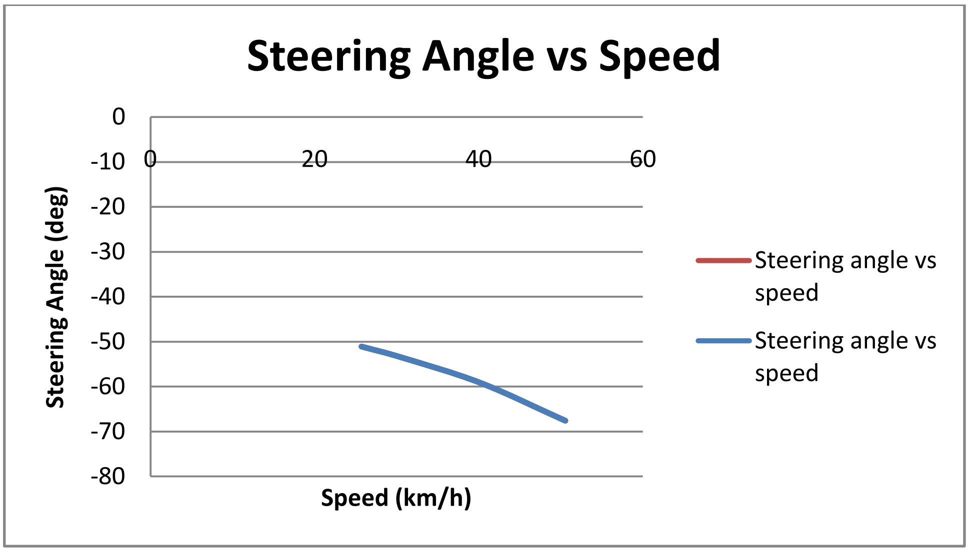


APPENDIX E

STEADY STATE CORNERING (Roundabout 1 inner diameter)



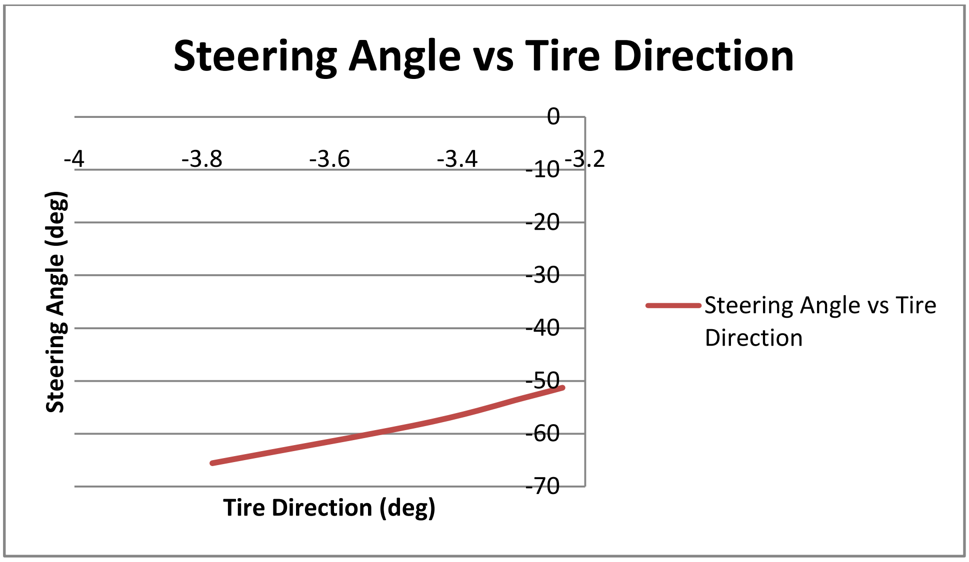
(a)



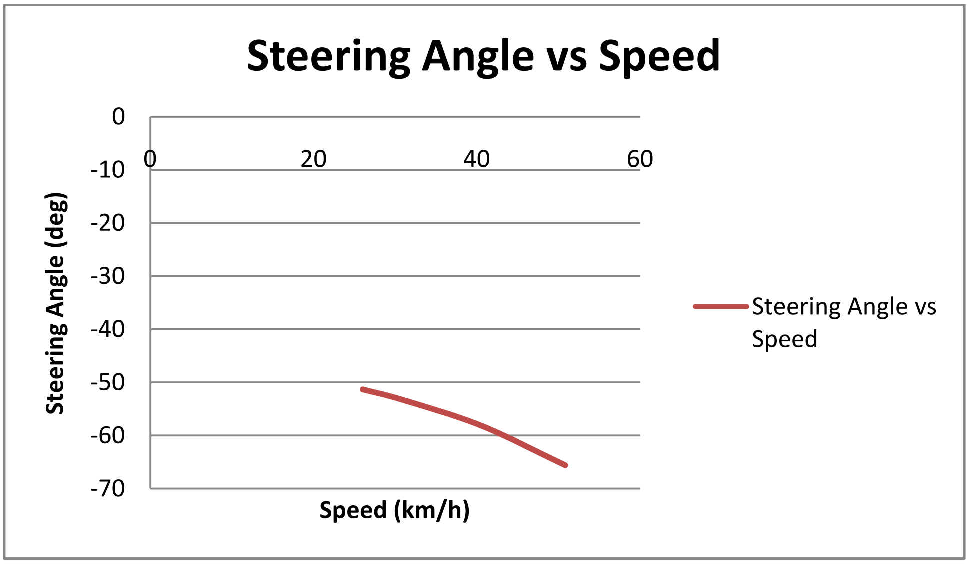
(b)

APPENDIX F

STEADY STATE CORNERING (Roundabout 1 outer diameter)



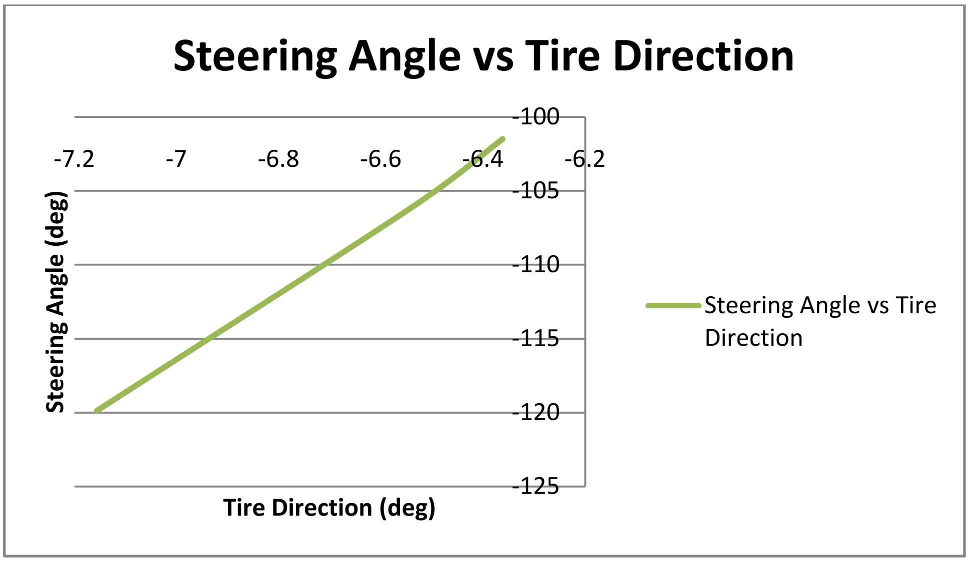
(a)



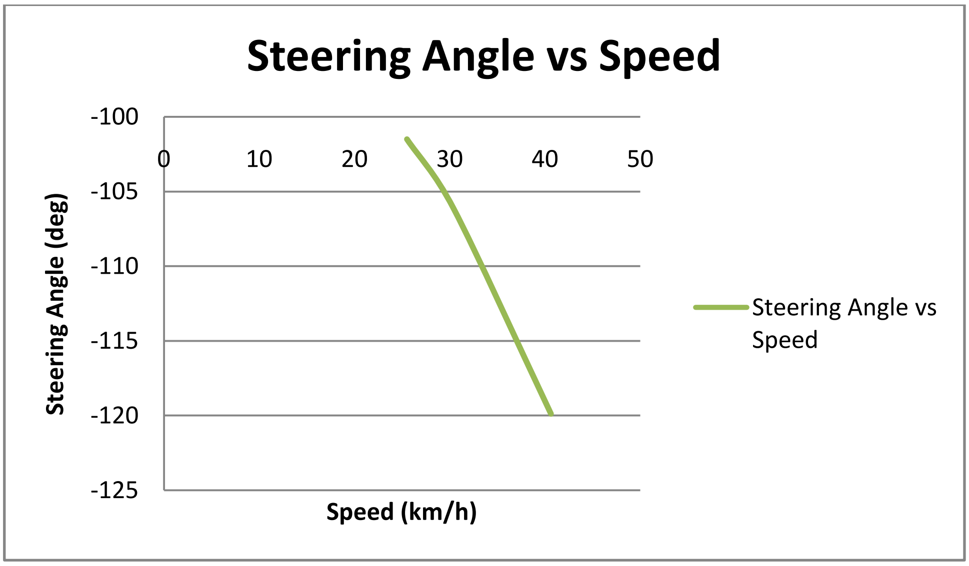
(b)

APPENDIX G

STEADY STATE CORNERING (Roundabout 2 inner diameter)



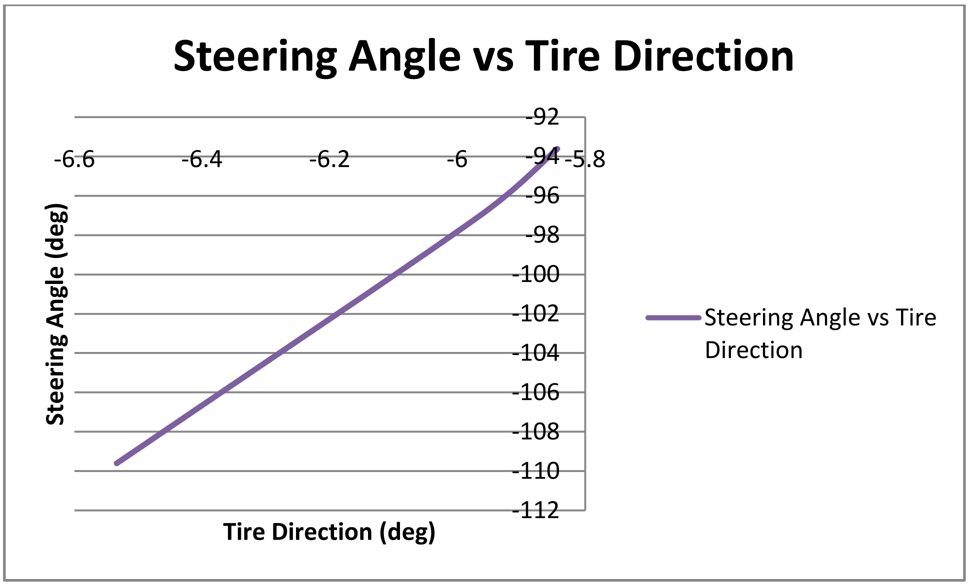
(a)



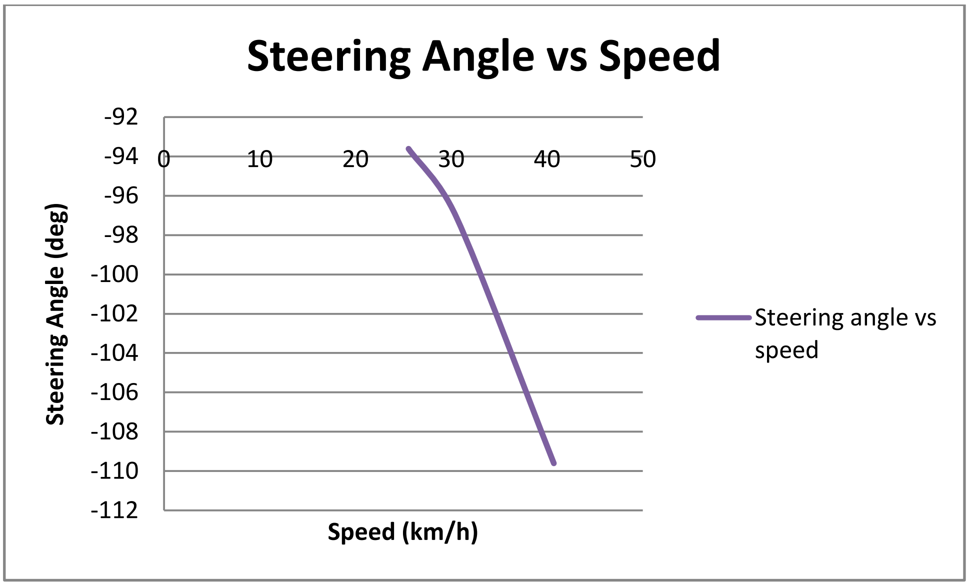
(b)

APPENDIX H

STEADY STATE CORNERING (Roundabout 2 outer diameter)



(a)



(b)

APPENDIX I

ROUNDABOUT 1 INNER DIAMETER

	Steering angle	Wheel steer angle	Reduced wheel steer angle	Speed
25 km/h	2.23104572	-7.035326421	-3.36505	25.70728613
	-50.98226558	-7.032530771	-3.362259271	25.52596267
	-50.82136279	-7.021944938	-3.351673438	25.77569417
	-51.039063	-7.034137883	-3.363866383	25.68275758
	-51.64252692	-7.074841633	-3.404570133	25.85407079
30 km/h	-53.84396435	-7.11820543	-3.44793393	31.0502942
	-53.1809244	-7.078887585	-3.408616085	30.36095625
	-53.47597355	-7.089690655	-3.419419155	30.5586197
	-53.5000308	-7.08899181	-3.41872031	30.59182725
	-53.9147056	-7.11001043	-3.43973893	30.7050951
40 km/h	-58.63188506	-7.2381489	-3.5678774	40.08009719
	-59.42597613	-7.280607733	-3.610336233	40.25199247
	-59.0306382	-7.254490727	-3.584219227	40.00200233
	-59.38659973	-7.268882913	-3.598611413	40.02111993
	-59.607687	-7.27240006	-3.60212856	40.7818908
50 km/h	-66.51131592	-7.542818508	-3.872547008	49.65681523
	-67.63446208	-7.605590142	-3.935318642	50.75226025
	-67.96898133	-7.614573717	-3.944302217	51.14837067
	-68.46383217	-7.642506917	-3.972235417	50.93540867
	-67.43501777	-7.586964131	-3.916692631	50.16760485

APPENDIX J

ROUNDABOUT 1 OUTER DIAMETER

	Steering angle	Wheel steer angle	Reduced wheel steer angle	Speed
25 km/h	-51.52182475	-6.909873583	-3.239601083	26.06355233
	-51.01736936	-6.894227508	-3.223955008	26.05230944
	-51.38317648	-6.907033976	-3.236761476	25.971241
	-51.51427608	-6.921368796	-3.251096296	26.032188
	-51.11016112	-6.895609292	-3.225336792	25.93449116
30 km/h	-53.66047195	-6.996157667	-3.325885167	30.95933048
	-53.42063948	-6.980931524	-3.310659024	30.63520324
	-53.21185386	-6.95762291	-3.28735041	30.98088057
	-52.77329038	-6.940807643	-3.270535143	30.73550152
	-53.09526395	-6.955364305	-3.285091805	30.6911989
40 km/h	-58.09530175	-7.13282075	-3.46254825	40.54632338
	-58.04530525	-7.119721588	-3.449449088	40.57551344
	-57.86841631	-7.109222931	-3.438950431	40.45445125
	-58.03763419	-7.119372425	-3.449099925	40.44813119
	-58.54414963	-7.142960581	-3.472688081	40.50692538
50 km/h	-64.25758423	-7.380986362	-3.710713862	50.07830331
	-65.36003923	-7.441229677	-3.770957177	50.35836123
	-65.29547892	-7.447313177	-3.777040677	51.31838254
	-65.84723838	-7.467636031	-3.797363531	51.29944308
	-67.18403131	-7.534288815	-3.864016315	50.95455069

APPENDIX K

ROUNDABOUT 2 INNER DIAMETER

	Steering angle	**Wheel steer angle**	**Reduced wheel steer angle**	**Speed**
25 km/h	-101.7742677	-10.0561464	-6.3858739	25.62953567
	-100.5384131	-9.972631354	-6.302358854	25.37932792
	-101.6934698	-10.03827727	-6.368004769	25.48164985
	-101.0197938	-10.00936186	-6.339089362	25.41436115
	-102.4601839	-10.08222973	-6.411957231	25.55500369
30 km/h	-105.7204775	-10.2071976	-6.5369251	30.14691609
	-105.9056093	-10.18650735	-6.516234855	30.813428
	-106.236686	-10.23073724	-6.560464736	30.11423036
	-105.503788	-10.16320625	-6.492933755	30.16627764
	-107.2336556	-10.26061467	-6.590342173	30.64203982
40 km/h	-118.9751925	-10.78645988	-7.116187375	40.5977265
	-119.0415313	-10.7828095	-7.112537	40.46151725
	-120.5777275	-10.83932188	-7.169049375	40.95196725
	-120.3571825	-10.85811913	-7.187846625	40.46698513
	-120.4600213	-10.86619813	-7.195925625	40.6223745

APPENDIX L

ROUNDABOUT 2 OUTER DIAMETER

	Steering angle	Wheel steer angle	Reduced wheel steer angle	Speed
25 km/h	-92.93357657	-9.475924229	-5.805651729	25.37489886
	-93.68261143	-9.533964186	-5.863691686	25.300733
	-92.96024107	-9.463787064	-5.793514564	25.5026975
	-94.07861714	-9.538495207	-5.868222707	25.72233571
	-94.45314329	-9.555954129	-5.885681629	25.80202814
30 km/h	-96.1731425	-9.585219958	-5.914947458	30.42692433
	-96.69613242	-9.622874442	-5.952601942	30.27313483
	-97.57623092	-9.679736933	-6.009464433	30.55263667
	-97.10027392	-9.6298556	-5.9595831	30.52056525
	-97.8200325	-9.669190217	-5.998917717	30.78145192
40 km/h	-108.7791248	-10.15824783	-6.487975333	40.58557867
	-108.7755689	-10.14944597	-6.479173467	40.81364344
	-109.1073289	-10.19870666	-6.528434156	40.92240944
	-110.2712804	-10.23470117	-6.564428667	40.83648122
	-111.0698296	-10.27967864	-6.609406144	40.29082411

APPENDIX M
REDUCED DATA FOR GRAPH PLOTTING

	steering angle	wheel steer angle	speed
ROUNDABOUT I INNER DIAMETER	-51.129	-3.369483845	25.70915427
	-53.5831	-3.426885682	30.6533585
	-59.21655723	-3.592634567	40.22742054
	-67.60272186	-3.928219183	50.53209193
ROUNDABOUT I OUTER DIAMETER	-51.30936156	-3.235350131	26.01075639
	-53.23230392	-3.29590431	30.80042294
	-58.11816143	-3.454547155	40.50626893
	-65.58887442	-3.784018312	50.80180817
ROUNDABOUT 2 INNER DIAMETER	-101.4972257	-6.361456823	25.49197566
	-106.1200433	-6.539380124	30.37657838
	-119.882331	-7.1563092	40.62011413
ROUNDABOUT I OUTER DIAMETER	-93.6216379	-5.843352463	25.54053864
	-97.07316245	-5.96710293	30.5109426
	-109.6006265	-6.533883553	40.68978738

APPENDIX N

ZIGZAG CONE TEST WITH 25M RADIUS

	Steering angle	**Wheel steer angle**	**Reduced wheel steer angle**	**Speed**
40km/h	-3.824625167	-3.660793717	0.009479	40.15608167
	1.5041465	-3.3523843	0.317888	40.1446965
	4.711598167	-3.239169617	0.431103	40.48042917
	6.3437786	-3.10103102	0.569241	40.8393784
	6.5937844	-3.16533738	0.504935	42.6475136
50 km/h	-7.938349538	-29.17093564	-25.5007	49.69031463
	-4.085559083	-3.624141567	0.046131	52.9955045
	-3.2619645	-3.568571533	0.101701	53.91168233
	-1.259331633	-3.522690233	0.147582	52.99114467
	6.693137161	-3.035871088	0.634401	49.5809055