PERFORMANCE ANALYSIS ON PERCENTAGE OF WHEEL SLIP FOR A PASSENGER CAR USING GPS AND WHEEL SPEED SENSOR

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UNIVERSITI MALAYSIA PAHANG

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JUDUL: **PERFORMANCE ANALYSIS ON PERCENTAGE OF WHEEL SLIP FOR A PASSENGER CAR USING GPS AND WHEEL SPEED SENSOR**

SESI PENGAJIAN: **2010/2011**

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PERFORMANCE ANALYSIS ON PERCENTAGE OF WHEEL SLIP FOR A PASSENGER CAR USING GPS AND WHEEL SPEED SENSOR

LAWRENCE BLASIUS

Report submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

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DECEMBER 2010

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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 concurrently submitted for award of other degree.

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Dedicated to my family who has never failed to give me financial and moral support, for giving all my need to complete my study and for teaching me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

This thesis deals with the analysis on percentage of wheel slip for a passenger car using GPS and wheel speed sensor. The objective of this thesis is to analyze the percentage of wheel slip for a passenger car in a various velocity, road condition and driving mode. The thesis describes the post-processing method to analyze the percentage of wheel slip and identify the effective rolling radius and the longitudinal tire stiffness for maximum tire life and performance. Driving and braking behaviour of vehicle were both studied in this thesis for paved and unpaved sandy road condition which commonly the contributing factors to the wheel slip to occur. The data used for the analysis is obtained through experimental test using UMP Test Car which has been installed with Wheel Pulse Transducer, Global Positioning System and DEWESOFT software for data acquisition purpose. The post-processing method was performed using Flexpro and Microsoft Office Excel. The post-processing method to analyze the percentage of wheel slip was performed using the SAE definition of wheel slip and the percent error in the distance travel by the car between free rolling and actual condition. Finally, the longitudinal force, the effective rolling radius and the longitudinal tire stiffness was determined for both driving and braking maneuver of vehicle on paved and unpaved sandy road condition. From the results, it is observed that the percentage of wheel slip during driving maneuver is higher for unpaved sandy road condition compares to that the paved road. It is also observed that the longitudinal force of the tire is lower for unpaved sandy road compare to the paved road condition. The effective rolling radius of the tire during driving maneuver was determined to be lower compare to the free rolling radius of the tire. During braking manuever, the results show that the percentage of wheel slip is higher for unpaved sandy road compare to that for paved road condition. The longitudinal force and tire stiffness also observed lower for unpaved sandy road condition. The effective rolling radius of the tire during braking determined higher compared to that in the free rolling radius. The results concluded that the percentage of wheel slip is strongly dependent to the longitudinal force and the tire road friction. Therefore, effective rolling radius and longitudinal tire stiffness obtained can significantly use to improve tire design and construction. The results also can be use to improve the energy usage efficiency and fuel consumption of vehicle.

ABSTRAK

Tesis ini berkaitan dengan analisis peratusan slip roda untuk kereta penumpang menggunakan GPS dan sensor kelajuan roda. Tujuan tesis ini adalah untuk menganalisis peratusan slip roda untuk kereta penumpang dalam pelbagai kelajuan, keadaan jalan dan mod memandu. Tesis ini menjelaskan kaedah pemprosesan pasca untuk menganalisis peratusan slip roda dan mengenalpasti jejari putaran berkesan dan kekerasan tayar membujur untuk maksimum hidup dan prestasi tayar. Perilaku memandu dan pengereman kenderaan dipelajari dalam tesis ini untuk kondisi jalan berturap dan tidak berturap berpasir yang umumnya faktor yang menyumbang kepada slip roda terjadi. Data yang digunakan untuk analisis diperolehi melalui eksperimen menggunakan Kereta Ujian UMP yang telah dipasang dengan Transduser Nadi Roda, System Kedudukan Global dan perisian DEWESOFT untuk tujuan pengambilalihan data. Kaedah pemprosesan pasca dilakukan menggunakan Flexpro dan Microsoft Office Excel. Kaedah pemprosesan pasca untuk menganalisis peratusan slip roda dilakukan dengan menggunakan definisi SAE slip roda dan peratus kesalahan terhadap jarak yang di lalui oleh kereta dengan keadaan putaran sebenar. Akhirnya, daya membujur, jejari putaran berkesan dan kekerasan tayar membujur ditentukan baik untuk memandu dan pengereman manuver kenderaan dalam keadaan jalan berturap dan tidak berturap berpasir. Dari hasil kajian, diperhatikan bahawa peratusan slip roda selama memandu manuver lebih tinggi untuk kondisi jalan berturap berpasir berbanding dengan jalan berturap. Hal ini juga mengamati bahawa daya membujur tayar lebih rendah untuk jalan berturap berpasir berbanding dengan keadaan jalan berturap. Jejari putaran berkesan selama manuver memandu di kira lebih rendah berbanding dengan jejari putaran sebenar tayar. Selama manuver pengereman, keputusan menunjukkan bahawa peratusan slip roda yang lebih tinggi untuk jalan tidak berturap berpasir berbanding dengan kondisi jalan berturap. Watak longitudinal dan simpulan ban juga mengamati lebih rendah untuk kondisi jalan berturap berpasir. Jejari putaran berkesan tayar semasa pengereman ditentukan lebih tinggi berbanding dengan jejari putaran sebenar tayar. Keputusan menyimpulkan bahawa peratusan slip roda sangat bergantung dengan daya membujur dan geseran antara jalan dengan tayar. Dengan itu, jejari putaran berkesan dan kekerasan tayar membujur yang diperolehi secara signifikannya dapat digunakan untuk memperbaiki pembinaan dan rekabentuk tayar. Keputusan ini juga boleh digunakan untuk meningkatkan kecekapan penggunaan tenaga dan penggunaan bahan bakar kenderaan.

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LIST OF SYMBOLS

a_x	Longitudinal acceleration
Cx	Longitudinal tire stiffness
D	Rim diameter
dA	Actual distance that the tire travel
dF	Ideal distance that the tire would freely travel with no slip
dGPS	Distance travel measured by GPS
dWPT	Distance travel calculated from WPT
F_D	Driving force
Fd	Drag force
F_I	Retarding inertia force
F_R	Reaction force
Frr	Force due to rolling resistance
Fx	Longitudinal force
Fxf	Longitudinal force of front tire
Fxr	Longitudinal force of rear tire
Fz	Normal force
g	Gravitational force
H	Tire height
H/W	Height-to-weight ratio of tire
M	Vehicle mass
N	Number of wheel revolution
R	Free rolling radius of tire
Re	Effective radius of tire

s	Slip
t	Time
T_B	Braking torque
T_D	Driving torque
Vx	Forward velocity
W	Tire width
θ	Grade angle
μ_{bp}	Peak coefficient of friction for braking
μ_{bs}	Sliding coefficient of friction for braking
μ_{dp}	Peak coefficient of friction for driving
μ_{ds}	Sliding coefficient of friction for driving
μ_p	Peak coefficient of friction
μ_s	Sliding coefficient of friction
$\mu_x(s)$	Longitudinal friction coefficient as a function of slip
ω	Wheel angular velocity
ω_e	Effective wheel angular velocity

LIST OF ABBREVIATIONS

ABS	Antilock Braking System
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
LLC	Limited Liability Company
SAE	Society of Automotive Engineers
UK	United Kingdom
UMP	Universiti Malaysia Pahang
USA	United States of America
WPT	Wheel Pulse Transducer

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In studies of vehicle traction the gross vehicle dynamics and tire/wheel dynamics can be captured by lumped mass models. Simplified models that are often considered for longitudinal braking and acceleration include the single-wheel model and a two-dimensional, two-wheel model (front and rear) or full four-wheel models for cornering (Gillespie, 1992), (Wong, 1978). The dynamics of these systems involve interactions between the vehicle, the tire/wheel assemblies, and the road surface. The force that ultimately slows or accelerates the vehicle is the longitudinal friction force between the road and tire, which can be empirically described in terms of a slip condition at the interface. Thus, writing the equations of motion for any rubber-tire vehicle system requires a description of the friction force generated at the tire/road interface, in addition to the usual laws of motion.

Experimental evidence shows that the longitudinal friction force is proportional to the normal force at the contact (Gillespie, 1992), (Wong, 1978), with a coefficient of friction serving as the constant of proportionality. This coefficient can be conveniently modeled in an empirical manner that depends on the slip (Bakker et al., 1987), (Bakker et al., 1989), which is a dimensionless measure of the difference between the vehicle speed and the circumferential speed of the tire relative to the wheel center. During braking (resp. acceleration), this difference is generated by a brake (resp. engine) torque on the wheel, which acts against (resp. with) the inertia of the vehicle. The slip depends on the dynamics of the vehicle and the tire/wheel, and it also influences their dynamics through the friction force. This feedback results in a system of coupled equations of

motion for the vehicle and the tire/wheel. These equations of motion are most often formulated in terms of the vehicle's speed relative to ground and the absolute rotational rate of the tire/wheel. This is a very natural formulation, wherein the slip is merely an internal variable defined in terms of the system's dynamic states, which is used to compute the friction force that appears in the equations of motion.

1.2 PROBLEM STATEMENT

Dynamics and performance of vehicles are result from vehicle operational properties including energy/fuel efficiency, cross-country mobility, tractive and velocity properties, vehicle turnability, and stability of motion and handling. No doubt, the fact that these vehicle operational properties can be considered depends on total power applied to all of the vehicle drive wheels. At the same time, the vehicle operational properties are strongly depending on the total power distribution among the drive wheels. For a given road or off-road conditions, the same vehicle with a constant total power at each drive wheels, but have different power distributions among the drive axles. Left and right wheels of each axle will perform differently; this is how the criteria of the above-listed operational properties will have different quantities (Vantsevich, 2007).

There might be one problem that will occur during driving or braking of vehicle that is wheel slip. While the vehicle wheels are spinning, the driving force on the tires will reduces considerably and the vehicle cannot speed up as desired. This might even become very difficult to control the vehicle under these conditions (Haskara et al., 2000). Wheel slip is one of the contributing factors that the energy losses of the engine to occur. Torque produce is wasted because of that the tire did not have interface contact with the road and the car didn't move with these power produced.

Due to the power losses, the wasted torque produce and the important of the wheel slip parameter in vehicle control system; it is important to study the relation between the longitudinal force and the percentages of the wheel slip so that we can calculate the effective radius of the tires and estimate the longitudinal tire stiffness for a maximum tire life and performance.

1.3 PROJECT OBJECTIVES

(i) To collect the experimental data using Global Positioning System (GPS) and high-resolution Wheel Pulse Sensors.

(ii) To analyze the percentage of wheel slip for a passenger car in a various velocity, road condition and driving mode.

1.4 PROJECT SCOPES

(i) Literature review on the tractive properties of tire, traction limited acceleration and Antilock Braking System.

(ii) Test car system installation and experiment procedures preparation for acceleration and braking test.

(iii) Analysis on percentage of wheel slip for driving and braking maneuver.

(iv) Conclude the project with details discussion on the result in a final report.

1.5 HYPOTHESIS

In preliminary testing, increased inflation pressure appeared to systematically lower the longitudinal stiffness. The data gathered must be consistent with the assumption of a linear relationship between force and slip at low levels of slip as predicted by classical tire models.

1.6 PROJECT FLOW CHART

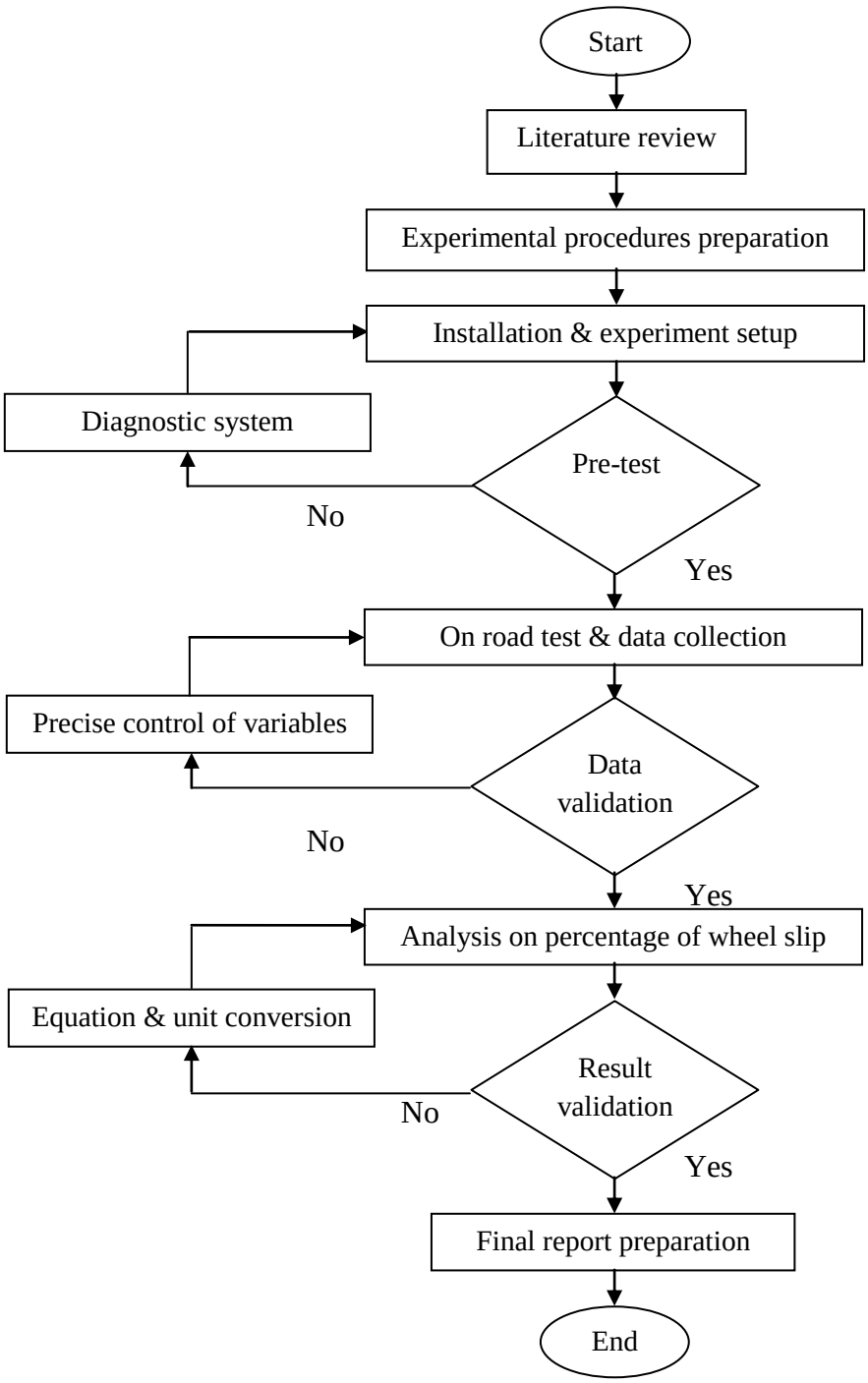


Figure 1.1: Flow chart of the project

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

While tire parameters are quite important to current vehicle systems and proposed future systems, these parameters are subject to considerable variability and are difficult to estimate while driving the unavailability of the absolute velocity (Miller et al., 2001). The study of the tire and vehicle characteristics is important before any measurement and testing is conducted to get the final result and conclusion.

The study for the tire and road interaction is covering most on the tire road friction, tractive and braking effort of the tire and the braking properties on wet roads. This chapter will cover on the longitudinal force and slip which will study both for driving and braking maneuver. This chapter concluded with the application of the slip parameters in the Antilock Braking System (ABS) for vehicle stability control.

2.2 TRACTIVE PROPERTIES OF TIRES

2.2.1 Tire-Road Friction

Tire are specifically designed to grip the road surface when the vehicle is being steered, accelerated, braked and/or negotiating a corner and so to control the tire to ground interaction is of fundamental importance (Heisler, 2002). Road grip or friction is the resistance to relative tangential motion during braking or driving at the compressive contact interface between a tire and the road surface (Brach, 2006).

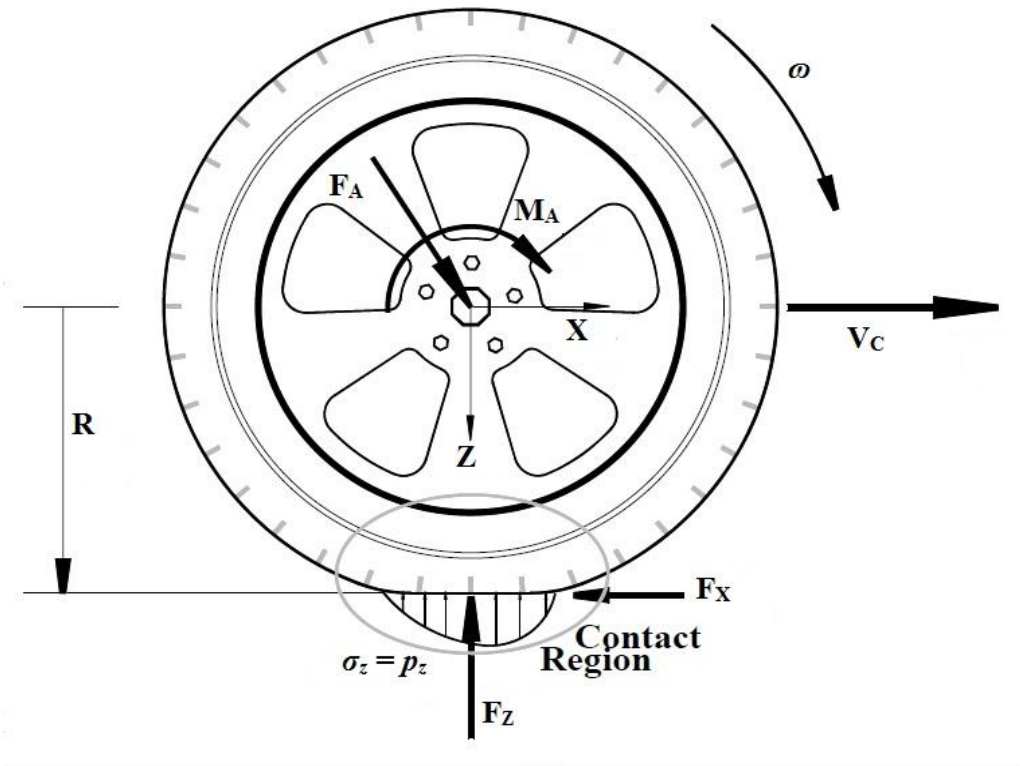


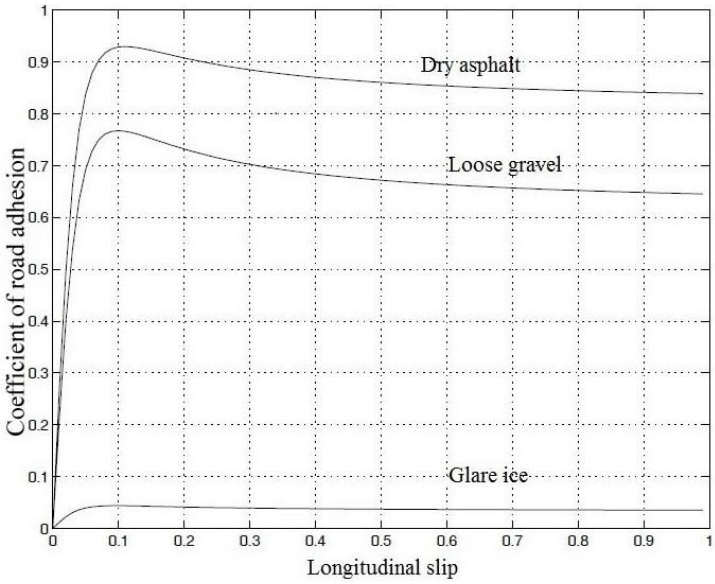
Figure 2.1: Free body diagram of rotating wheel

Source: Brach (2006)

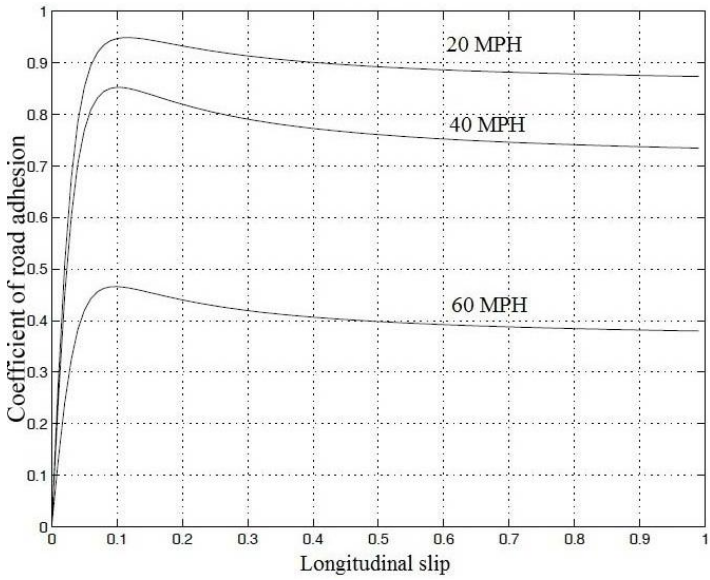
Figure 2.1 show a rotating wheel of a vehicle. R, F_A and M_A is the force system applied to the wheel, F_Z is the normal force between the tire and the road surface, F_X is the frictional force between the tire and the road surface.

The normalized traction force, μ, is defined as:

$$\mu = \frac{\sqrt{Fx^2+Fz^2}}{Fz} \tag{2.1}$$



(a)



(b)

Figure 2.2: Tire - road friction for different (a) road surfaces and (b) vehicle velocities

Source: Harned et al. (1969)

In longitudinal motion, the lateral force F_Y can be neglected. The above equation then becomes:

$$\mu = \frac{Fx}{Fz} \tag{2.2}$$

The ratio of tangential force, *Fx*, to the normal force, *Fz*, is defined as the coefficient of friction, μ. This normalized tire friction, μ, is a nonlinear function of the normalized velocity between the road and the tire with a distinct maximum (Canudas-de-Wit and Tsiotras, 1999). The variation of friction coefficient is depending on the velocity of the vehicle and road surface condition, among other factors as shown in Figure 2.2 below (Harned et al., 1969).

2.2.2 Tractive and Braking Effort

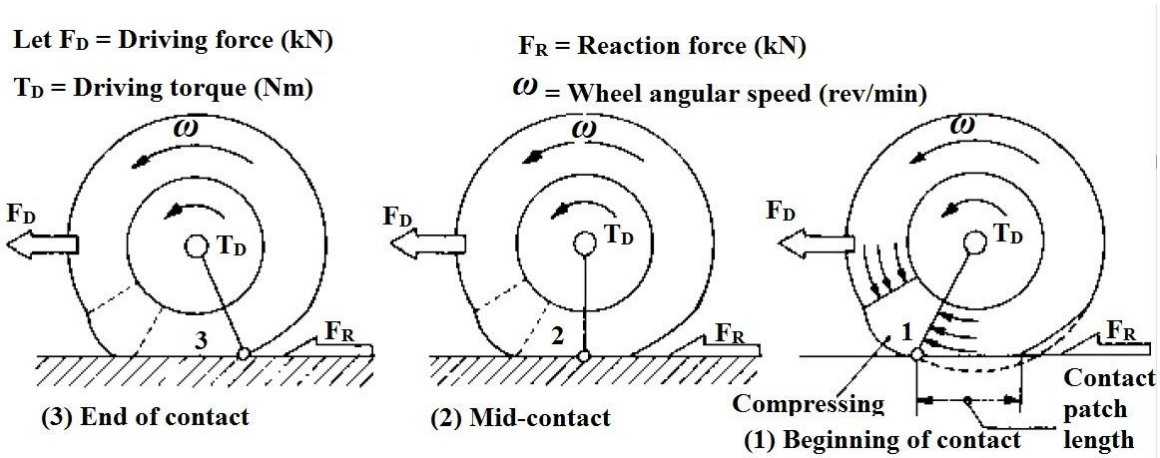


Figure 2.3: Deformation of tire under driving torque

Source: Heisler (2002)

Tractive effort of a tire to the ground is produced when a driving torque is transmitted to the wheel and tire. The twisting of the tire carcass in the direction of the leading edge of the tread contact patch is continuously opposed by the tire contact patch reaction on the ground. A portion of the tread and casing will be deformed and compressed before it enters the contact patch region (Wong, 1978). Hence, the distance

that the tire treads travels when subjected to a driving torque will be less than that in free rolling as shown in Figure 2.3 below.

When a braking torque is applied to the wheel and tire, the vehicle inertia will tend to pull the wheel forward while the interaction between the tire contact patch and ground will opposed this motion. Because of this action, the casing and the tread elements on the leading edge of the tire become stretched just before entering the contact patch region as shown in Figure 2.4. Braking torque will increase the distance travel by the tire and will be greater compare when the tire is subjected to free rolling (Heisler, 2002).

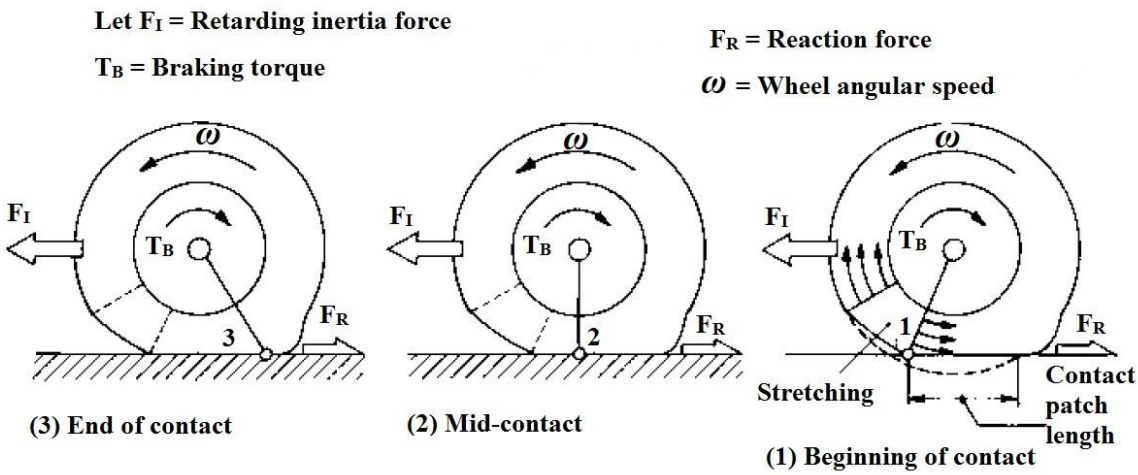


Figure 2.4: Deformation of tire under braking torque

Source: Heisler (2002)

The phenomenon of the gain or loss in the distance the tread travel under tractive or braking conditions relative to that the free rolling is known as longitudinal slip. Figure 2.5 shows the effect of driving torque to the tire slip. Tractive effort will increase slightly matched proportionally with the percent slip. The tread elements will eventually reach its distortion limit and parts of the tread elements will begin to slip until the limiting tractive effort is developed. Further increase in the percentage of slip will cause the vehicle under unstable condition because of that the decrease of the tractive effort until pure wheel spin is developed (Heisler, 2002).

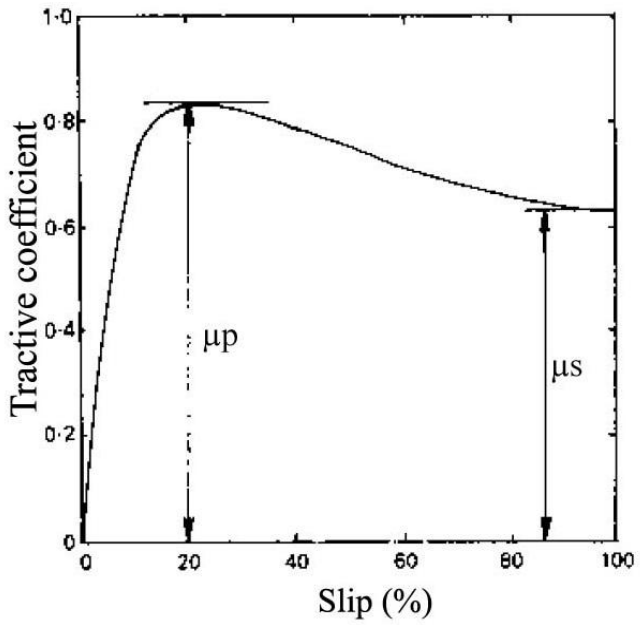


Figure 2.5: Effect of the tractive effort to the wheel slip

Source: Heisler (2002)

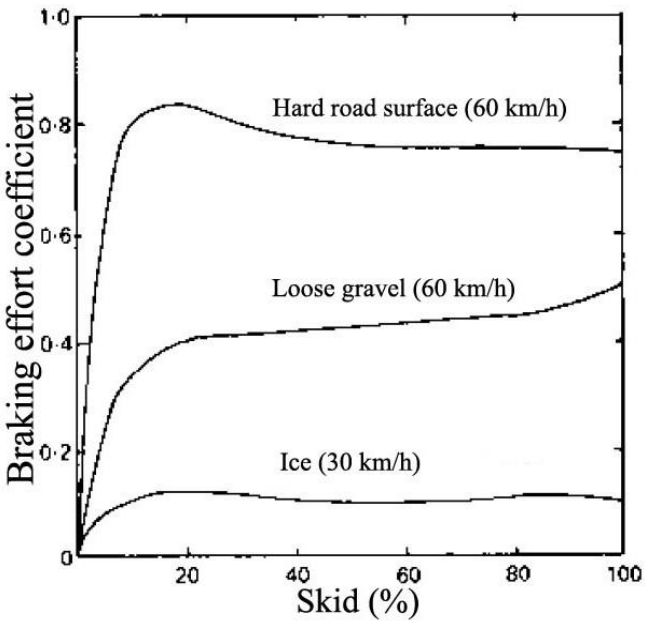


Figure 2.6: Effect of the braking effort to the wheel skid

Source: Heisler (2002)

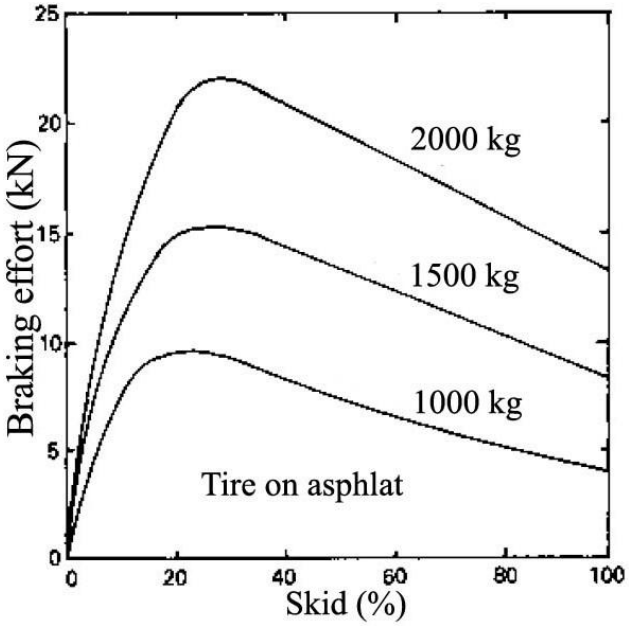


Figure 2.7: Effect of the vertical load to the braking effort

Source: Heisler (2002)

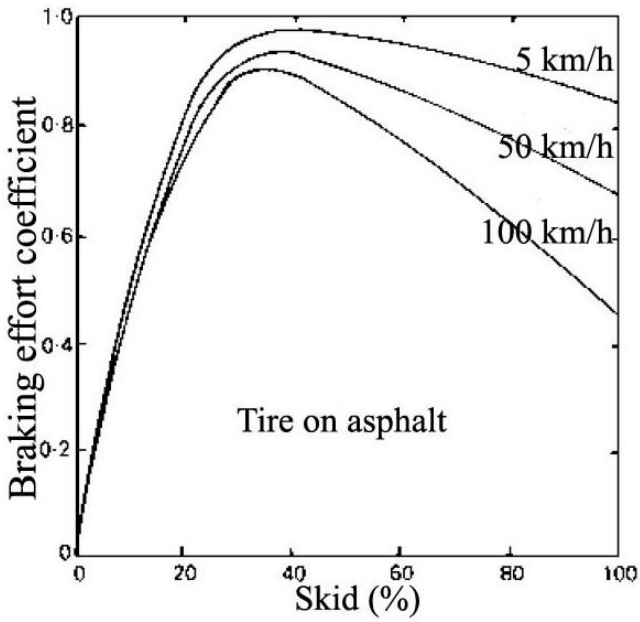


Figure 2.8: Effect of vehicle velocity on the braking effort

Source: Heisler (2002)

Skid is referred to as slip when the wheel is subjected to a braking torque. Figure 2.6 show the effect of the braking effort to the wheel skid. It can be seen in Figure 2.6 that the maximum braking effort is largely dependent to the road surface. Maximum braking effort also dependent to the normal wheel load while the wheel speed is influences more on the unstable skid region of a braking sequence as shown in Figure 2.7 and Figure 2.8.

2.2.3 Braking Characteristics on Wet Road

Maximum tire-road friction is developed under slow movement or creep. Figure 2.9 show the typical curve on a smooth wet road. When the brake is applied instance steadily, the retardation rate measured as a fraction of the gravitational acceleration (*g* m/s^2) will rise rapidly in a short time interval up to 0.5 g. During emergency braking, the vehicle retardation slightly will increase to its peak value of just over 0.6 g. In order to prevent the wheels locked up by the brake, the driver should raise the foot brake effort and release the brake immediately in repeated sequence.

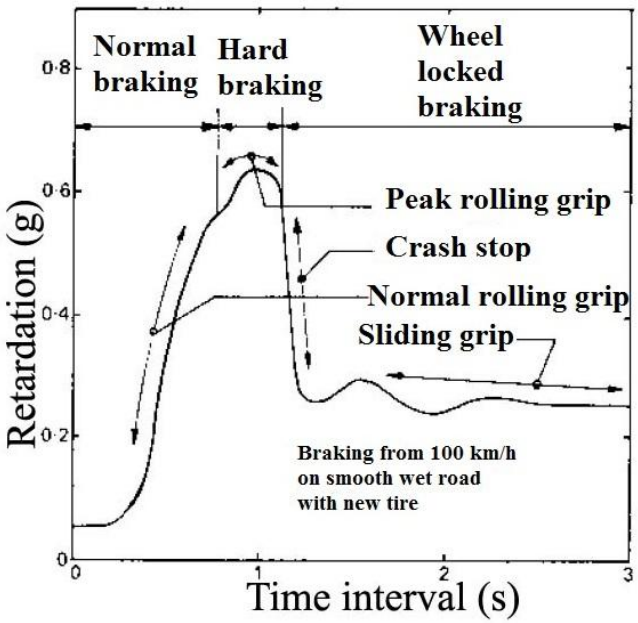


Figure 2.9: Possible retardation braking cycle on a wet road

Source: Heisler (2002)

As the wheels are prevented from rotating, the tire-road interaction coefficient drops drastically as shown in the crash stop phase. The retardation rate will steady at much lower value of just over 0.2 g if the wheels are still locked by the brake. The tire now will experience entirely sliding mode with no directional stability and with retardation at about one third of the attainable peak value.

2.3 LONGITUDINAL FORCE AND SLIP

The longitudinal slip of a tire is defined as:

$$s = \frac{R\omega}{Vx} - 1 \tag{2.3}$$

Where, R is the tire's geometric and free rolling radius, ω is the tire's angular velocity, and Vx is the tire's forward velocity. Slip ratio is positive for driving and is negative for braking (Jazar, 2008).

To accelerate or stop a vehicle, longitudinal forces must develop between the tire and the road. When torque is applied to the spin axis of the tire, slip will occurs and a longitudinal force Fx is generated at the tire contact patch (Jazar, 2008). The force Fx is proportional to the normal force, Fz.

$$Fx = \mu_x(s)\, Fz \tag{2.4}$$

Where, the coefficient $\mu_x\,(s)$ is called the longitudinal friction coefficient and is a function of slip, s as shown in Figure 2.10 below. The friction coefficient reaches a driving peak value μ_{dp} at $s \approx 0.1$, before dropping to an almost steady-state value μ_{ds} (Jazar, 2008). The friction coefficient $\mu_x\,(s)$ may be assumed proportional to slip when slip value is very small.

$$\mu_s\,(s) = C_x\, s \qquad s \ll 1 \tag{2.5}$$

The tire will spin when slip, $s \geq 0.1$ and the friction coefficient remains almost constant (Jazar, 2008). The same phenomena happen in braking at the values μ_{bp} and μ_{bs}.

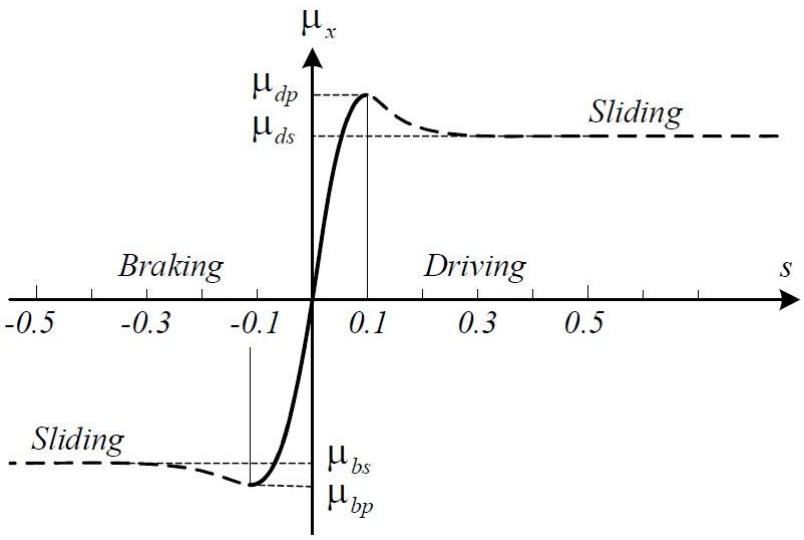


Figure 2.10: Longitudinal friction coefficient as a function of slip

Source: Jazar (2008)

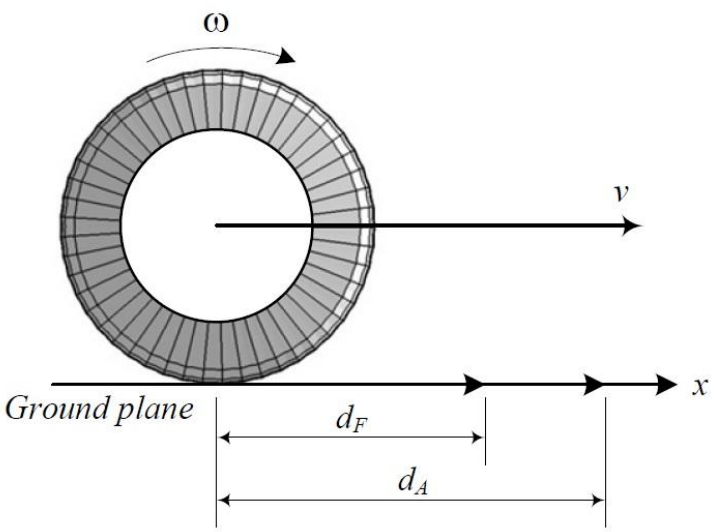


Figure 2.11: Rotating tire on ground plane

Source: Jazar (2008)

Slip ratio, or simply slip, can also defined as the difference between the actual velocity of the tire, Vx and the equivalent tire velocity $R_e\omega$. Figure 2.11 illustrates a turning tire on the ground. The ideal distance that the tire would freely travel with no slip is denoted by dF, while the actual distance the tire travels is denoted by dA. Thus, for a slipping tire, $dA > dF$, and for a spinning tire, $dA < dF$ (Jazar, 2008).

The difference $dF - dA$ is the tire slip and therefore, the slip ratio of the tire is:

$$s = \frac{dF - dA}{dA} \tag{2.6}$$

To have the instant value of slip, we must measure the travel distances in an infinitesimal time length, and therefore:

$$s = \frac{\Delta dF - \Delta dA}{\Delta dA} \tag{2.7}$$

If the angular velocity of the tire is ω then, $\Delta dF = R\omega$ and $\Delta dA = Re\omega$ where, R is the geometric tire radius or the free rolling radius and R is the effective radius of the tire.

Therefore, the slip ratio, s can be defined based on the actual speed, $Vx = Re\omega$, and the free speed, $R\omega$ (Jazar, 2008):

$$s = \frac{R\omega - R_e\omega}{V_x} \tag{2.8}$$

$$s = \frac{R\omega}{V_x} - 1 \tag{2.9}$$

A tire can exert longitudinal force only if a longitudinal slip is present. Longitudinal slip is also called circumferential or tangential slip. During acceleration, the actual velocity, Vx is less than the free velocity, $R\omega$, and therefore, $s > 0$. However,

during braking, the actual velocity, Vx is higher than the free velocity, $R\omega$ and therefore, $s < 0$ (Jazar, 2008).

The frictional force, Fx between a tire and the road surface is a function of normal load, Fz, vehicle speed, Vx, and wheel angular speed, ω. In addition to these variables there are a number of parameters that affect Fx, such as tire pressure, tread design, wear, and road surface. It has been determined empirically that a contact friction of the form $Fx = \mu x(\omega, Vx)Fz$ can model experimental measurements obtained with constant Vx, ω (Jazar, 2008).

2.3.1 Driving Maneuver

When driving torque is applied to the tire axis, the tread of the tire will be compressed circumstantially in the tire contact patch. Hence, the tire is moving slower than a free tire (Jazar, 2008).

$$R_e\omega < R\omega \tag{2.10}$$

Therefore $s > 0$ and the equivalent radius for a driving tire is less than the free radius.

$$R_e < R \tag{2.11}$$

Equivalently, this condition can be express using the equivalent angular velocity ωe and deduce that a driving tire turns faster than a free tire.

$$R\omega_e < R\omega_w \tag{2.12}$$

The driving moment can be high enough to overcome the friction and turn the tire on pavement while the car is not moving. In this case $Vx = 0$ and therefore, $s = \infty$. It shows that the longitudinal slip would be between $0 < s < \infty$ when accelerating (Jazar, 2008).

$$0 < s < \infty \quad for\ a > 0 \tag{2.13}$$

The tire speed $R\omega$ equals vehicle speed Vx only if acceleration is zero. In this case, the normal force acting on the tire and the size of the tire contact patch are constant in time. No element of the tire contact patch is slipping on the road (Jazar, 2008).

2.3.2 Braking Maneuver

When braking torque is applied to the wheel axis, the tire tread of the tire will be stretched circumstantially in the tire print zone. Hence, the tire is moving faster than a free tire (Jazar, 2008).

$$R_e\omega > R\omega \tag{2.14}$$

Therefore, $s < 0$ and the equivalent radius for a braking tire is more than the free radius.

$$R_e > R \tag{2.15}$$

Equivalently, this condition can be express using the equivalent angular velocity ωe and deduce that a braking tire turns slower than a free tire

$$R\omega_e > R\omega_w \tag{2.16}$$

The brake moment can be high enough to lock the tire. In this case $\omega w = 0$ and therefore, $s = -1$. It shows that the longitudinal slip would be between $-1 < s < 0$ when braking (Jazar, 2008).

$$-1 < s < 0 \quad for\ a < 0 \tag{2.17}$$

2.4 ANTILOCK BRAKING SYSTEM AS WHEEL SLIP CONTROL

Electronic sensors measure the wheel velocities and the brake pressure, the vehicle velocity and/or the vehicle acceleration. Electronic Control Unit (ECU) usually microprocessor-based system and the electrically controlled valves used to control the pressure in brake cylinder or chambers as shown in Figure 2.12.

The function of an ABS is to prevent wheels from being totally locked during panic braking or braking on slippery road surface. The objective of an ABS is to achieve the shorter stopping distance and maintain a good steering stability during braking. When a lockup wheel is detected, ECU releases the brake pressure until the wheel lockup is avoided. Then ABS re-applies braking when the wheel velocity speeds up again.

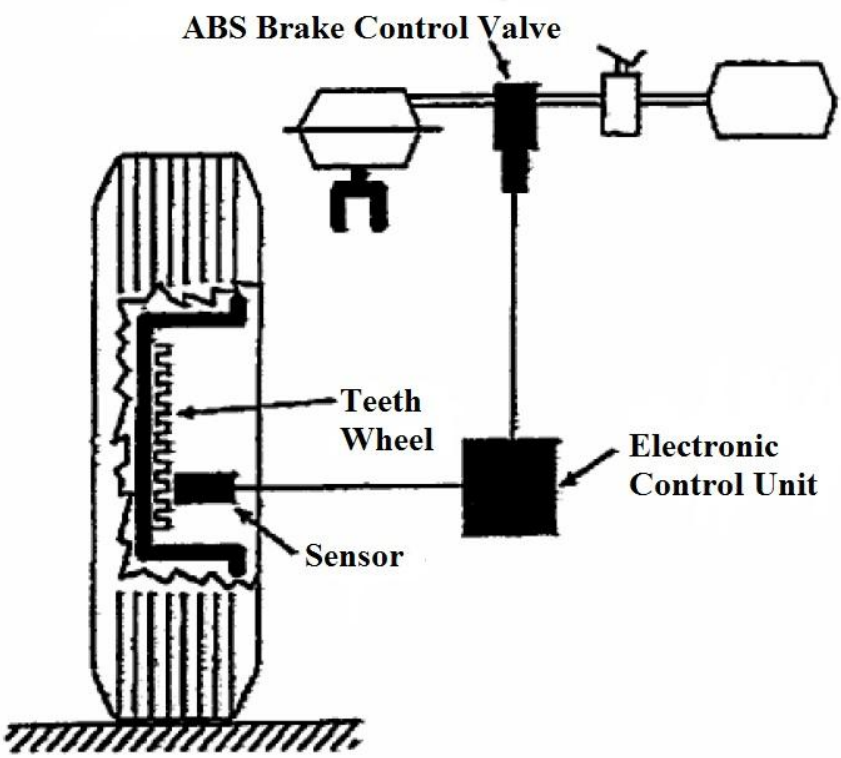


Figure 2.12: Configuration of an ABS

Source: Wong (1978)

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter will discuss the experimental system that had been used in this project consist with the vehicle specification, Global Positioning System (GPS), Wheel Pulse Transducer (WPT) and the DEWESoft. This chapter also deals with the experimental test for both driving and braking maneuver on paved and unpaved sandy road condition. Finally, this chapter will discuss the post-processing method that used for the wheel slip analysis and the calculation of the effective rolling radius together with the longitudinal tire stiffness.

3.2 EXPERIMENTAL SYSTEM

3.2.1 Vehicle Specification

The test vehicle used for this project is Proton Persona Elegance 1.6 (M/T), a 4-door sedan provided by Universiti Malaysia Pahang. Proton Persona is manufactured by National carmaker Proton Holdings Berhad which has maintained its second spot on the passenger car list with its 2010 half-year sales (Mahalingam, 2010).

Table 3.1 show the vehicle specification of the test vehicle and Figure 3.1 show the picture of the UMP Test Car. This vehicle is installed with various sensors for vehicle dynamics testing including the Wheel Pulse Transducer, Global Positioning System, and computer host for data acquisition system.

Figure 3.1: UMP Test Car

Table 3.1: Vehicle specification for Proton Persona Elegance 1.6 (M/T)

Vehicle Properties	**Details**
Make	Proton
Model	Persona Elegance 1.6 (M/T)
Body style	4-door sedan
Wheel Base (mm)	2600
Overall Length (mm)	4477
Overall Width (mm)	1725
Overall Height (mm)	1438
Front Track (mm)	1475
Rear Track (mm)	1470
Min. Turning Radius (m)	0
Kerb Weight (kg)	1195
Ground Clearance (mm)	0
Steering	Rack & Pinion, Hydraulic Power Assisted
Front Suspension	MacPherson strut
Rear Suspension	Multi-Link, Stabilizer Bar
Front Brakes	Vent Disc
Rear Brakes	Drum
Std. Tire Size	190/60 R15
Std. Wheel Size	15

Source: Proton (2010)

3.2.2 Global Positioning System

Specifically GPS velocity is used to obtain vehicle course, velocity, and road grade, as well as to correct inertial sensors errors, providing accurate longitudinal and lateral acceleration, and pitch, roll, and yaw angular velocities. Additionally, it is shown that transient changes in sideslip (or lateral velocity), roll, and pitch angles can be measured (Bevly, 2004).

Figure 3.2: Global Positioning System (GPS) receiver location

The use of GPS velocity information has an even greater benefit beyond the generation of an accurate slip measurement. By comparing the wheel slip to estimate of the forces acting on the vehicle, the tire force versus slip characteristic can be obtained (Miller et al., 2001). Figure 3.2 below shows the position of the GPS receiver installed to the UMP Test Car. This device must be installed on the centerline of the car's roof, as close as possible to the car's center of gravity.

3.2.3 Wheel Pulse Transducer

The CORRSYS-DATRON Wheel Pulse Transducer is a universally adaptable measuring unit for the acquisition data derived from vehicle wheel rotation. The WPT delivers 1000 pulses per rotation. Output signals generated by the WPT provide the basis from which wheel rotation speed, acceleration, distance and speed are calculated. The sensor installation is shown in Figure 3.3.

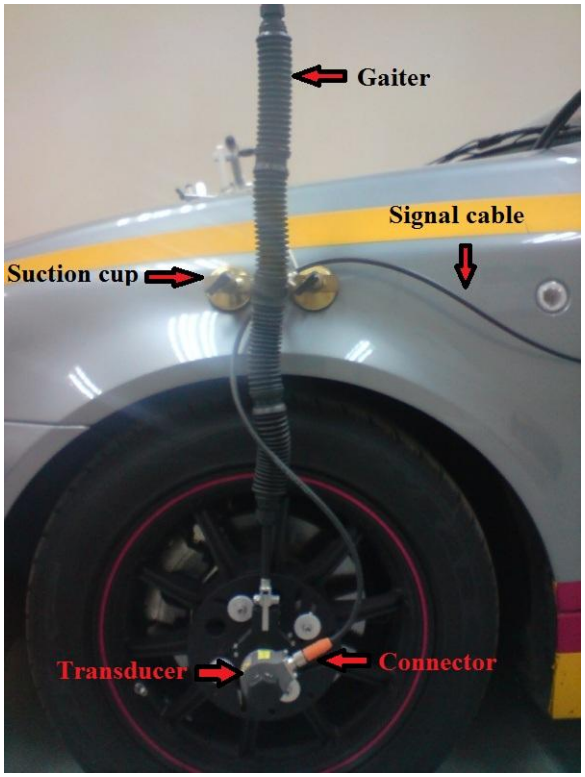


Figure 3.3: Wheel pulse transducer mounting

3.2.4 Computer Host for Data Acquisition System

DEWESoft 6 is the fast and easy to use data acquisition software develops by DEWETRON. Dewesoft is taking a major role in all kinds of data recording applications in automotive industry, especially in development laboratories and test facilities, where the ability to acquire data from all different sources creates major advantage. This software not only about standard interfaces like analog, digital, counters, CAN, GPS and video channels, but made to support special devices like gyro

platform from Genesys or torque wheels from Kistler, everything of course perfectly synchronized with other sources.

Figure 3.4: Computer host for data acquisition system

3.3 ACCELERATION TEST

Tractive effort of a tire to the ground is produced when a driving torque is transmitted to the wheel and tire. This acceleration test is performed to identify the tractive properties of a tire during driving maneuver. The primary measurement parameters for the driving maneuver from straight-line vehicular motion for wheel slip calculation are the vehicle mass, angular velocity of the tire, the absolute velocity and the distance travel in the longitudinal system.

The test car will be driven from zero velocity until 60 km/h and 90 km/h. The percentage of wheel slip during driving maneuver is calculated base on the difference between the GPS distance and the distance travel using the wheel revolution. Another approach is that by using linear regression to estimate the effective radius of the tire, tire stiffness, longitudinal force, speed ratio, and the longitudinal acceleration of the vehicle

as will discuss later in this chapter. This testing performed in a straight line road including two experimental road condition of paved road and unpaved road condition.

3.3.1 Paved Road Condition

The particular test road for paved road condition is located inside UMP with an approximately 2 km straight line road completely paved with tar. This road provides a safe distance for the acceleration test that is required a straight line road and some distance for the car to accelerate from the initial velocity of 0 km/h. Figure 3.5 below show the straight line paved road for the acceleration test take place.

For paved road condition, the maximum permitted velocity for acceleration test is 90 km/h. This is due to the safety precaution and to minimize the effect of the aerodynamics effect in the streamline body of the car. The road grade is assumed zero as the road is flat and no inclination is found along this testing road.

Figure 3.5: Straight line paved road for acceleration test

3.3.2 Unpaved Sandy Road Condition

The particular test road for unpaved sandy road condition is located inside UMP which is there is an approximately 0.5 km straight line unpaved road with sandy. This testing road is actually the project site for the construction of UMP Pekan. The sandy characteristic of this road give the variation in the tire-road friction to extend the study of wheel slip behavior. This is shown in Figure 3.6 below.

For unpaved sandy road condition, the maximum permitted velocity for acceleration test is 60 km/h. This is due to the safety precaution because the potential of car accident is typically high due to the soft sand. Higher speed may cause the test car unstable in this soft sandy because of that the traction is generally low. The road grade is assumed zero as the road is flat and no large road inclination is found along this testing road.

Figure 3.6: Straight line unpaved road for acceleration test

3.4 BRAKING TEST

Braking from straight-line vehicular motion provides information on the deceleration capability of a vehicle as well as the tire slip achievable during this state. The primary measurement parameters for the braking maneuver from straight-line vehicular motion for wheel slip calculation are the vehicle mass, angular velocity of the tire, the absolute velocity and the distance travel in the longitudinal system.

The driving maneuver is performed on an even road from a starting speed of 90 km/h and 60 km/h and the test car should stop at a distance of 40 m from a reference point of where the driver start to push the brake pedal. The parameters that used to calculate the percentage of wheel slip during braking maneuver are the effective radius of the tire, tire stiffness, longitudinal force, speed ratio, and the longitudinal deceleration of the vehicle. In extend for the variation of the tire-road interaction characteristic; two experimental road conditions of paved and unpaved road condition are being tested.

3.4.1 Paved Road Condition

The particular test road for paved condition is located inside UMP campus. There is approximately 2 km straight line road completely paved with tar. This is the same testing road used for the acceleration test. This road provides a safe distance for the braking test that is required a straight line road and some distance for the car to accelerate from the initial velocity of 0 km/h until reach 90 km/h and 60 km/h and then the driver should start to initiate the braking maneuver.

For paved road condition, the maximum permitted velocity for braking test is 90 km/h. Higher vehicle speed is required for this braking test to investigate the tire characteristics in term of wheel slip. The testing road for braking test is shown in Figure 3.7.

Figure 3.7: Straight line paved road for braking test

3.4.2 Unpaved Sandy Road Condition

The particular test road for unpaved sandy road condition is the same as that in the acceleration test. It is located inside UMP which is there is an approximately 0.5 km straight line unpaved road with sandy. This testing road is actually the project site for the construction of UMP Pekan. During braking maneuver, the tire road friction is one of the contributing factors to determine the vehicle braking performance. This tire-road interaction can be analyzed in term of wheel slip. Figure 3.8 show the testing road for this condition.

The maximum permitted velocity for braking test is 60 km/h due to the safety precaution. The behavior of vehicle on soft sand is unstable and it is dangerous to brake the car which is accelerating at high speed. The road grade is assumed zero as the road is flat and no large road inclination is found along this testing road.

Figure 3.8: Straight line unpaved sandy road for braking test

3.5 POST – PROCESSING METHOD

The standard SAE definition of wheel slip is (Carlson and Gerdes, 2002):

$$s = -\frac{(Re\omega - V_x)}{V_x} \tag{3.1}$$

Another approach to calculate the longitudinal slip is by comparing the distance measured by the GPS and the distance travel by the wheel rotation in post processing according to:

$$s = \frac{dWPT - dGPS}{dGPS} \times 100\% \tag{3.2}$$

Where the distance travels by tire that is measured by the WPT is calculated using:

$$dWPT = R \times 2 \times \pi \times N \tag{3.3}$$

The free rolling radius, R of the tire is calculated using the height-to-weight ratio of the tire (Reimpell et al., 2001) according to:

$$H/W = \frac{H}{W} \times 100\% \tag{3.4}$$

$$R = \frac{2(H/w \times W)+D}{2} \tag{3.5}$$

The relation between force and slip is roughly linear at low values of slip below the point at which significant sliding occurs in the contact patch (Miller et al., 2001). In this region, force can be approximated as proportional to slip using an effective longitudinal stiffness of the tire, C_x:

$$Fx = Cx\,.\,s \tag{3.6}$$

The equation of motion of a vehicle in the longitudinal direction is:

$$Fxf + Fxr - Frr - Fd - Mg\,sin\,\theta = Ma_x \tag{3.7}$$

Where F_{xf} and F_{xr} are the longitudinal forces (driving or braking) on the front and rear axles, respectively, F_{rr} is rolling resistance, F_d is drag and θ is the grade angle. As a first approximation, rolling resistance, drag and grade are neglected and mass is assumed known. The equation of motion then becomes:

$$Fx = Fxf + Fxr = Ma_x \tag{3.8}$$

This admittedly a simplification and better results could be obtained by including estimates of the road grade, mass and other road loads obtained online. Grade can be estimated from the GPS receiver by examining the ratio of vertical velocity to horizontal velocity after which the mass and road loads can be estimated if a value of engine torque is available (Miller et al., 2001).

The acceleration can be obtained from the MTi Gyro sensor for the acceleration in the x-axis. Acceleration is also found by differencing the GPS velocity measurements in post-processing according to:

$$a(k) = \frac{[v(k+1) - v(k-1)]}{2\Delta t} \tag{3.9}$$

The longitudinal stiffness of the tire can be determined after the longitudinal force and wheel slip is calculated by:

$$Cx = \frac{Fx}{S} \tag{3.10}$$

The effective rolling radius of the tire is related with the translational and rotational wheel velocities as (Vantsevich, 2007):

$$Re = \frac{VGPS}{\omega} \tag{3.11}$$

Or

$$Re = \frac{dGPS}{2\pi N} \tag{3.12}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

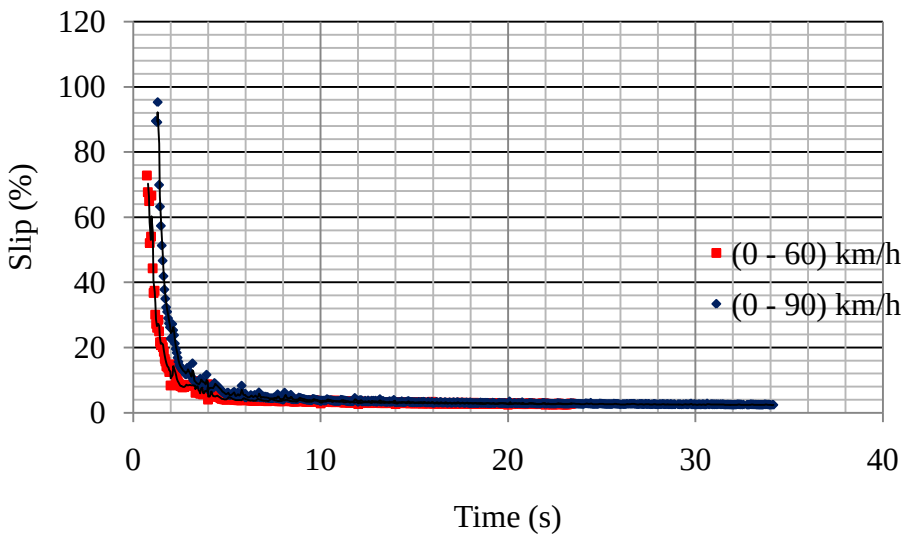
This longitudinal forces that produce acceleration and braking on the ground vehicles with pneumatic tires arise due to deformation and sliding in the tire contact patch (Pacejka, 2005). While the actual motions that take place in the contact patch are somewhat complex, the force generation can generally be described with sufficient accuracy in terms of wheel slip.

This chapter will discuss the characteristic of the tire road interaction in term of wheel slip. The experiment of acceleration and braking test result will be discuss here for both paved and unpaved sandy road condition. The relationship between the longitudinal force and wheel slip is the main topic and the variations of the effective rolling radius together with the longitudinal tire stiffness are also covered in this chapter.

4.2 WHEEL SLIP ANALYSIS FOR DRIVING MANEUVER

A tractive force at the tire to ground is produced when a driving torque is transferred to the tire and wheel. The tire will compressed at the tire road contact patch, thus resulting lower distance travel by the car compared to that in the free rolling condition. Therefore, the study of the acceleration performance is required to investigate the behavior of percentage of wheel slip during driving maneuver.

4.2.1 Relationship of Wheel Slip against Velocity and Time



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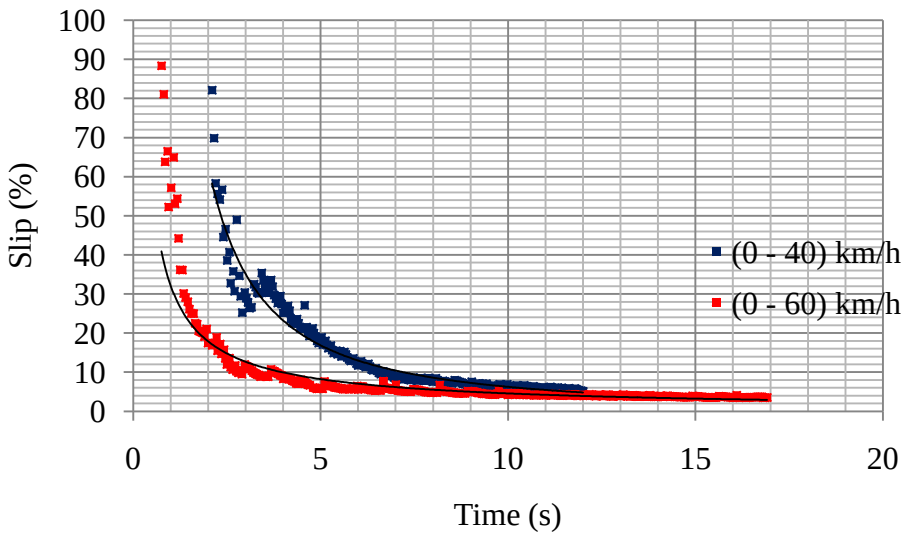
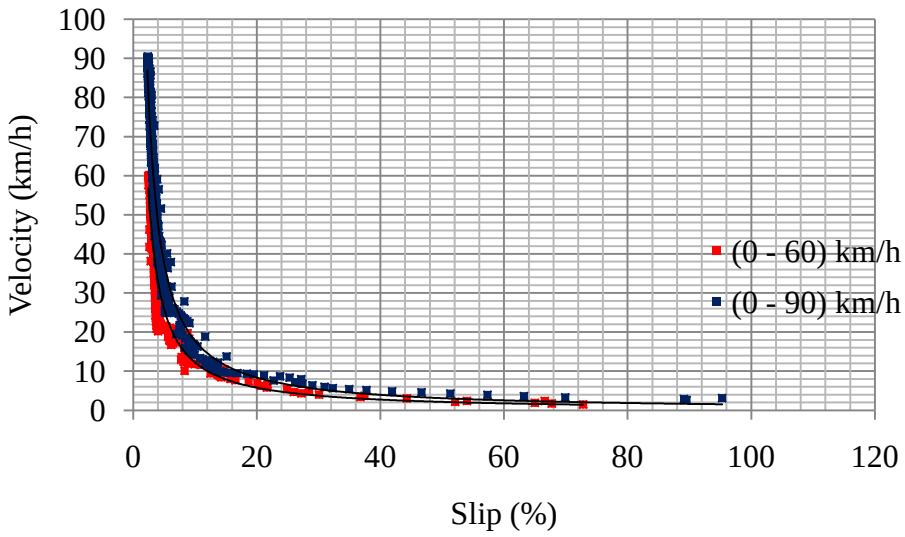
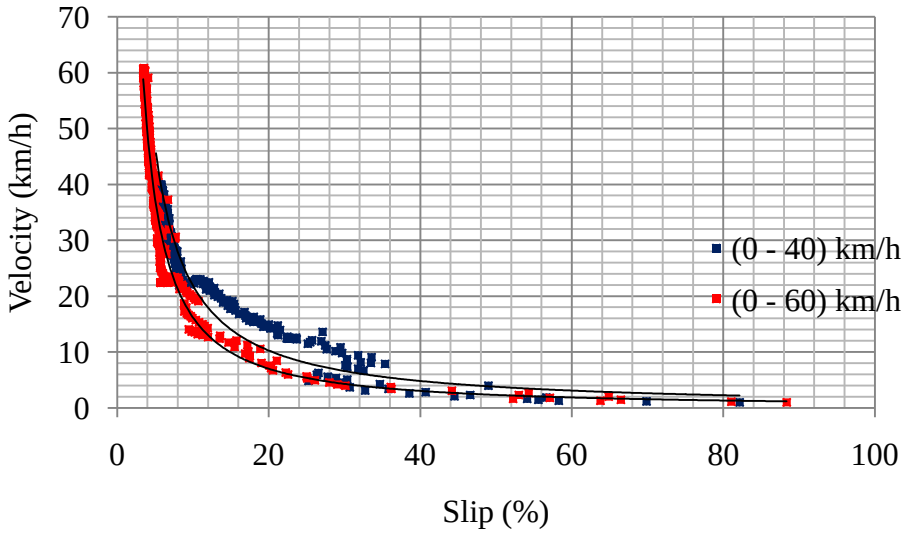


(b)

Figure 4.1: Graph of slip versus time for (a) paved road and (b) unpaved sandy road condition



(a)



(b)

Figure 4.2: Graph of velocity versus slip during driving for (a) paved road and (b) unpaved sandy road condition

Figure 4.1 and Figure 4.2 show the relationship of percentage of wheel slip against time and the variation of wheel slip with the increase of vehicle velocity. The percentage of wheel slip is higher during the initial velocity and time. The value of percentage of wheel slip will reduce drastically just after the initial velocity of the

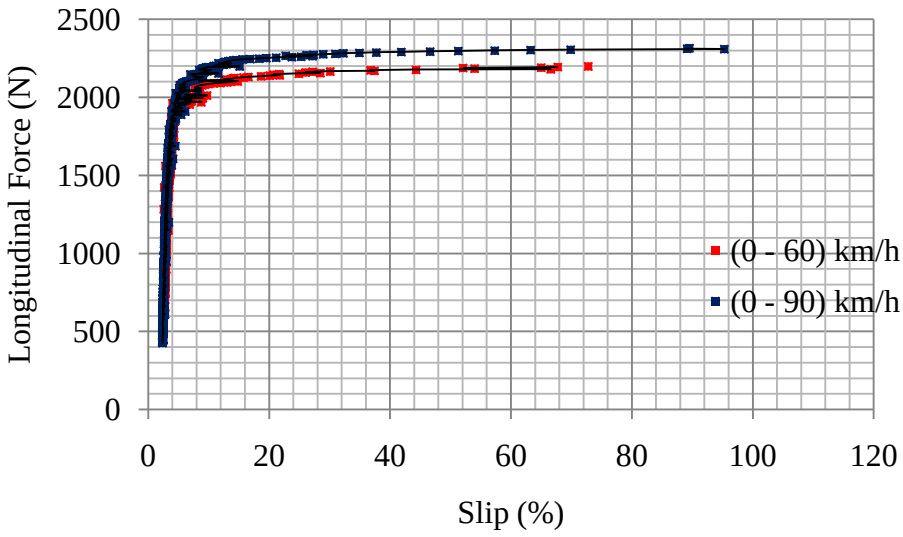
vehicle. The percentage of wheel slip decrease between of 5 – 10 sec after the car start moving for both road conditions. While for the vehicle speed, the percentage of wheel slip will reduce after the car moving approximately at 2 – 5 km/h for both road conditions.

According to the Newton's 1st Law, every object in a state of motion will tends to remain in the state of motion unless an external force is applied to it. At the initial velocity and time, the car is tends to remain in its static condition. Thus when the tire is rotating and transferring the longitudinal force to move the car, the car will not moving until the force applied is able to overcome the weight. This is why during initial time and velocity the percentages of wheel slip is higher and decrease after certain time and vehicle speed.

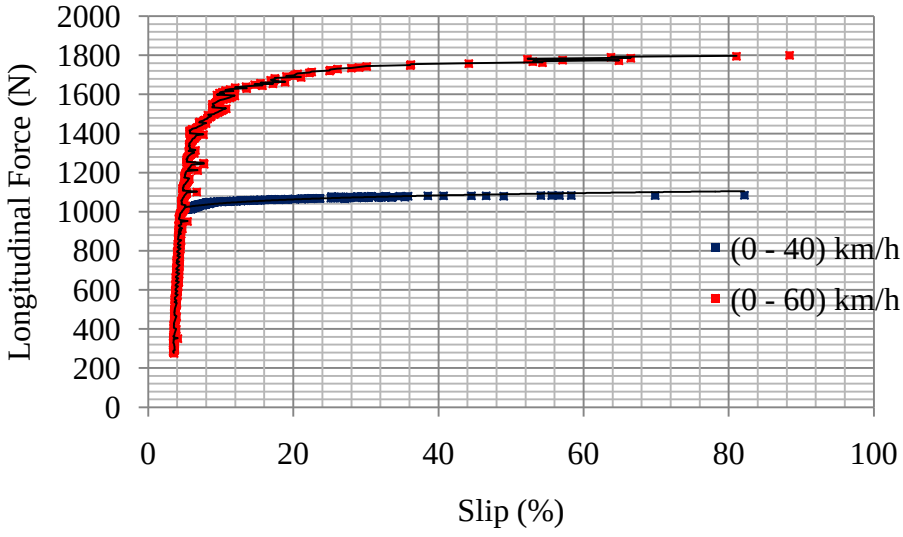
4.2.2 Longitudinal Force

When a driving torque is applied to a pneumatic tire, a tractive force is developed at the tire road contact patch. At the same time, the tire treads in front of and within the contact patch is subjected to compression. A corresponding shear deformation of the side wall of the tire is also developed. As tread elements are compressed before entering the contact region, the distance that the tire travels when subject to a driving torque will be less than that in free rolling.

Figure 4.3 (a) and Figure 4.3 (b) shows the relationship of the longitudinal or tractive force of the tire with the wheel slip percentage both for paved road and unpaved road condition. The trend for both of the graph shows that the longitudinal force of the tire is increase linearly with the percent of wheel slip at low values of slip. In this region, force can be approximated as proportional to slip. A further increase in the wheel torque and tractive force results part of the tire tread sliding on the ground. The additional force generated per unit slip begins to decrease and ultimately reaches a peak.



(a)



(b)

Figure 4.3: Graph of longitudinal force versus slip during driving for (a) paved road and (b) unpaved sandy road condition

From Figure 4.3 (a), the maximum linear tractive force during driving maneuver on a paved road is reached somewhere between 15 – 20 % of slip at 2133.924 N for 0 – 60 km/h and 2247.985 N for 0 – 90 km/h. For driving maneuver on unpaved road condition, the linear relationship between the longitudinal forces with the wheel slip

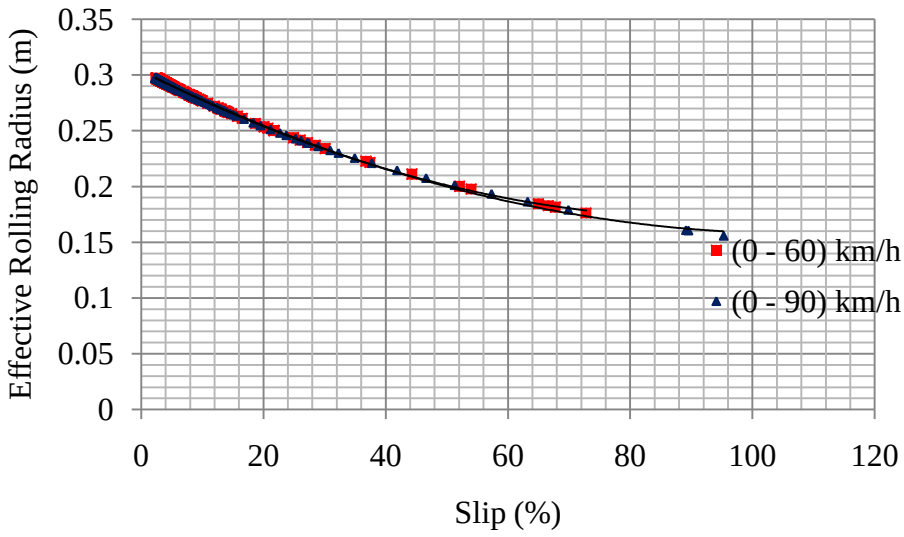
becomes nonlinear at slip between 15 – 20 % similar to that in the paved road condition. For vehicle speed of 0 – 40 km/h, the maximum force before the nonlinear region start is determined to be at 1062.748 N and 1681.5 N for 0 – 60 km/h as shown in Figure 4.3 (b).

These results shows that the traction force of vehicle during driving maneuver is higher on paved road compare to the unpaved sandy road condition. When a driving torque is applied to soft sand, the sand will be packed when the tire passes. This will cause the tire tractive force of the tire reduces when driving torque is applied. Higher slip value is obtained from unpaved sandy road condition with typical value of tractive force applied to the paved road condition. This result shows that the coefficient of friction between unpaved sandy road conditions is lower than the paved road condition.

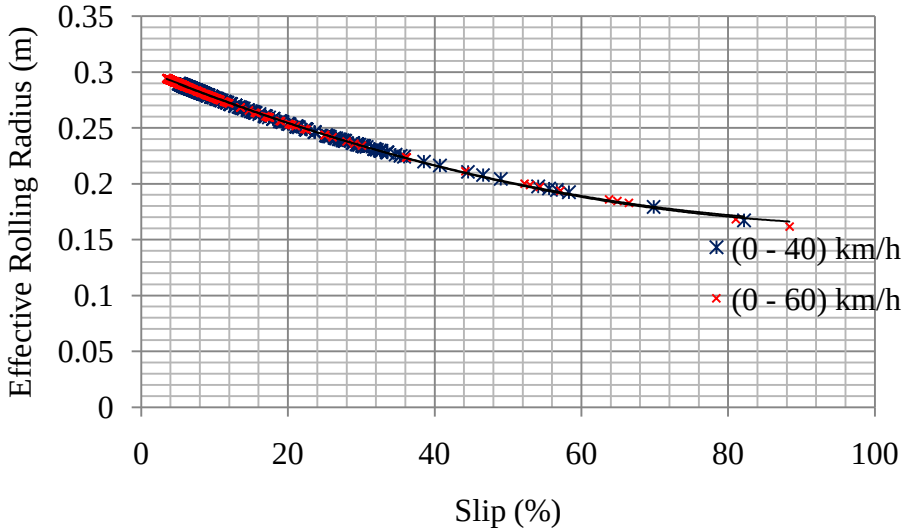
4.2.3 Effective Rolling Radius

The actual forward speed of a wheel rolling in a rectilinear motion divided by the angular wheel speed gives the effective rolling radius of the tire. This effective rolling radius also can be determined by measuring the wheel travel and the number of revolution that the wheel does moving from its initial point to the final point.

Figure 4.4 (a) and Figure 4.4 (b) show the variation of the effective rolling radius with respect to the percent of wheel slip for paved road condition and unpaved sandy road condition. The effective rolling radius for both road conditions will decrease with the increase of the percentage of wheel slip. The average effective rolling radius of tire during driving maneuver on paved road condition is 0.2908 m for vehicle speed of 0 – 60 km/h and 0.2900 m for 0 – 90 km/h. For unpaved sandy road condition, the average effective rolling radius during driving maneuver is 0.2667 m for vehicle that is accelerating from 0 – 40 km/h and 0.2832 m for 0 – 60 km/h.



(a)



(b)

Figure 4.4: Graph of effective rolling radius versus slip during driving for (a) paved road and (b) unpaved sandy road condition

High value of slip means that the difference in the distance travels by the car for actual condition and the distance travel by the tire in the free rolling condition is higher. When driving torque is applied, the tire will be compressed in the tire road contact patch. Therefore, in actual condition, the rolling radius of the tire will be less than the

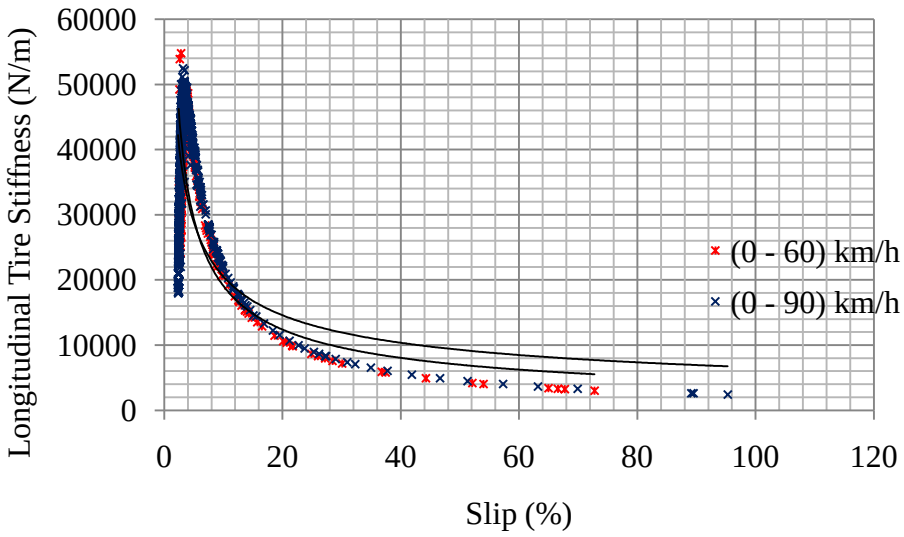
free rolling radius of the tire during driving maneuver. Higher value of slip during the driving maneuver for unpaved sandy road condition lead to the lower effective radius is obtained compare to the paved road condition.

4.2.4 Longitudinal Tire Stiffness

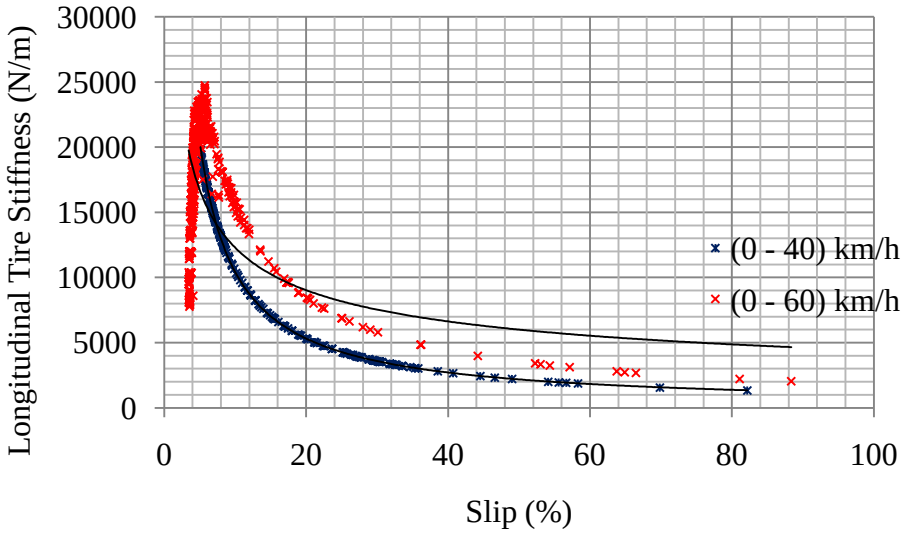
The longitudinal force of tire is considered to be directly proportional with the percentage of wheel slip during low level of slip using the longitudinal tire stiffness. Hence, at this low level of slip region, the longitudinal tire stiffness can be obtained by dividing the longitudinal force of the tire by the percentage of slip on the tire.

Figure 4.5 (a) and Figure 4.5 (b) show the relationship of the longitudinal tire stiffness against the percentage of wheel slip both for paved road condition and unpaved sandy road condition. For both road conditions, the longitudinal tire stiffness will increase during driving maneuver at low level of slip. This linear relationship between longitudinal tire stiffness will reach its peak between 15 – 20 % of slip. After this peak value of longitudinal stiffness, increase in the wheel slip will decrease the longitudinal tire stiffness. The peak longitudinal tire stiffness of the tire is found to be 54761.06 N for vehicle that accelerate from 0 – 60 km/h and 52485.68 N for 0 – 90 km/h during driving maneuver on paved road condition. For unpaved sandy road condition, the peak value of the longitudinal tire stiffness is found to be 19781.23 N for 0 – 40 km/h and 24723.97 N for 0 – 60 km/h.

This result clearly shows that the longitudinal tire stiffness is strongly depends on the longitudinal force and slip produced by the tire. Larger the force will give higher longitudinal tire stiffness with typical low level of slip. After the peak value, both longitudinal force and tire stiffness will decrease with the increase of the tire slip. Lower value of longitudinal tire stiffness is obtained for unpaved sandy road condition compare to the paved road condition is cause by the lower traction is developed during driving maneuver.



(a)



(b)

Figure 4.5: Graph of longitudinal tire stiffness versus slip during driving for (a) paved road and (b) unpaved sandy road condition

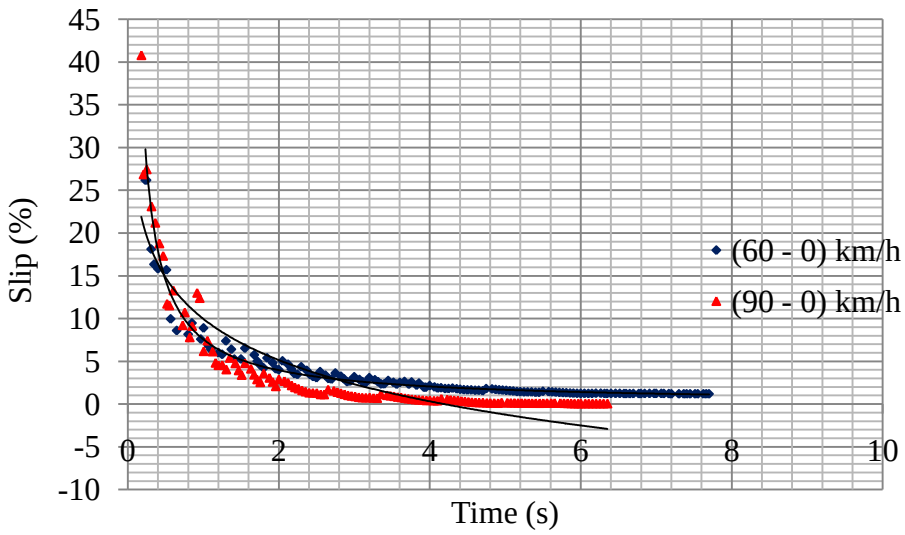
4.3 WHEEL SLIP ANALYSIS FOR BRAKING MANEUVER

When brake torque is applied to the tire, the tread will be stretched at the tire road contact patch, thus resulting higher distance travel by the car compared to that in the free rolling condition. Therefore, the study of the braking performance is required to investigate the behavior of percentage of wheel slip during braking and this can be apply to the development of the Antilock Braking system.

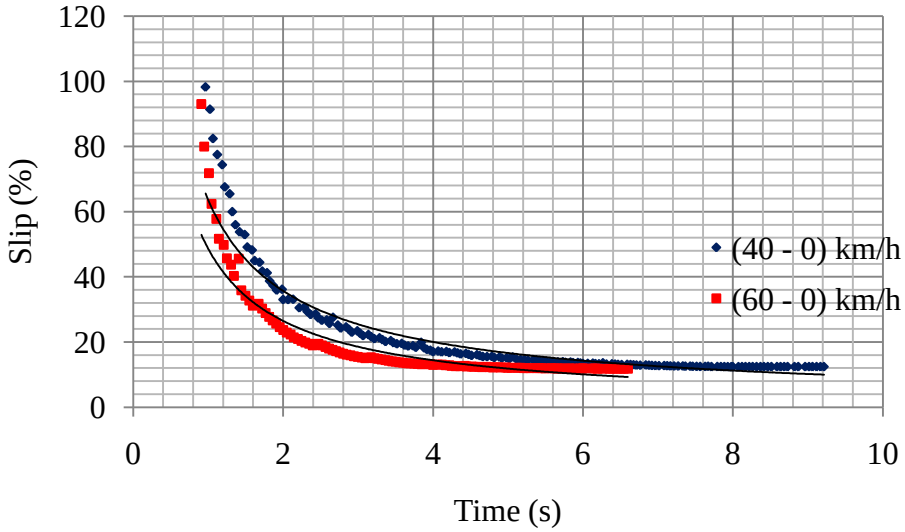
4.3.1 Relationship of Wheel Slip against Velocity and Time

Figure 4.6 and Figure 4.7 below show the variation of percentage of wheel slip against time and the variation of wheel slip with the increase of vehicle velocity. The percentage of wheel slip is higher during the initial velocity and time. The value of percentage of wheel slip will reduce drastically just after the initial velocity of the vehicle. The percentage of wheel slip decrease between of 5 – 10 sec after the car start moving for both road conditions. While for the vehicle speed, the percentage of wheel slip will reduce after the car moving approximately at 2 – 5 km/h for both road conditions.

This phenomenon is cause by the inertia force of the vehicle which tries to maintain its motion. When the brake is initiated, the wheel will reduce its rotation and slow down the movement of vehicle. Because of the inertia force, the vehicle body will continue moving faster than the wheel angular velocity. This cause the distance travel by the car body is larger than that in the free rolling radius. Thus, higher level of slip is observed during initial testing for braking maneuver.

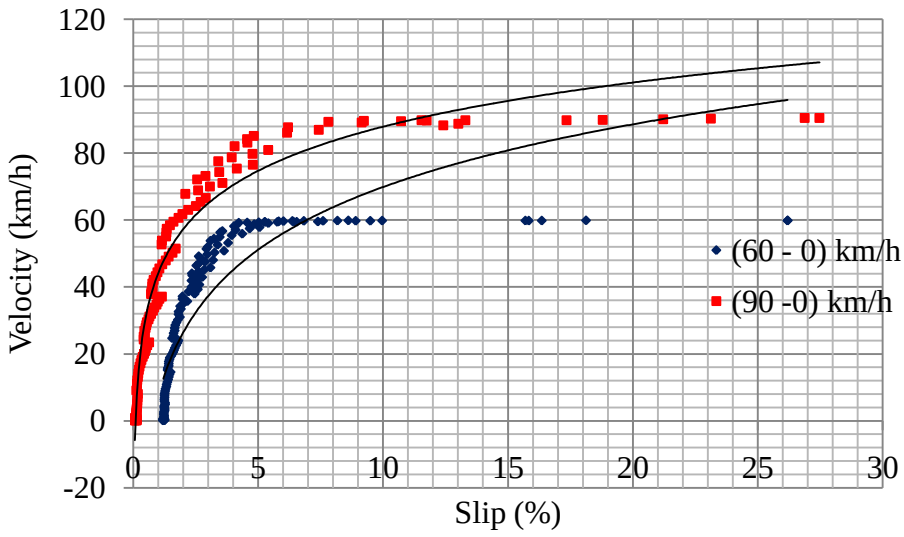


(a)

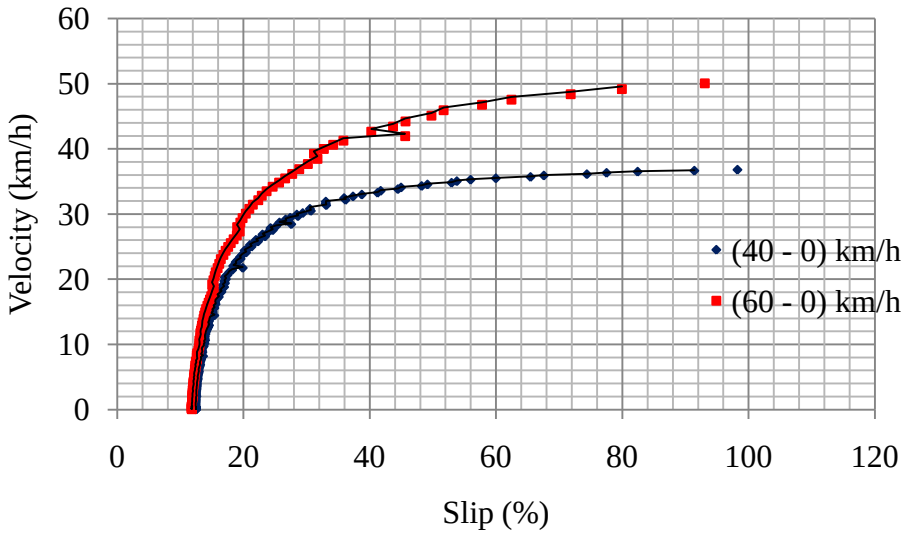


(b)

Figure 4.6: Graph of slip versus time during braking for (a) paved road and (b) unpaved sandy road condition



(a)



(b)

Figure 4.7: Graph of velocity versus slip during braking for (a) paved road and (b) unpaved sandy road condition

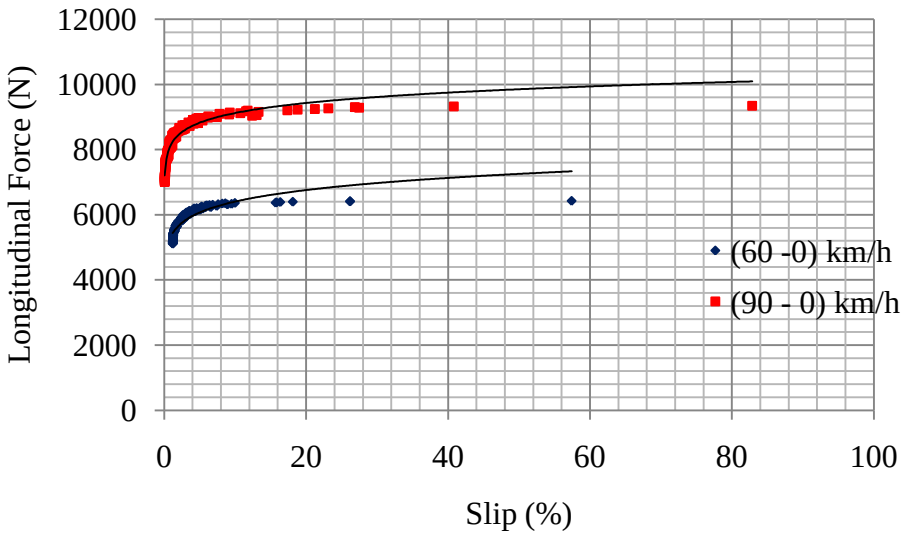
4.3.2 Longitudinal Force

When a braking torque is applied to a pneumatic tire, a stretching of the tread elements occurs at the tire road contact patch. This will cause the distance travel by the car during braking is higher than that in the free rolling radius. For wheel locked up, the wheel angular velocity is zero, which is the linear velocity of the tire center, is not zero, the tire is not rolling but the vehicle is moving.

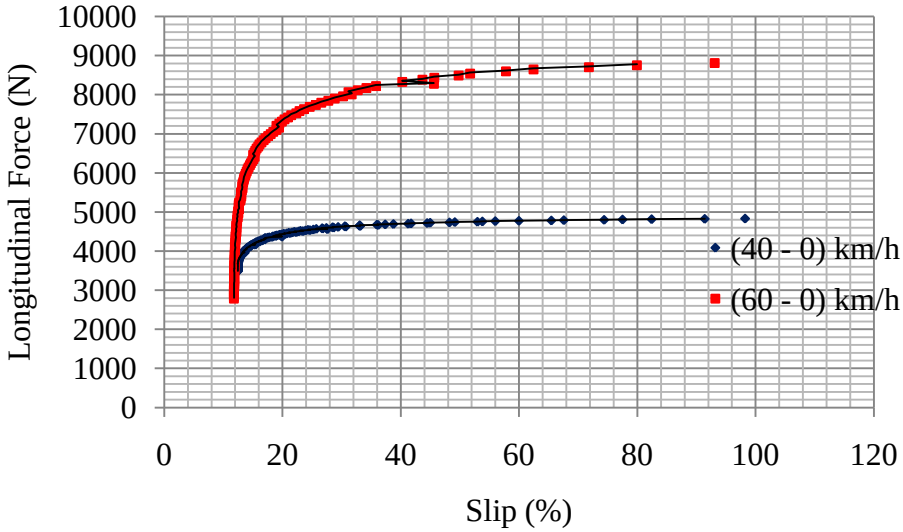
Figure 4.8 (a) and Figure 4.8 (b) shows the variation of longitudinal force against the percentage wheel slip both during braking maneuver for paved road and unpaved sandy road condition. At low level of slip, the longitudinal force found to linearly proportional to the percentage of wheel slip. The nonlinear relationship occurs after the peak value of the longitudinal force.

From Figure 4.8 (a), the maximum longitudinal force where the nonlinearity occurs between 15 – 20 % of slip found to be 6396.00 N for vehicle braking starting from 60 – 0 km/h and 9229.82 N 90 – 0 km/h for paved road condition. While for the unpaved sandy road condition, the peak force which the nonlinear relationship to occur is 4343.41 N for braking start from 40 – 0 km/h and 6491.05 N for 60 – 0 km/h as shown in Figure 4.8 (b).

This results show that the traction forces of the tire is lower for unpaved sandy road condition. This is clearly showed that the tire-road friction is one of the contributing factors that determine the braking performance of the tire. When a brake torque is applied to the tire, the soft sand will be removed in the contact patch of the tire causing the tire to start to slide. Thus, lower traction force developed and the distance that the tire travels will larger than that in the free rolling radius.



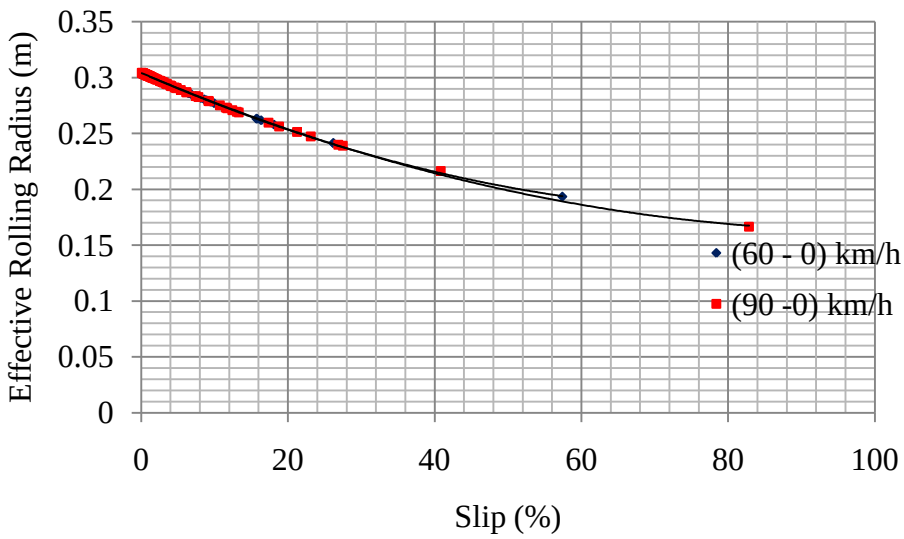
(a)



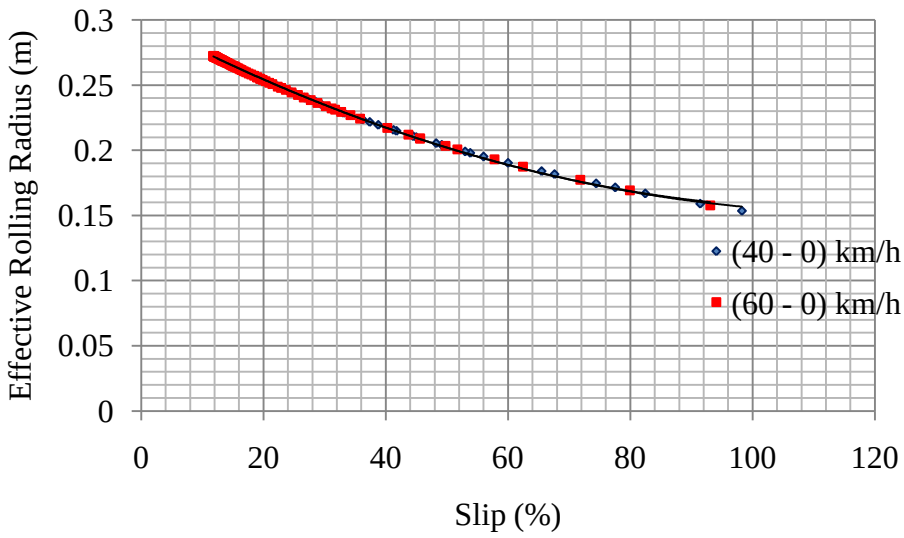
(b)

Figure 4.8: Graph of longitudinal force slip during braking for (a) paved road and (b) unpaved road sandy condition

4.3.3 Effective Rolling Radius



(a)



(b)

Figure 4.9: Graph of effective rolling radius versus slip during braking for (a) paved and (b) unpaved sandy road condition

The effective rolling radius of the tire determine by dividing the distance travel by the car measured by the GPS by the number of revolution of the wheel. Another approach is by dividing the forward speed of the tire by the angular velocity of the wheel.

Figure 4.9 (a) and Figure 4.9 (b) show the graph trend of effective rolling radius of the tire against percentage of wheel slip during braking maneuver for both paved and unpaved sandy road condition. For both graph, the effective rolling radius of the tire decrease with the increase of the percentage of wheel slip. For paved road condition, the average effective rolling radius is found to be at 0.3010 m for vehicle that braked start from 40 – 0 km/h and 0.3043 m for 60 – 0 km/h. While for braking maneuver on unpaved sandy road condition, the average effective rolling radius is 0.2078 m for vehicle that braked start at 40 – 0 km/h and 0.2570 m for 60 – 0 km/h.

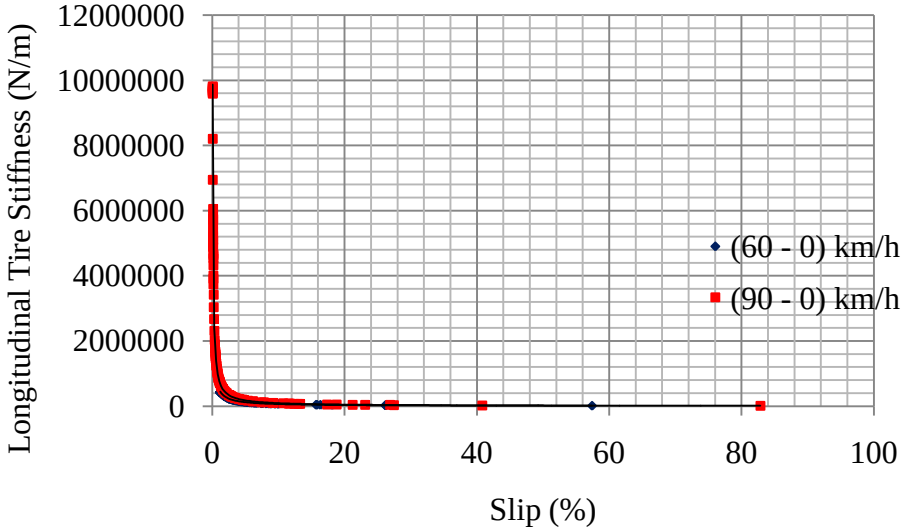
This result shows that the effective rolling radius of tire is decrease with the increase of the percentage of wheel slip. Higher effective radius is found for paved road condition as the percent slip is lower than that for unpaved sandy road condition.

4.3.4 Longitudinal Tire Stiffness

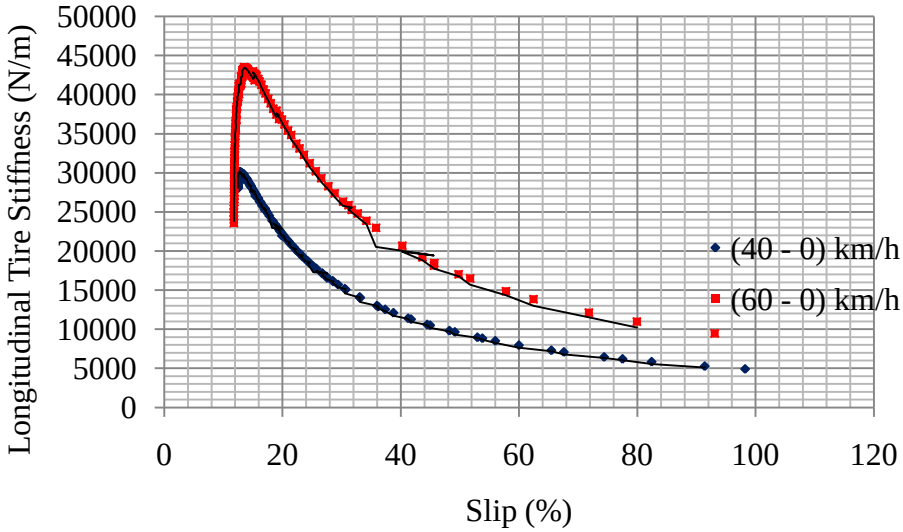
At low level of slip, the longitudinal tire force is considered directly proportional with the percentage of wheel slip. Hence, at this low level of slip region, the longitudinal tire stiffness can be obtained by dividing the longitudinal force of the tire by the percentage of slip on the tire.

Figure 4.10 (a) and Figure 4.10 (b) show the relationship of the longitudinal tire stiffness against the percentage of wheel slip both for paved road condition and unpaved sandy road condition during braking maneuver. For both road conditions, the longitudinal tire stiffness will increase during driving maneuver at low level of slip. This linear relationship between longitudinal tire stiffness will reach its peak between 15 – 20 % of slip. After this peak value of longitudinal stiffness, increase in the wheel slip will decrease the longitudinal tire stiffness. The peak longitudinal tire stiffness of the tire is found to be 35294.29 N for vehicle that decelerate from 60 - 0 km/h and

53106.91 N during braking maneuver on paved road condition. For unpaved sandy road condition, the peak value of the longitudinal tire stiffness is found to be 24503.99 N for 40 - 0 km/h and 29481.88 N for 60 - 0 km/h.



(a)



(b)

Figure 4.10: Graph of longitudinal tire stiffness versus slip during braking for (a) paved road and (b) unpaved sandy road condition

This result clearly shows that the longitudinal tire stiffness is strongly depends on the longitudinal force and slip produced by the tire. Larger force will give higher longitudinal tire stiffness with typical low level of slip. After the peak value, both longitudinal force and tire stiffness will decrease with the increase of the tire slip. Lower value of longitudinal tire stiffness is obtained for unpaved sandy road condition compare to the paved road condition is cause by the lower traction is developed during driving maneuver.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this thesis, the percentage of wheel slip has been analyzed for straight line driving and braking maneuver both tested for paved and unpaved sandy road condition. Experimental data had been collected and post-processed using Flexpro 7 and Microsoft Office Excel 2010.

The difference between the distance travel by the vehicle and the calculated distance travel from the Wheel Pulse Transducer divide by the distance travel by the vehicle is the slip ratio in the tire. It is observed that vehicle traction for unpaved sandy road condition is lower compare to the paved road condition.

The wheel slip is function of longitudinal force and tire-road friction. At low level of slip, the longitudinal force consider directly proportional with the percent of slip. Further increase in the slip value cause the longitudinal force become unstable with nonlinear relationship commonly occur at 15 -20 % of slip value.

5.2 RECOMMENDATIONS FOR FUTURE STUDY

For future work will concentrate on increasing the amount of collected data and refining data processing to establish more definitive statistical information regarding the effectiveness and sensitivity of the measurement system. It is also suggested that the experimental test should be more specific to certain study. All parameters that related to the test must take into consideration so that the data obtained is accurate.

Besides that, this study only considers straight line driving and braking maneuver. In future, this project could be extended to steady state cornering which will consider both longitudinal and lateral system. This thesis only considers paved and unpaved road condition as the tire-road interaction medium. Thus, the medium can be extended to wet road condition to widen the investigation of the behavior of wheel slip.

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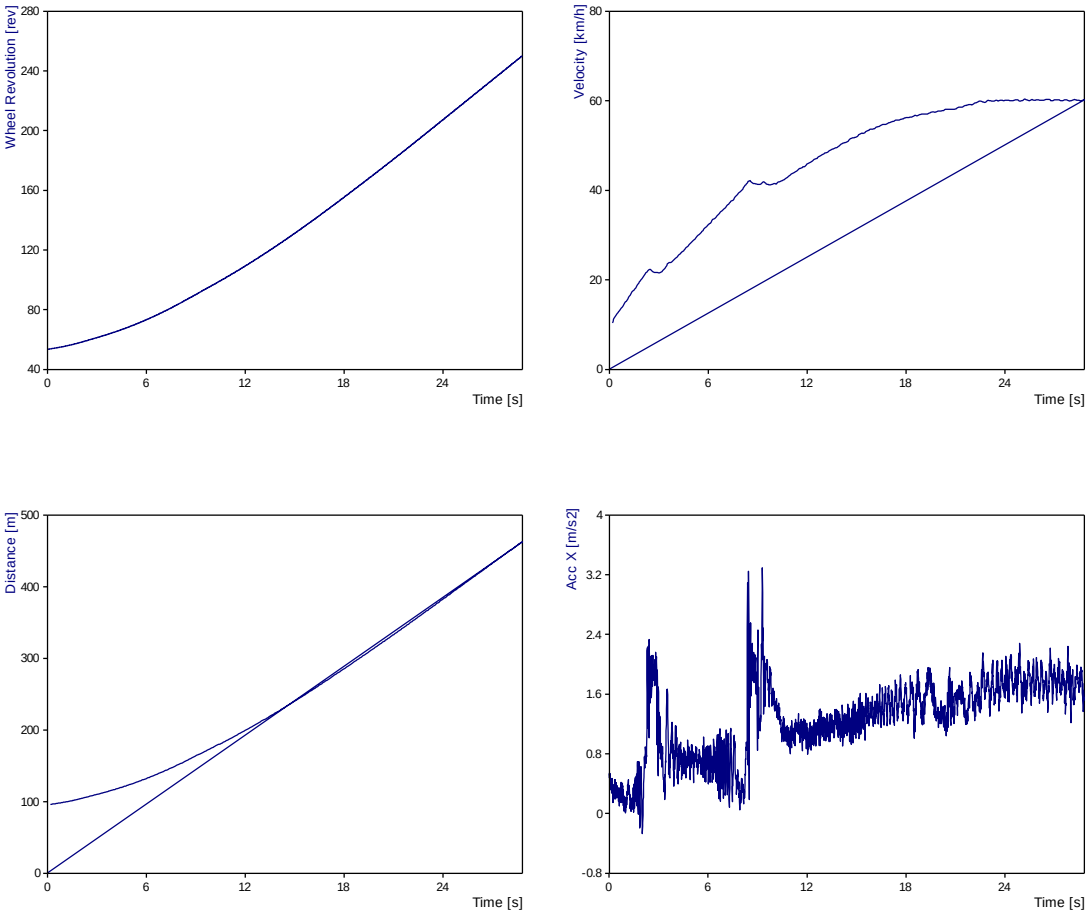
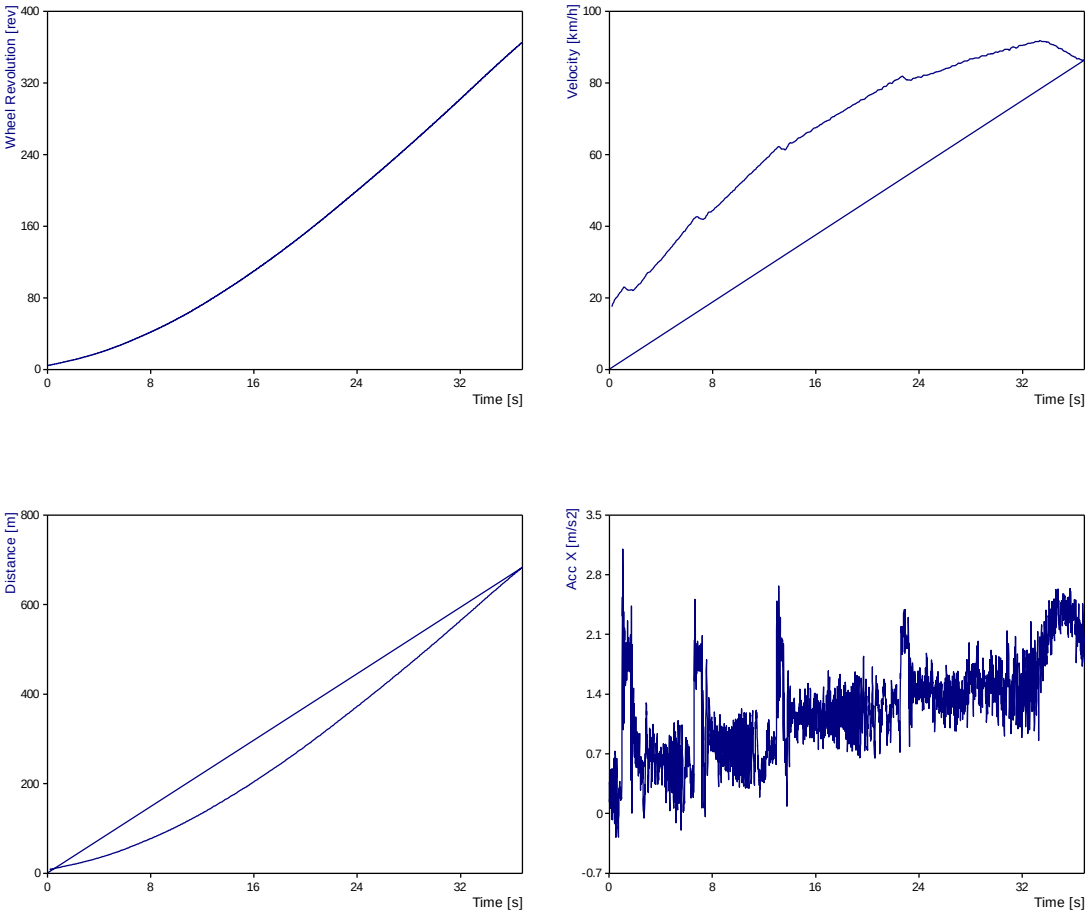
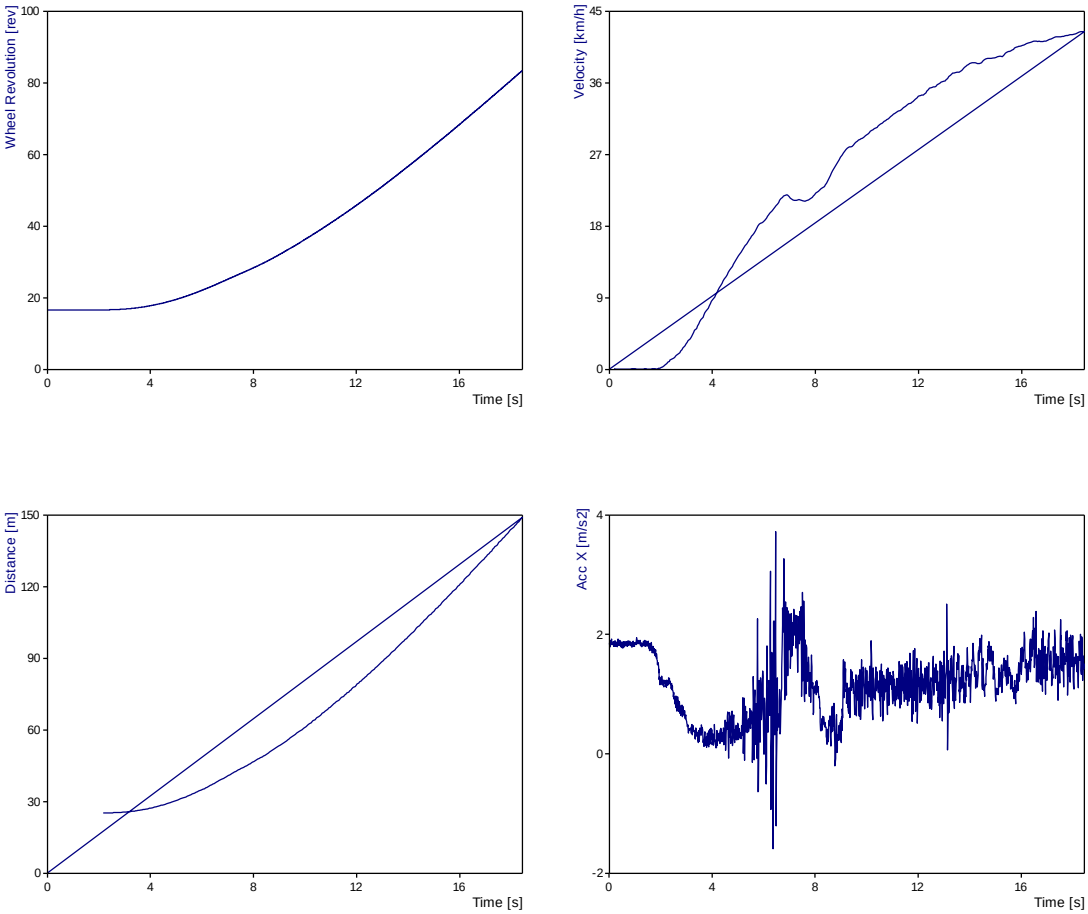
APPENDIX A1
ACCELERATION TEST ON PAVED ROAD FOR 60 KM/H



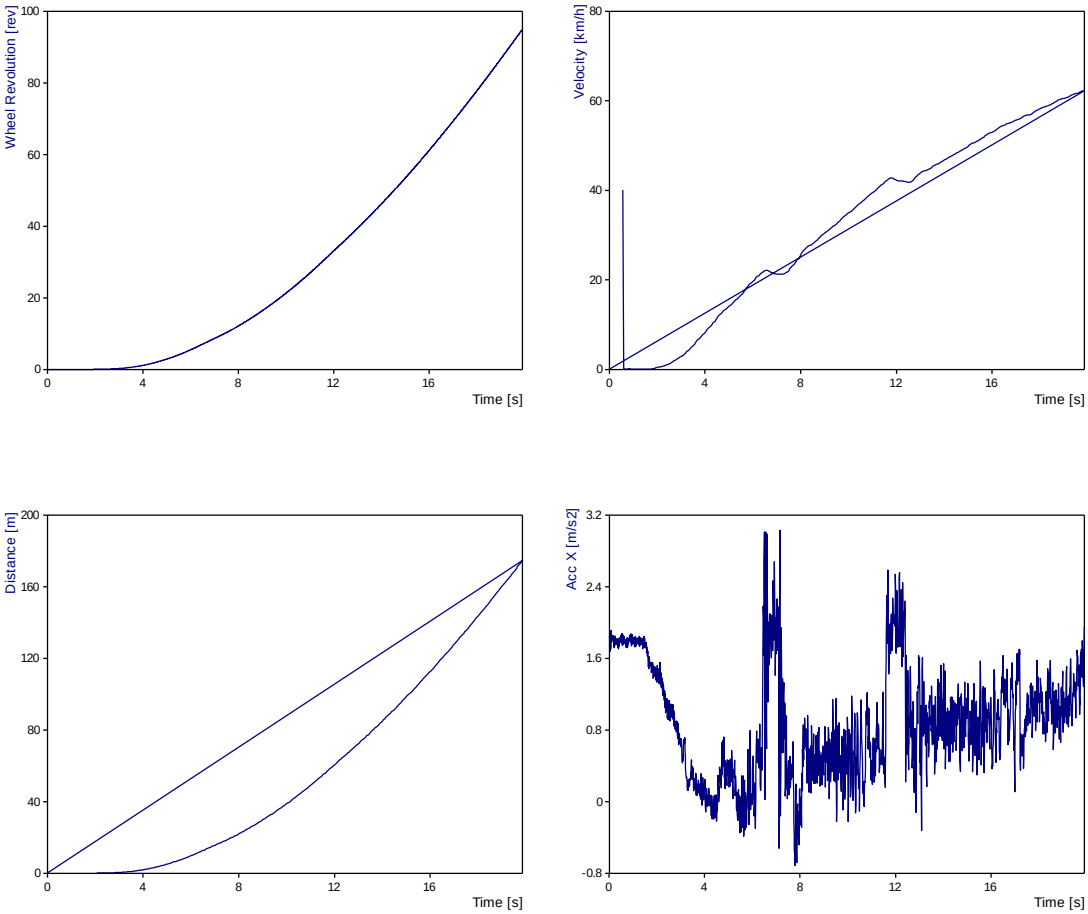
APPENDIX A2
ACCELERATION TEST ON PAVED ROAD FOR 90 KM/H



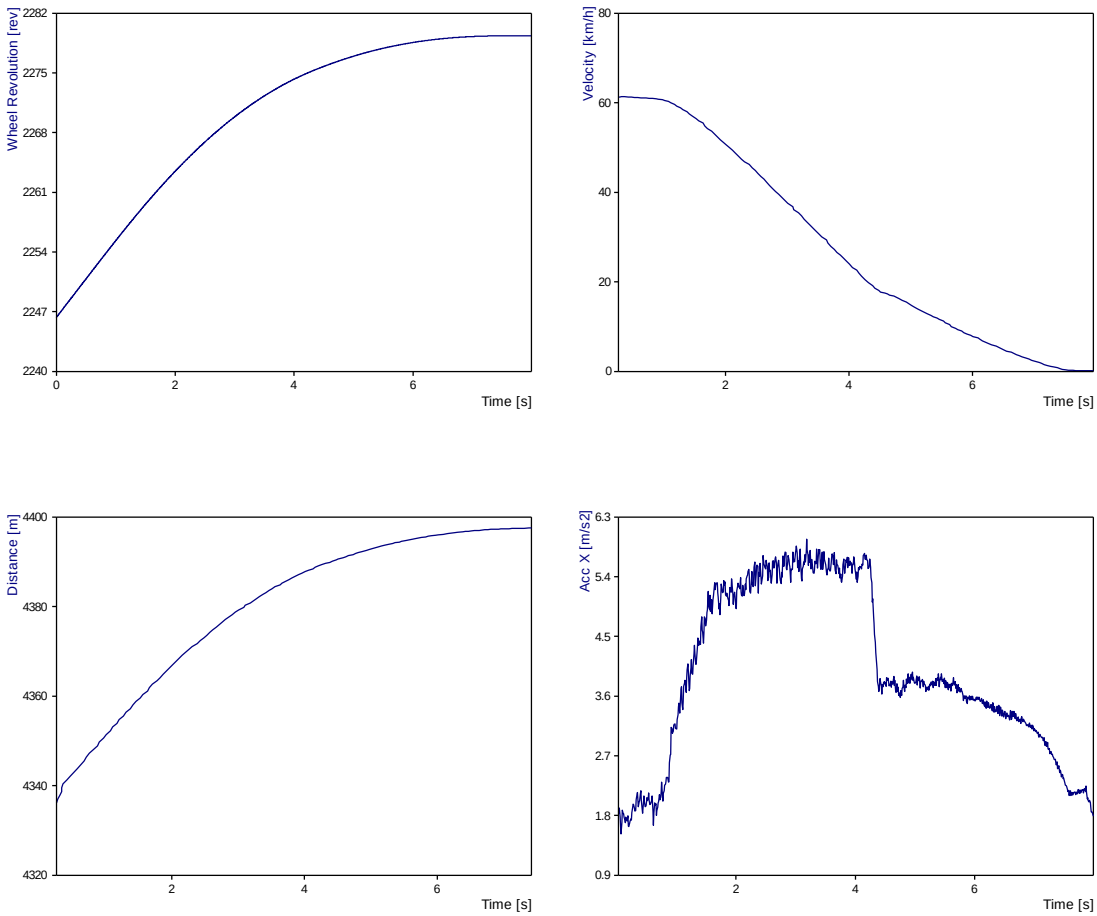
APPENDIX B1
ACCELERATION TEST ON UNPAVED SANDY ROAD FOR 40 KM/H



APPENDIX B2
ACCELERATION TEST ON UNPAVED SANDY ROAD FOR 60 KM/H



APPENDIX C1
BRAKING TEST ON PAVED ROAD FOR 60 KM/H



APPENDIX C2
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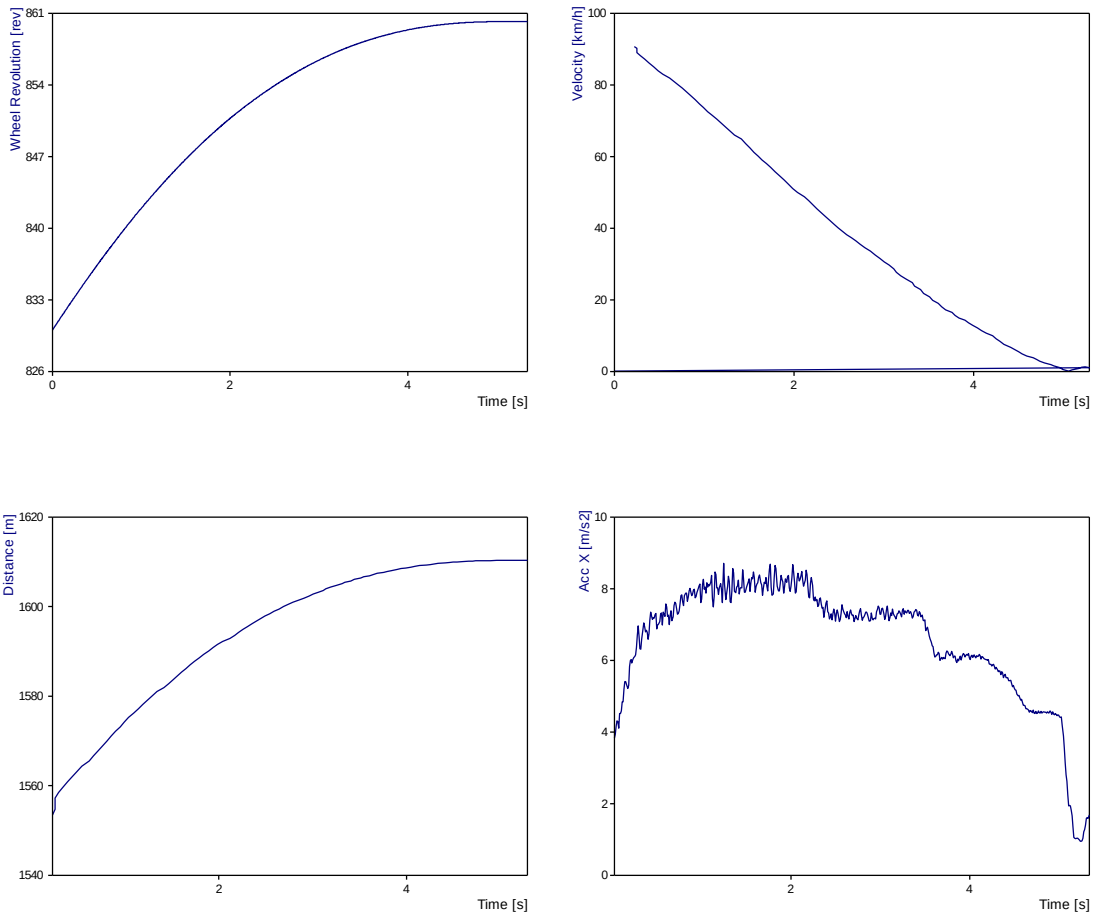

APPENDIX D1
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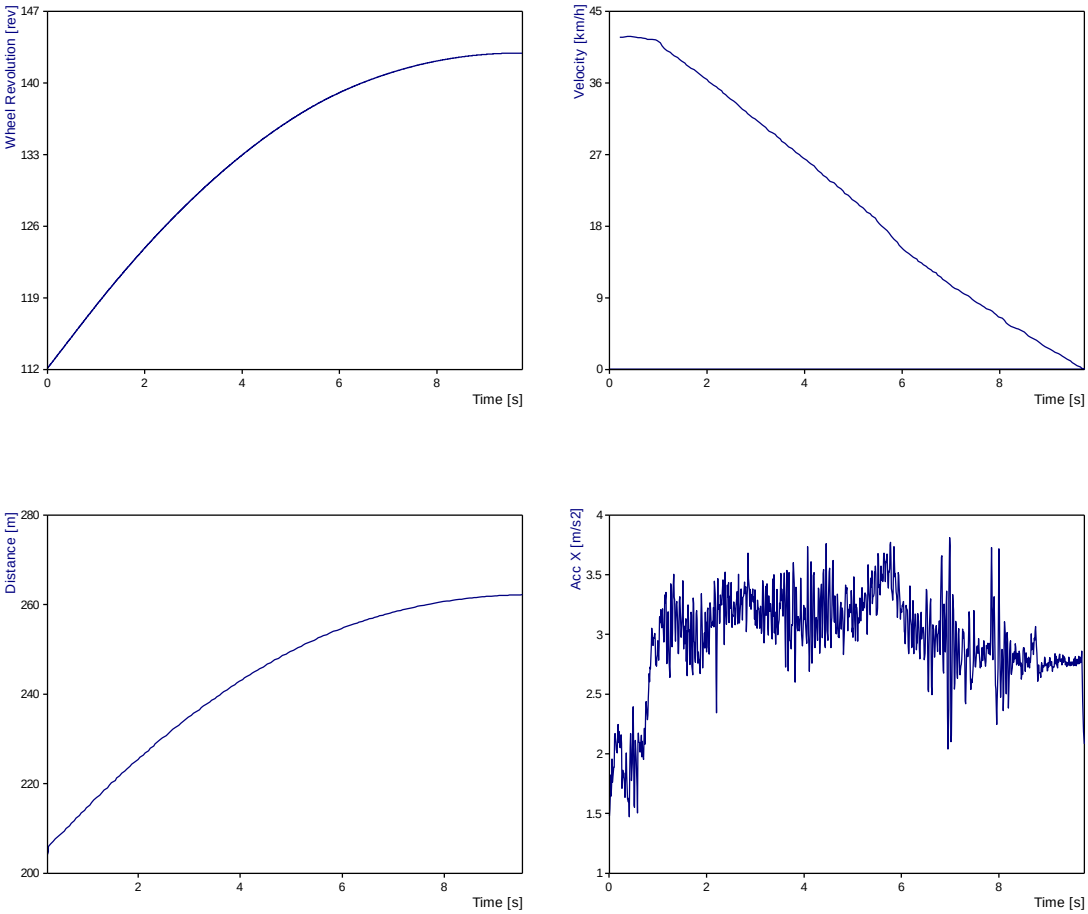

APPENDIX D2
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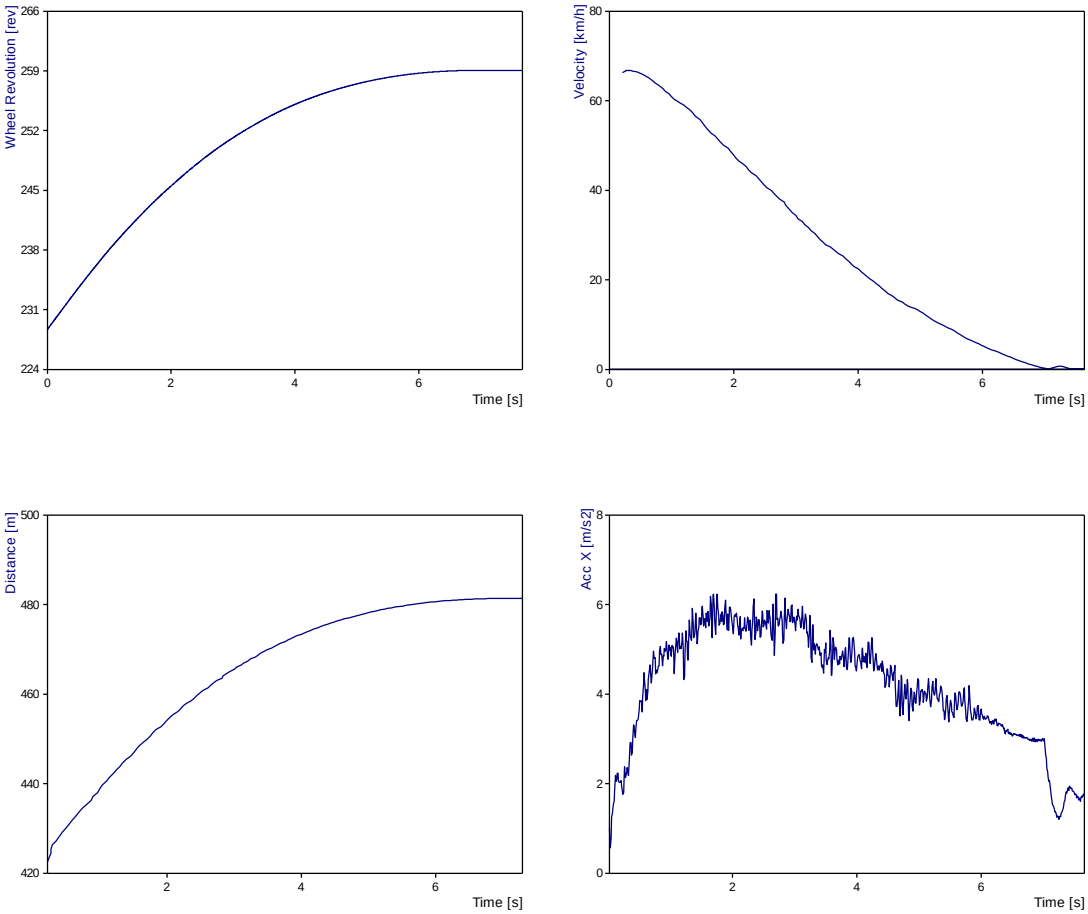

APPENDIX E1

GANTT CHART FOR 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	Wheel Slip Theory & Related Formula		■														
3	GPS & Wheel Pulse Sensor Study			■													
4	Test Car System General Setup				■	■	■	■	■								
5	GPS Installation Procedure						■										
6	Wheel Pulse Sensor Installation Procedure							■									
7	Data Acquisition System Installation Procedure								■								
8	Road Condition Evaluation									■							
9	Vehicle velocity selection										■						
10	Driving Mode Factor											■					
11	Design of Experiment												■	■			
12	FYP 1 Presentation														■		

APPENDIX E2

GANTT CHART FOR FINAL YEAR PROJECT 2

NO	ITEM\WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Installation & experiment setup	■	■	■	■												
2	GPS Installation		■														
3	Wheel Pulse Sensor Installation			■													
4	Data Acquisition System Installation				■												
5	Data collection					■	■	■									
6	Analysis on percentage of wheel slip								■	■	■	■	■	■			
7	Effective Radius Calculation												■				
8	Longitudinal tire stiffness Estimation													■			
9	Final Report Preparation														■		