RESEARCH REPORT UMP GRANT
Laporan Prestasi Skim Geran UMP

Final	√	Progress		Progress Period : 01.08.2016 – 31.07.2019	√ Please tick

PROJECT DETAILS *(Keterangan Projek)*

A		
	Grant No	RDU160138
	Faculty/CoE	Faculty of Mechanical and Automotive Engineering Technology
	Project Title	Investigation on Electric Motor as an Actuator of Anti Skid Control System to Improve the Safety of Small Electric Vehicle
	Project Leader	Dr. Mohamad Heerwan Bin Peeie
	Project Member	1. Dr. Syafiq Fauzi Bin Kamarulzaman 2. Dr. Mohd Razali Bin Hanipah 3. Dr. Ahmad Fitri Bin Yusop 4. Dr. Saiful Anwar Bin Che Ghani 5. Dr. Gigih Priyandoko 6. Prof. Dr. Md. Mustafizur Rahman 7. Prof Rizalman Bin Mamat

PROJECT ACHIEVEMENT *(Pencapaian Projek)*

B

ACHIEVEMENT PERCENTAGE				
Project progress according to milestones achieved up to this period	**0 - 25%**	**26 - 50%**	**51 - 75%**	**76 - 100%**
Percentage (please state %)				100%

EXPENDITURE *(Perbelanjaan)*

C

Budget Approved *Peruntukan diluluskan*	**Amount Spent** *Jumlah Perbelanjaan*	**Balance** *Baki*	**% of Amount Spent** *Peratusan Belanja*
RM 93,000	**RM 91,621.95**	**RM 1,378.05**	**98.52%**

RESEARCH OUTPUT *(Output Penyelidikan)*

D

NO OF PUBLICATION

KPI FOR NO OF PUBLICATION

	ISI	Scopus	Index Proceedings	Others
KPI			**2**	
Achievement	**1**		**3**	

The contribution of funder (UMP, MOHE, MOSTI, Industry etc.) as the fund provider must be acknowledged at all times in all forms of publications. Please state the grant number (RDU/UIC) and grant name.

Number of articles/ manuscripts/books *(Please attach the First Page of Publication)*	**ISI**	**Scopus**
	1. International Journal of Automotive and Mechanical Engineering (IJAME)	1. 2.

	2.	
	International	**National**
Conference Proceeding *(Please attach the First Page of Publication)*	1. 2018 SICE International Symposium on Control Systems (SICE ISCS) 2. 1st International Postgraduate Conference on Mechanical Engineering (IPCME2018) 3. 3rd International Conference on Automotive Innovation Green Energy Vehicle	1. 2.

HUMAN CAPITAL DEVELOPMENT

KPI FOR HUMAN CAPITAL DEVELOPMENT

	PhD Student	Master Student
KPI		**2**
Achievement		**2**

Human Capital Development	**Number**				**Others** (please specify)
	On-going		**Graduated**		
Citizen	Malaysian	Non Malaysian	Malaysian	Non Malaysian	
PhD Student					
Masters Student	1		1		
Undergraduate Student					
Total					

Name of Student: **ID Matric No:** **Faculty:** **Thesis title:** **Graduation Year:** **Name of Student:** **ID Matric No:** **Faculty:** **Thesis title:** **Graduation Year:** *** enter for more space*	Muhammad Asyraf Bin Shahrom MMM17015 Facultyof Mechanical and Automotive Engineering Technology Investigation on Electric Motor Braking Control Performance 2020 Muhamad Sollehudin Bin Ibrahim MMA18004 Faculty of Mechanical and Automotive Engineering Technology

INTELECTUAL PROPERTIES

KPI FOR INTELECTUAL PROPERTIES

Patent, Copyright, Trademark,Industrial Design: ____________

Patent, Copyright, Trademark, Industrial Design ect	

OTHERS

KPI FOR OTHERS

Prototype, Technology,Collaborations etc: _____________

	Prototype, Technology, Collaborations etc	

ASSET *(Aset)*

E

Bil	**Peralatan** *(Equipment)*	**Model**	**No Daftar Aset** *(Asset Tagging No)*	**Amount** (RM)	**Lokasi** *(Location)*

PRODUCT DESCRIPTION FOR UMP R&D DIRECTORY (SHORT & BRIEF) *Only for Final Report*

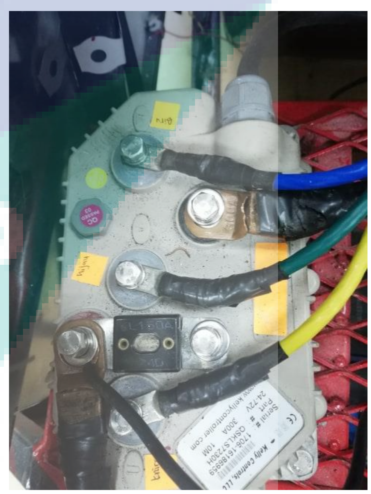
F

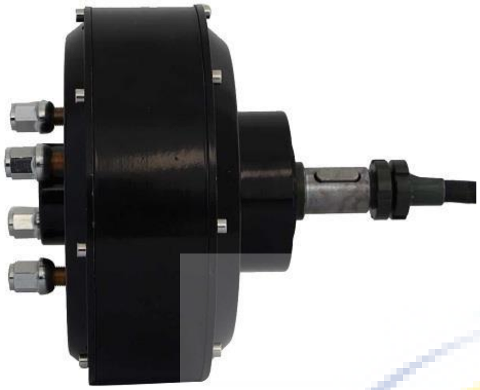
In this study, we have developed an electric motor braking control system. By using this system, we can prevent the electric vehicle from skidding during braking, especially during descending on the slope. The user will set the desired speed, and the motor controller will send the signal to the motor driver to control the speed of the electric vehicle. The rotational speed of the tire is measured by the rotary encoder and the speed of all tires are processed in the micro controller.Then, the control algorithm in the micro controller will process the data and minimize the error between the desired speed from the user with the actual speed from the rotary encoder.

PRODUCT PICTURE FOR UMP R&D DIRECTORY *Only for Final Report*

G

Small electric vehicle


Controller



In-wheel electric motor

SUMMARY OF RESEARCH FINDINGS (*Ringkasan Penemuan Projek Penyelidikan)*

H

Findings from this study as follows:
1. During braking, the electric motor generate the regenerative braking torque.
2. The regenerative braking torque can improve the braking performance of the vehicle
3. Without the regenerative braking torque, the stopping distance and time of electric vehicle is higher than with regenerative braking torque.
4. The regenerative braking torque can be controlled to prevent the vehcile from skidding.
5. The response performance of electric motor is fast. During braking on the slope, the speed of the vehicle is maintain at the desired speed.

PROBLEMS / CONSTRAINTS IF ANY *(Masalah/ Kekangan sekiranya ada)*

I

At the early stage of this study, the problem is to conduct the experiment due to the limitation of budget. However, the experiment still can be performed by using the small electric vehicle. The problem of small electric vehicle is on its controller and electric motor because it used BLDC motor. The implementation of the proposed control system to the BLDC controller is very challenging because the algorithm in the controller can't be modified. To overcome with this problem, we implementing the control system on the separate micro controller, which is NI MyRio. The response performance of our proposed controller has been validated by using DC motor and the result shows that our proposed control system can prevent the vehicle from skidding.

Date **:**
Tarikh

Project Leader's Signature:
Tandatangan Ketua Projek

COMMENTS, IF ANY/ ENDORSEMENT BY FACULTY (*Komen, sekiranya ada / Pengesahan oleh Fakulti)*

J

Recommend / Not Recommend / KIV / Need Ammendment

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....

	.... **Name:** *Nama:* **Signature:** *Tandatangan:* **Date:** *Tarikh:* **** Dean/TDR/Director/Deputy Director**
COMMENTS, IF ANY/ ENDORSEMENT BY RMC PNI (*Komen, sekiranya ada / Pengesahan oleh RMC PNI)*	
K	**Recommend / Not Recommend / KIV / Need Ammendment** .... **Name:** *Nama:* **Signature:** *Tandatangan:* **Date:** *Tarikh:*

FINAL REPORT

INVESTIGATION ON ELECTRIC MOTOR AS AN ACTUOTAOR OF ANTI-SKID CONTROL SYSTEM TO IMPROVE THE SAFETY OF SMALL ELECTRIC VEHICLE

Name of Project Leader: Dr Mohamad Heerwan Bin Peeie

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1. Dr. Mod Razali Bin Hanipah
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Field: Vehicle Dynamics and Control

ABSTRACT (120 words)

Small electric vehicle (EVs) only employed seat belt and a mechanical brake system as a safety system. Without ABS and hydraulic braking system, the tire can be locked up and the possibility of an accident is increased. The main objective of this research is to improve the safety by using the electric motor as an actuator of anti-skid control system. During braking, if the slip ratio greater than the optimum value, the motor controller will send the signal to the motor to turning forward, and if the slip ratio becomes smaller than the optimum value, the motor will be running backwards. In this research, the simulation will be developed in MATLAB/Simulink, and the experiment will be conducted on the small EV.

1. INTRODUCTION

In recent years, dilemma of decreasing gasoline sources around the world has become a global issue where researchers and scientists has been struggling to discover a new alternative energy sources for automobiles. Besides that, deterioration of air quality caused by carbon emission expelled from gasoline vehicles has become a fact of causing global warming.

In order to solve this issue effectively, electric cars become the alternative-design automobile to replace gasoline vehicles. Electric car uses an electric motor to run the car where the electricity is supplied by batteries. It produce zero emission and the system operate smoothly and quietly. Thus, these advantages bring impact to the environment as well as human being. Compared to traditional vehicles with gasoline engine, electric automobiles are ninety-seven cleaner and producing no tailpipe emissions that brings negative impact to air. (Patel, 2016)

As humanities realised how serious it is for the issue of climate change, everyone is trying to save the environment and natural resources such as crude oil and gases in the earth. Many countries actively promote electric automobiles to their citizens. Norway as the largest seller of electric car plan to sell only electric and hydrogen cars from 2025. Then, Japan plan to increase the usage of plug-in hybrid and electric vehicles to 15-20% of total new car sales by 2020. Furthermore, “National Electromobility Development Plan” that promoted by Germany encourage the industries for technology development and infrastructure construction with the goal of supplying 1 million electric vehicles by

2020. From the facts above, major countries are promoting electric vehicles to the society aggressively but the penetration rate of electric cars is different in each country. For example, the rate of sales of electric vehicles in Norway is 28.8%, Sweden 3.2%, Netherlands 2.3%, Switzerland 1.7%, US 0.8% and India 0%. From this scenario, some country should put more effort to promote electric vehicles to their citizens. Better environment can be preserved if everyone can make a step on it. (Abhale & Nigam, 2015; Yonga & Park, 2017)

In addition, in an urban areas, small electric vehicles become more popular due to its size and easy for handling. Anti-skid control system such as an anti-lock brake system (ABS) is necessary for safety driving on low adherent road surfaces. However, due to the space limitation on the driving tire, most of the small electric vehicles (EVs) do not have an ABS. For the same reason, small EVs employ a mechanical braking system rather than a hydraulic braking system. Although the mechanical brake system is compact, the stiffness and the response performance of the mechanical braking system are lower than the hydraulic braking system(S.Kobayashi et.al, 2010). As a result, during braking on low adherent road surfaces or heavy braking, the tire will lock up and the vehicle will skid. As such, small electric vehicles may be considered to provide insufficient safety.

Based on the advantages of the in-wheel motor such as fast torque response and each motor can be controlled precisely, a more effective anti-skid braking system to increase the safety of the small EV can be performed. To improve the safety system of the EV and prevent the tire from lock up, the anti-skid control system is introduced to the four in-wheel independent small EV. The computational analysis and experiment will show that the in-wheel motors can control the regenerative braking force on each tire and finally prevent the vehicle from skidding.

2. RESEARCH METHODOLOGY

In this study, the experiment has been conducted to analyse the braking performance of a small electric vehicle without ABS. Then, the vehicle is modelled in the

Matlab Simulink to determine the effect of the ABS and regenerative brake control on the slippery surface.

2.1 Experimental Vehicle Model

Figure 2.1 shows the experimental vehicle model that consisted of two in-wheel motors at the rear tires. It is a single-seat formula SAE vehicle and runs entirely on electricity and its specifications were shown in table 2.1.

Figure 2.1: Electric Vehicle (EV)

Table 2.1: EV Specifications

Weight	250 kg
Wheelbase	1.15m
Wheel track	1.43m
Battery	4 units of 12V batteries (connected in series)
Type of Motor	BLDC Motor
No. of Motor	2 units (attached on rear wheels)
Motor Capacity	3000W/unit
Maximum Speed	45km/h

The electricity that supplied to EV was based on 4 units of 12V battery connected in series which total up 48V supplied to two BLDC motor attached on rear wheels to drive the vehicle.

Besides that, this EV can drive up to 45km/h but it is dangerous to do so due to its light weight and easily lose balance if driving at its maximum speed. Therefore, we set the speed at its 60% or 28km/h as the optimum speed to ensure the car is safe to drive.

Next, the weight distribution of EV was 45:55 as front side sustain the weight of 45% and rear side bear the weight of 55%. The rear part is heavier than the front part because the batteries and in-wheels motor are placed on the rear side.

2.2 Hardware Components

Hardware components which used to drive the electric vehicle are in-wheel hub motors, motor controller and batteries. A brushless DC (BLDC) motor was selected as a suitable type in the vehicle application due to its durability and less friction generated by the motors. In EV, 2 units of QS 3000W E-car BLDC motor were used on left and right rear wheels. The image and specifications of in-wheel motor are shown in Figure 2.2.1 and table 2.2.1 respectively.

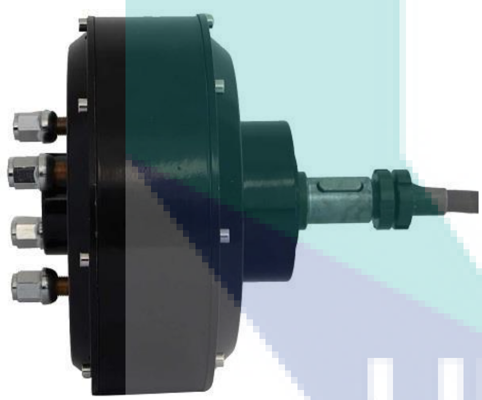

Figure 2.2.1: BLDC in-wheel motor

Table 2.2.1: BLDC Motor Specification

Motor Type	BLDC Hub Motor with Permanent Magnet
Motor Design	Single axle out without rim
Suitable Rim Size	Rim with PCD of 4x100mm
Magnet Height	50mm, 16 pole pairs
Stator	Aluminium core
Rated/Peak Power	3000W/6000W
Rated Voltage	72V (48-96V Can be optional)

Speed	70km/h (30-75km/h can be customized)
Max Torque	180N.m
Max Efficiency	90%
Weight	15kg
Working Temperature	70°C max, 120°C peak
Waterproof Grade	IP54

To control the BLDC motor efficiently, a suitable motor controller which capable with speed control must be chosen correctly. Kelly KLS7230H Sinusoidal Wave Controller has been selected as the motor controller. Two units of Kelly controller was installed on left and right rear wheels respectively. Each controller will control the speed of each wheel and the motor controller functioned using PWM voltage control. The controller works based on sinusoidal wave control method which could reduce the torque ripples inside the motor as well as reduce the vibration produced. An exact image of Kelly KLS7230H Sinusoidal Wave Controller and its specifications are shown in figure 2.2.2 and table 2.2.2 respectively.

Figure 2.2.2: Kelly KLS7230H Sinusoidal Wave Controller

Table 2.2.2: Kelly KLS7230H Sinusoidal Wave Controller's Specification

Frequency of Operation	10kHz or 20kHz
Standby Battery Current	<0.5Ma
Sensor Supply Current	40Ma
Controller supply voltage range	PWR, 18V to 90V for controllers rated equal or

	lower than 72V
Supply Current	PWR, 30Ma typical
Battery Voltage Range	B+, 18V to1.25*Nominal Voltage
Standard Throttle Input	0-5V (3-wire resistive pot), 1-4V (hall active throttle)
Throttle Input	0-5V, can use 3-wire pot to produce 0-5V signal
Full Power Operating Temperature	0°C to 70°C (MOSFET temperature)
Operating Temperature Range	-40°C to 100°C (MOSFET temperature)
Motor Current Limit, 30 sec	300A, depending on the model
Motor Current Limit, continuous	100A, depending on the model
Waterproof Grade	IP66

Next, a correct wiring connection of motor controller with motors and batteries is important to avoid the occurrence of an incident such as a short circuit. Therefore, all the components are connected based on the wiring diagram as shown in figure 2.2.3.

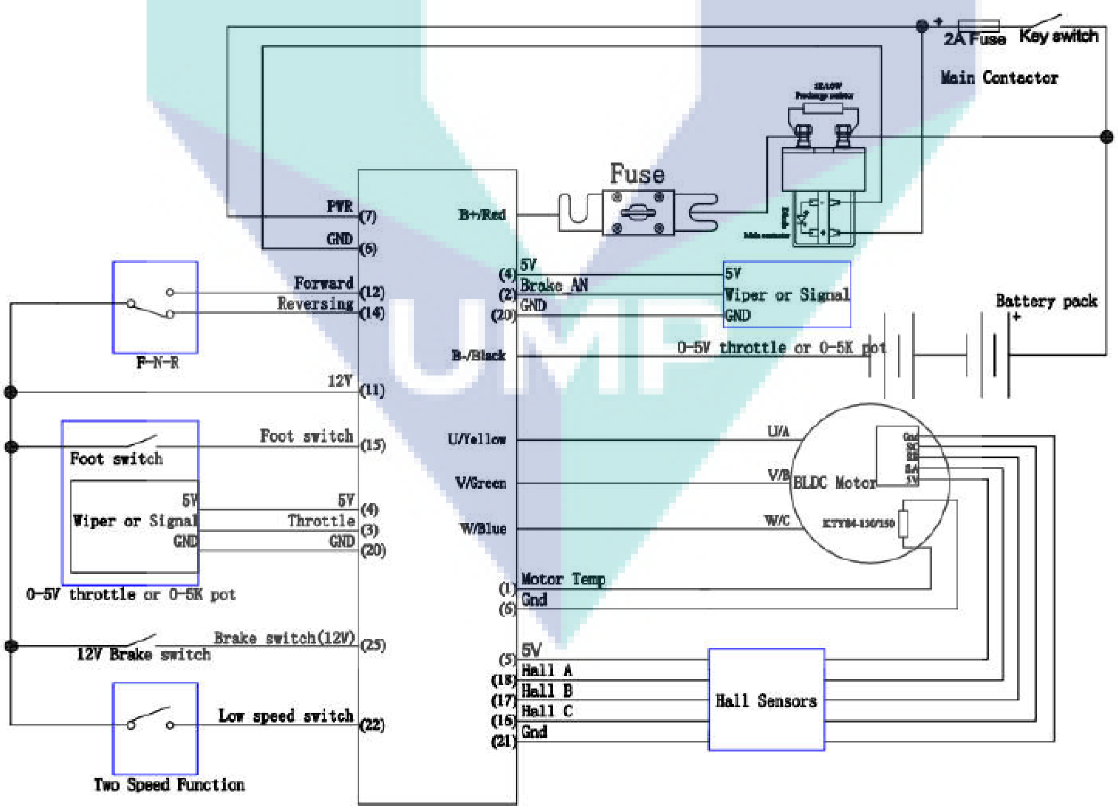

Figure 2.2.3: Wiring Diagram of Motor Controller

A rotary encoder is used to record wheel rotational speed into a digital signal. Besides that, its function to monitoring or guiding motion parameters such as speed, direction, distance or position of a rotating object. Two rotary encoders are being used in the experiment and attached to the centre of rear left and right wheels of EV. Full image and its specification of the rotary encoder are shown in figure 2.2.4 and table 2.2.3 respectively.

Figure 2.2.4: Rotary Encoder

Table 2.2.3: Specification of Rotary Encoder

Product Code	3806-500B-5-24F
Resolution	500 Pulse/revolution
Input Voltage	5-24VDC
Max. Rotating Speed	6000 RPM
Allowable Radial Load	<=20N
Allowable Axial Load	<=10N
Shaft Diameter	5.5mm

To calculate the linear velocity of the vehicle during braking there are two equations to be used as shown in equation 2.1 and 2.2.

$$\omega = \frac{Pulse\ frequency\ in\ \frac{pulse}{sec}}{\frac{500\ sensor\ pulse}{revolution}} \times 2\pi \qquad \text{Equation 2.1}$$

Where the rotary encoder sensor is 500 pulse/ revolution

$$v = r\omega \qquad \text{Equation 2.2}$$

Where,

V = linear velocity (m/s)

r = radius of wheel (m)

ω= angular velocity (rad/s)

Gyroscope sensor is used on the road test braking experiment to record the accelerometer data as well as rotational motion of vehicle during braking such as pitch motion.

There are four parameters can be obtained from the gyroscope sensors such as acceleration data on X, Y, Z directions, gyroscope data like pitching, rolling and yawing on X, Y and Z directions and magnitude data as well as temperature data. However, only acceleration at x-direction and pitching motion data will be taken for the road test experiments as these parameters provide dynamic behaviour of vehicle during braking.

In order to attain the acceleration and the pitch motion data accurately, the gyroscope sensor is placed on the centre of gravity of EV during the experiment. Full image and specification of the gyroscope sensor is shown in figure 2.2.5 and table 2.2.4 respectively.

Figure 2.2.5: Gyroscope Sensor

Table 2.2.4: Specification of Gyroscope Sensor

Input voltage	4.5 to 34V or 3V3
Typical power consumption	550mW @ 5V
Start-up time	2.4 s
IP-rating	IP67 (encased)
Temperature (in use)	-40 to 85°C
Output frequency	Up to 2 kHz
Latency	<2 ms (suitable for real-time applications)
Clock drift	10 ppm or external reference
Vibration and shock	MIL STD-202/ 2000g

2.3 Experimental Procedures

In order to conduct the experiments, the proper location must be selected to ensure the safety precaution of the driver, as well as other road users. The location that has been selected for the experiment is inside of the Faculty of Mechanical Engineering, UMP. The road users are considered very low after 5.30 p.m. onwards and thus, it is considered as the proper time to conduct the experiments. However, if the weather condition is rainy, the experiments need to be postponed to the other time. To conduct the experiments in dry road condition, the weather must be sunny on that day.

The location as in Figure 2.3.1 is considered as a proper location due to their long straight line which is perfect for conducting experiments in a straight line. Before to be able to conduct the experiments, permissions from UMP Safety Department must be obtained, and the UMP Safety Department will be notified about the experiments which will be conducted on that location. If required, the safety cones can be requested from the UMP Safety Department, and can be used to notify the other road users that the road is being used for the experiments.

As for the safety of the driver, the driver is equipped with PPE (personal protective equipment). The driver is fully covered with the jacket, shoes as well as safety helmet.

Figure 2.3.1 Experimental locations which have a 300 m straight line.

Figure 2.3.2 shows the illustration of the experiment. Before the experiment, several preparations must be made as follows:

1. By using the gloves, the batteries must be connected in series. The key switch is turned on.
2. Set the desired speed of the motor by using the USB cable which will connect the laptop to the motor controller.
3. The Arduino board, and gyroscope sensor is connected to the laptop via USB.
4. Ensure the road is clear from other vehicle and obstacle.

After the experimental is ready and the road is clear, the driver will start pushes the throttle paddle. When the vehicle reaching the stopping line, the brakes are applied. After the vehicle is completely stopped, the driver will turn off the switch and saved the data into the laptop. The experiments are repeated three times to get an accurate result.

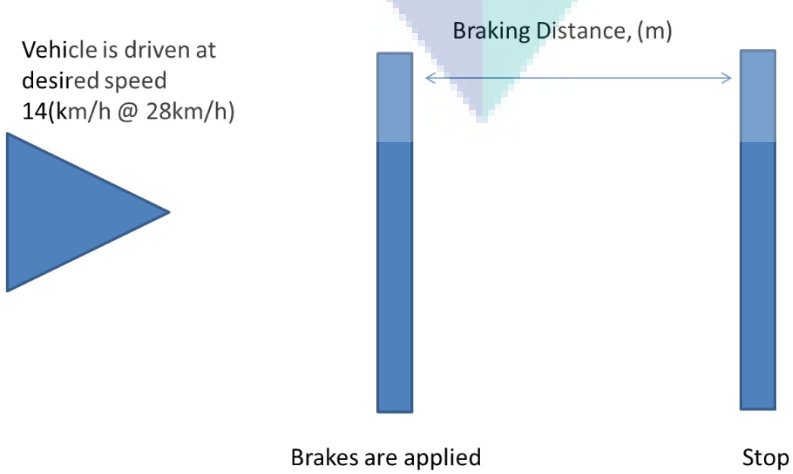

Figure 2.3.2 Illustration of experiments.

2.4 Numerical Analysis

In the first phase of the simulation, the vehicle model is developed in the Matlab Simulink. Figure 2.4.1 shows the force diagram of the vehicle and this model consisted of two axes; longitudinal and lateral axis. The equation of motion for the longitudinal and lateral axes are shown in Eq 2.4.1 and Eq 2.4.2.

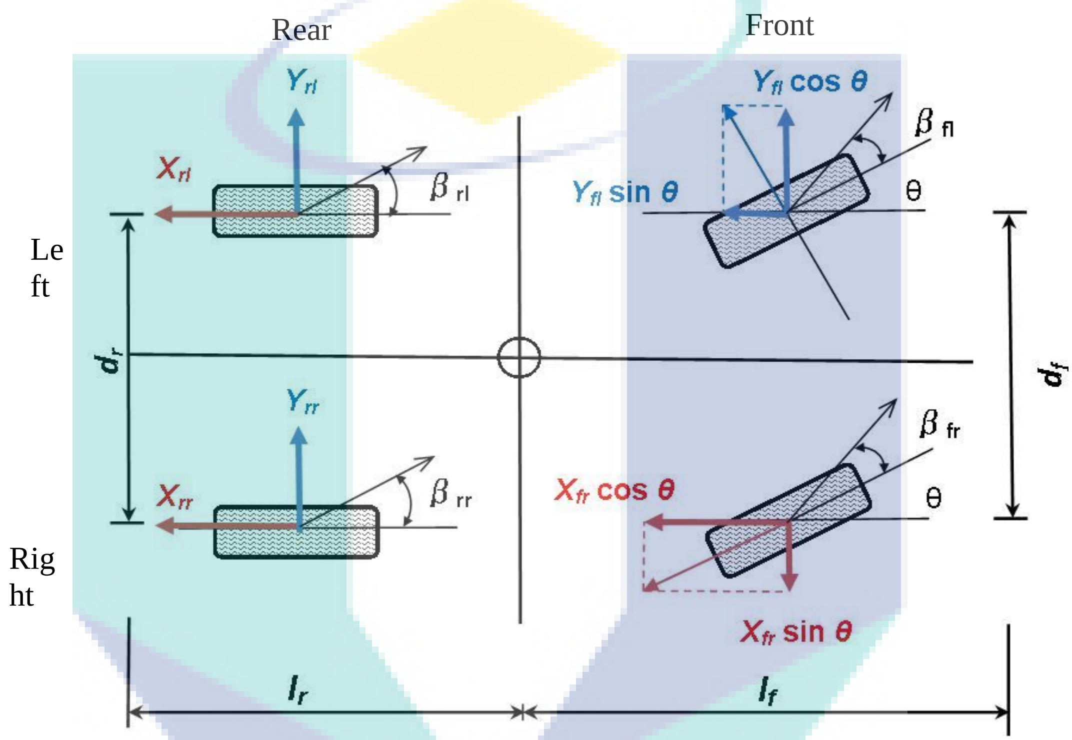

Figure 2.4.1 Force diagram of the vehicle

$$m\left(\frac{du}{dt} - v\Upsilon\right) = \left(-X_{fr} - X_{fl}\right)\cos\theta + \left(-Y_{fr} - Y_{fl}\right)\sin\theta - X_{rr} - X_{rl}$$ Equation 2.4.1

$$m\left(\frac{dv}{dt} + u\Upsilon\right) = \left(Y_{fr} + Y_{fl}\right)\cos\theta + \left(-X_{fr} - X_{fl}\right)\sin\theta + Y_{rr} + Y_{rl}$$ Equation 2.4.2

$$I\frac{d\Upsilon}{dt} = l_f\left(Y_{fr}\cos\theta + Y_{fl}\cos\theta - X_{fr}\sin\theta - X_{fl}\sin\theta\right) - l_r(Y_{rr} + Y_{rl}) +$$

$$\frac{d_f}{2}\left(-X_{fr}\cos\theta + X_{fl}\cos\theta - Y_{fr}\sin\theta + Y_{fl}\sin\theta\right) + \frac{d_r}{2}(-X_{rr} + X_{rl})$$

Equation 2.4.3

where u and v is the velocity of the vehicle in longitudinal and lateral axis, Υ is the vehicle yaw rotational speed, X_{fr}, X_{fl}, X_{rr}, X_{rl} are the friction force while Y_{fr}, Y_{fl}, Y_{rr}, Y_{rl} are the cornering force.

For the forces acting on the tire, the brush tyre model has been used to determine the friction and cornering forces. This model allows elastic deformation in both the longitudinal and lateral directions. In cases of braking situation, we use Eq. 2.4.4 while in the driving situation, the Eq. 2.4.5 is used.

$$\xi_p = 1 - \frac{K_s\lambda}{3\mu W_z(1-\rho)}$$

$$\lambda = \sqrt{\rho^2 + \left(\frac{K_\beta}{K_s}\right)^2 tan^2\,\beta_T}$$

$$K_s = \frac{b{l_T}^2}{2}K_x \quad , \quad K_\beta = \frac{b{l_T}^2}{2}K_y$$

$$X\begin{cases} = -\dfrac{K_s\rho}{1-\rho}{\xi_p}^2 - 6\mu W_z\dfrac{\rho}{\lambda}\left(\dfrac{1}{6}-\dfrac{1}{2}{\xi_p}^2+\dfrac{1}{3}{\xi_p}^3\right) & (\xi_p > 0) \\ = -\mu W_z\dfrac{\rho}{\lambda} & (\xi_p < 0)\end{cases}$$

$$Y\begin{cases} = -\dfrac{K_\beta\tan\beta_T}{1-\rho}{\xi_p}^2 - 6\mu W_z\dfrac{K_\beta\tan\beta_T}{K_s\lambda}\left(\dfrac{1}{6}-\dfrac{1}{2}{\xi_p}^2+\dfrac{1}{3}{\xi_p}^3\right) & (\xi_p > 0) \\ = -\mu W_z\dfrac{K_\beta\tan\beta_T}{K_s\lambda} & (\xi_p < 0)\end{cases}$$

Equation

2.4.4

$$\xi_p = 1 - \frac{K_s\lambda}{3\mu W_z}$$

$$X \begin{cases} = -K_s \rho {\xi_p}^2 - 6\mu W_z \frac{\rho}{\lambda}\left(\frac{1}{6} - \frac{1}{2}{\xi_p}^2 + \frac{1}{3}{\xi_p}^3\right) & (\xi_p > 0) \\ = -\mu W_z \frac{\rho}{\lambda} & (\xi_p < 0) \end{cases}$$

$$Y \begin{cases} = -K_\beta \tan\beta_T (1+\rho)\, {\xi_p}^2 - 6\mu W_z \frac{K_\beta \tan\beta_T (1+\rho)}{K_s \lambda}\left(\frac{1}{6} - \frac{1}{2}{\xi_p}^2 + \frac{1}{3}{\xi_p}^3\right) & (\xi_p > 0) \\ = -\mu W_z \frac{K_\beta \tan\beta_T (1+\rho)}{K_s \lambda} & (\xi_p < 0) \end{cases}$$

Equation 2.4.5

Where, *b*, *l* is the width and length of the interacted tyre surface, K_x, K_y are the rigidness of tyre in longitudinal and lateral axis,and β_T is the side slip angle of the tyre. In this research, *b*=10 *cm*, *l*=15 *cm*, $K_x = 3.3 \times 10^7 N/m^3$,$K_y = 3.3 \times 10^7 N/m^3$ was set as constant.

The numerical analysis in this study can be explained by using Fig. 2.4.2. This figure illustrates the calculation flow chart of hydraulic-mechanical hybrid brake system with ABS and regenerative brake control. When a braking torque T_B is applied to the tyre, a corresponding torque friction of the tyre T_f is developed on the tyre ground contact patch, which acts in the opposite direction of the applied braking torque T_B. The difference between T_B and T_F causes an angular acceleration $\dot{\omega}$ of the tyre:

$$\begin{cases} T_{ffr} - T_{Bfr} = I_{fr}\frac{d\omega_{fr}}{dt} \\ T_{frr} - T_{Brr} = I_{rr}\frac{d\omega_{rr}}{dt} \end{cases} , \quad \begin{cases} T_{ffl} - T_{Bfl} = I_{fl}\frac{d\omega_{fl}}{dt} \\ T_{frr} - T_{Brr} = I_{rr}\frac{d\omega_{rr}}{dt} \end{cases}$$

Equation 2.4.6

where I is the inertia of the tyre. The inertia moment of front tyre is 0.43 kgm^2 and the inertia moment of rear tyre is 2.53 kgm^2.

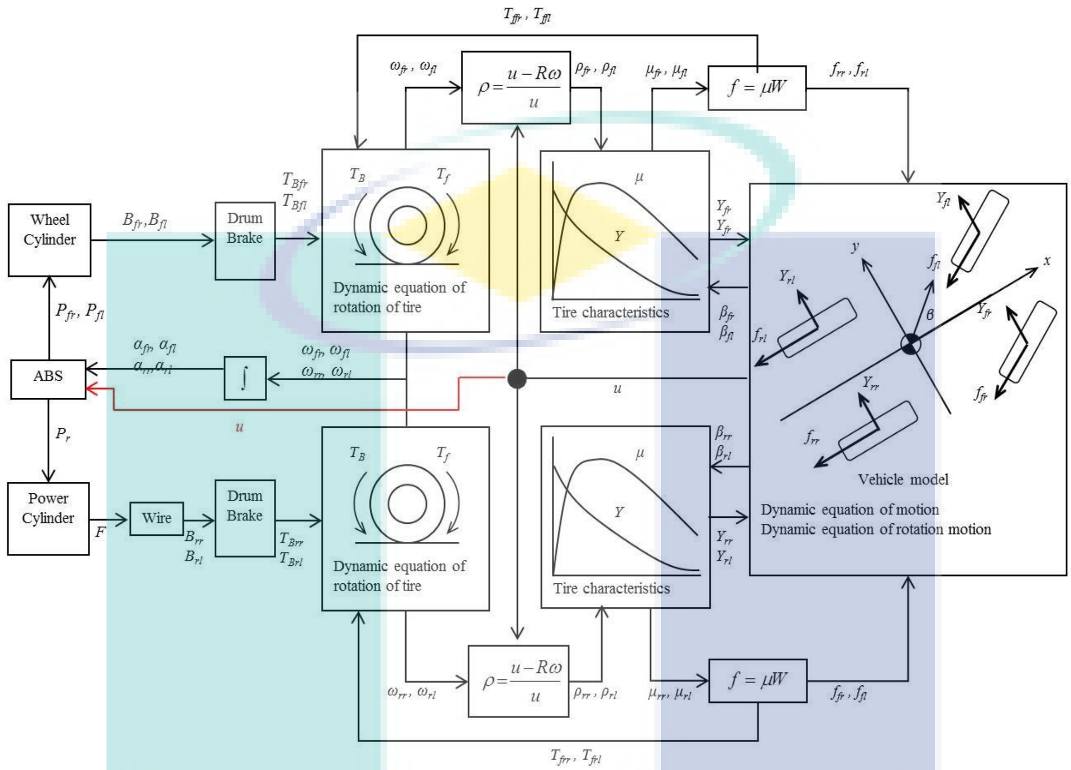

Figure 2.4.2. Calculation flow chart

In the numerical calculation, we consider that in-wheel motor will produce the regenerative braking torque. Then, the total braking torque for a rear tyre is the sum of the mechanical braking torque and the regenerative braking torque. On the other hand, the braking torque for a front tyre is only the hydraulic braking torque. Equation Eq. 2.4.7 shows the braking torque at each tyre.

$$\begin{cases} T_{Bfr} = BEF_{fr} \times r_{fr} B_{fr} \\ T_{Bfl} = BEF_{fl} \times r_{fl} B_{fl} \end{cases} \qquad \begin{cases} T_{Brr} = BEF_{rr} \times r_{rr} B_{rr} + T_{Rr} \\ T_{Brl} = BEF_{rl} \times r_{rl} B_{rl} + T_{Rl} \end{cases}$$ Equation 2.4.7

Where BEF is braking efficiency factor and the value of BEF is 1.5.

If ρ is not in the optimum range (0.2 to 0.3), the ABS control unit will start to operate to control the braking pressure at the master cylinder. The braking pressure from the master cylinder will be directed to the front wheel cylinder and rear power cylinder. Without a time delay response from the master cylinder to the front wheel cylinder, and ABS is enough to maximize the slip ratio and cornering force of the front tyre. However, for the rear braking system, due to the rigidness of the mechanical braking system, a time delay response was occurred during ABS operational. To compensate with the lost of friction force, the in-wheel motor will produce the regenerative braking torque. The regenerative braking control timing will be operational when the value of ρ is not in the optimum range. From the operation of the ABS and regenerative brake control timing, we can keep the optimum value of ρ and we also can maximize the braking force and cornering force, thus assuring the stability of the vehicle.

3. LITERATURE REVIEW

Electric braking is a system in which a braking action is applied to an electric motor by causing it to act as a generator. Regenerative, dynamic and plugging braking are three main kind of electrical braking system which are commonly used nowadays. Dynamic braking also known as rheostat braking is similar to regenerative braking, but instead of storing energy, it is dissipated on a resistance. Dynamic braking operate when the kinetic energy of the rotor is dissipated in the internal or external resistor as heat energy after the main supply is cut off. Many industrial application use dynamic braking as the braking method because it allows the electrical motor to stop at any speed without mechanical wear and tear. During dynamic braking, stator will remained at steady state while rotor will still rotate for a moment due to inertia. Rotor in synchronous motor has a supply even the stator is cut off from main supply and rotor is a permanent magnet for permanent magnet synchronous motor. For the case of induction motors, it is different compare to above two types of motor as its rotor has a residual magnetism to control the rotor. Therefore, all these types of motors show us that there are source of magnetic flux in rotors. When stator is steady and rotor is rotating, the magnetic flux in the rotor will induce the voltage in the stator. In order words, electric motors are now performing as a generator and kinetic energy produced from rotors is transmitted to the stator as electrical energy. With this system of dissipating kinetic energy from rotor to electrical energy at internal or external resistor, this braking method is known as dynamic braking. (Rongmei, S.L, Chatterji, & Sharma, 2012)

In dynamic braking, electric motor act as a generator and the field connection is reversed by enabling the current flows in the opposite direction. A clear image of dynamic braking concept is shown at figure 3.1 where the kinetic energy stored in rotating parts convert the connected load into electrical energy and this energy is dissipated as heat in the braking resistance R and armature circuit resistance Ra.

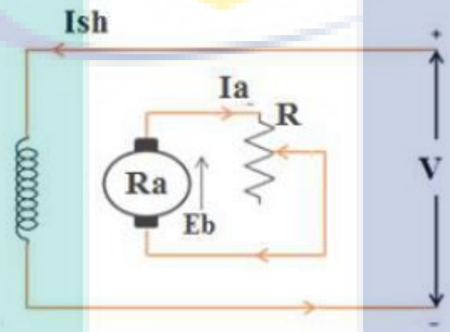

Figure 3.1: Concept of Dynamic Braking

Source: (P.K, 2016)

Plugging braking is an electric braking method that commonly used in high duty system which required very high inertia and it can stop the object in a short period of time. It is different from dynamic and regenerative braking in a sense that both current and voltage are reversed by phase sequence. This type of braking system require high consumption of energy to fully stop a system (Can Gökçe, 2013).

The second type of electrical braking is plugging brake system. For traditional plug braking, shown in figure 3.2, the direction of revolving magnetic field is changed to oppose the direction of magnetic field by shifting the phase sequence of three-phase voltage at the stator windings. In this phenomenon, a moving object will be stopped by the opposing torque within a short period of time. However, plug braking require current which is larger than the current when starting from rest to run the braking. This situation caused the motor to be overheated and the heat energy produced are four times greater than the other two types of braking. In short, plug braking is difficult to be operated compare to dynamic braking and regenerative braking, but it is able to slow down or stop a vehicle in any speed even in low speed which require high braking torque.(Rongmei et al., 2012).

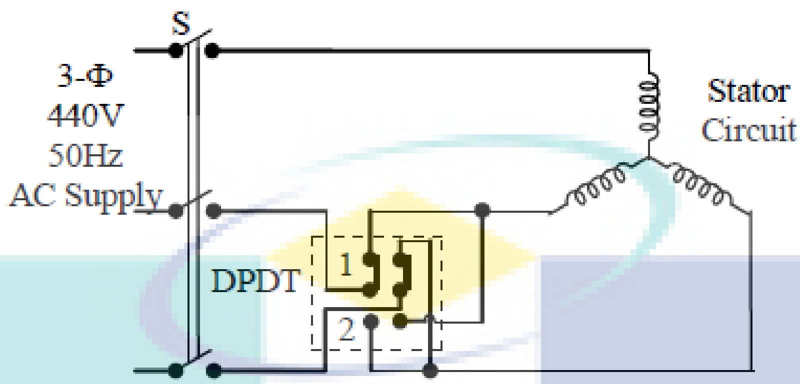

Figure 3.2: Plugging Braking

Source: (Rongmei et al., 2012)

The third type of braking system is a regenerative brake system. According to the European regulations, "Electric regenerative braking means a braking system which, during deceleration, provides for the conversion of vehicle kinetic energy into electrical energy". (Erlangung, 2018)

Instead of wasting the kinetic energy from the automobile and dissipate as heat, regenerative braking convert the kinetic energy into electrical energy and stored in batteries and capacitors which it is known as motor based regenerative braking. In this phenomenon, electric motor acts as a generator and the conversion stage is shown in figure 3.3. Besides that, the wasted energy can be utilised by flywheel using flywheel based regenerative method where the wasted energy is returned as mechanical energy and use again on flywheel. In this way, large amount of wasted energy will be saved and reuse later for accelerating or other electrical purposes.

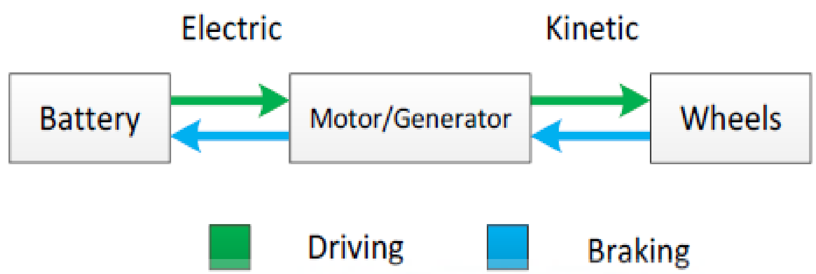

Figure 3.3: Energy Flow of Regenerative Braking

Source: (Erlangung, 2018)

In general, the driving system of the small EVs is in-wheel motors. There are several advantages of the in-wheel motor such as fast and precise torque response [7,15]. Based on the advantages of the in-wheel motors, the performance and safety system of the small EVs can be increased. To increase the steer performance of the electric vehicle, J.Hu and J.Ni have developed the 2 degrees of freedom (DOFs) linear dynamic model of skid steered vehicle with distributed drive, which took yaw moment as input variable. The result shows that, the steering characteristics of the vehicle is influenced by the value of yaw moment [19]. H.Zhao et al have established a non-linear control allocation scheme based on model predictive control (MPC) to improve the stability of an electric vehicle (EV) with four in-wheel motors. To avoid unintended side effects, skidding or discomforting the driver in critical driving condition, the MPC method, which permits us to consider constraints of actuating motors and slip ratio is used to deal with this challenging problem. The results show that the designed MPC allocation algorithm for motor torque can improve the stability of the vehicle [17]. Although electric motor can improve the stability of the EVs, due to the space limitation on the driving tire, the hydraulic unit of anti-lock brake system (ABS) cannot be installed on the small EVs [2,16]. ABS is a basic skid control method to prevent tire lock up during braking on low adherent road surfaces or heavy braking[6,11,18]. There are two major functions of ABS: to keep the braking force on high adhesive coefficient; and, to maintain the lateral force of tires, which can maintain vehicle steering control [12-14]. Without ABS on small EVs, during braking on low adherent road surfaces or emergency braking, the tire will lock up and the vehicle will skid. On the other hand, the most suitable braking system on the driving tire is mechanical brake system. The hydraulic brake system cannot be installed on the driving tire because the space is not enough. Although mechanical brake system is compact, the stiffness and the response performance of the mechanical brake system are lower than hydraulic brake system [3]. As such, small EV can be considered to provide insufficient safety. During braking, the in wheel motor will running backwards and produce the regenerative braking force. Regenerative brake is a braking method that utilizes the mechanical energy from the motor by converting kinetic energy into electrical energy, which is fed back into the battery. In regenerative braking mode, the electric motor work in reverse direction and produce the regenerative braking torque [9]. Although regenerative brake can improve the braking performance of the small EVs, during braking on slippery road or emergency braking, the regenerative braking torque that was applied to the front and rear tires to stop their rotation often exceeds the force that is making them rotate. This cause the tire to stop rotating rapidly and begin skidding. In this situation, the tires no longer have the ability to provide directional control to the vehicle, no matter how much steering input is attempted by the driver [11]. Previously, based on the advantages of the electric motor, K.Maeda et al have proposed an idea that in wheel motors can be an actuator of ABS to prevent tire lock up [7,8]. However, K.Maeda et al only focus on yaw stability control and there are no research to approve that electric motor can be an actuator of ABS. C.Mi et al have developed a slip ratio model and a vehicle observer to control the anti-lock performance of the hybrid electric vehicles (HEV). By using an iterative learning process, the motor torque was optimized to prevent the tire from lock up during braking on slippery road. Recently, M.H.Peeie et al have developed the simulation model of ABS and regenerative brake control on small EVs with two in wheel motors [10]. In that simulation, for the front tire (no in wheel motor), the hydraulic unit of ABS is installed between the master cylinder and front wheel cylinder. However, for the rear tire (driving tire), the hydraulic unit of ABS is installed between the master cylinder and rear power cylinder. Due to the stiffness of the mechanical brake system between the power cylinder and rear drum brake, the response performance of the ABS on rear tires are very low. Based on the slip ratio of the front tire, the in wheel motors on the rear tires will turn on and off to control the regenerative braking force. The disadvantages of this model is when the slip ratio on the front and rear tires are not similar. From the past research, it can be concluded that to prevent each tire from lock up, the braking force on each tire must be controlled individually. In this research, to control the regenerative braking force on each tire during emergency braking, the automatic emergency braking system is proposed.If the slip ratio greater than the optimum value, the regenerative brake will turns off and the in wheel motor turning forwards. However,if the slip ratio lower than the optimum value, the regenerative brake turns on and the in wheel motors running backwards. From this mechanism, the slip ratio of each tire can be controlled precisely and prevent tire from lock up.

4. FINDINGS

4.1 Introduction

The EV, which are powered by 48V batteries have only the maximum speed of 45 km/h. For the experiments, there are two different speeds used; 30% at 14 km/h and 60% at 28 km/h. For the safety purpose, the experiments are not tested on the maximum speed of the EV. For the motor brake, the motor brake forces are applied to 25% and 50%. The tire speeds, vehicle speeds, pitches as well as displacements data are recorded and analysed.

4.2 Speed 30% @ 14 km/h with 25% Motor Brake

As explained before, there are five different methods of braking used for the experiments. First, only motor brakes are used for the braking purpose. Second, only front brakes are used, and third method is the combination of front brakes and motor brakes. For the fourth method, there would be front and rear disc brakes to be tested. For the fifth method, the combination of motor brakes, as well as front and rear disc brakes will be tested during experiments. The experiments will be conducted at least 3 times to obtain the average data.

As can be seen from the Figure 4.2.1, the average stopping time is 5.8 s. The average pitch recorded at the stopping time is 3.99° and the average stopping distance is 14.6 m. The stopping distance and stopping time is high due to there are only motor brakes applied for this experiment. From Figure 4.2.2 and 4.2.3, the torque and power produced during braking are solely from the motor brake. The peak torque produced is -58.35 Nm and the peak power produced is -448.6 W. The negative sign shows that the vehicle is in braking mode.

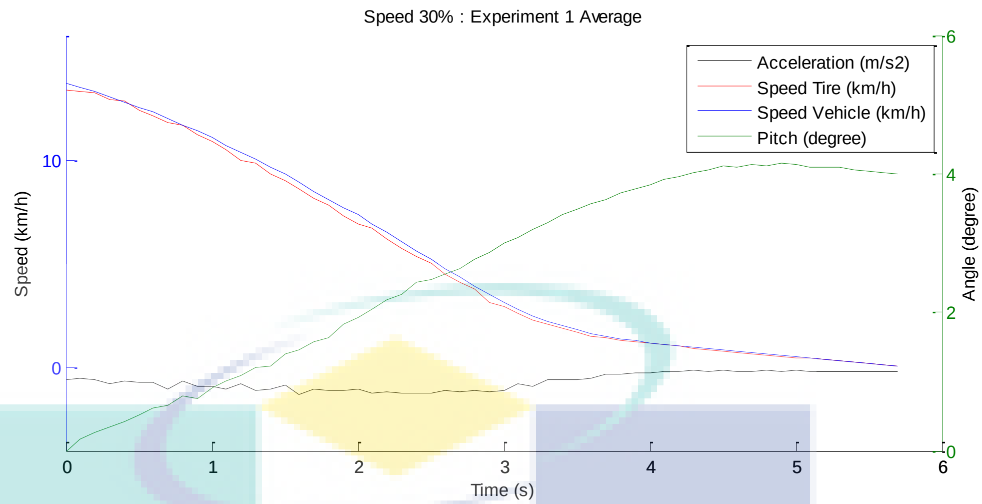

Figure **Error! No text of specified style in document.**.2.1 Experiment results for the average of Speed 30% : Experiment 1.

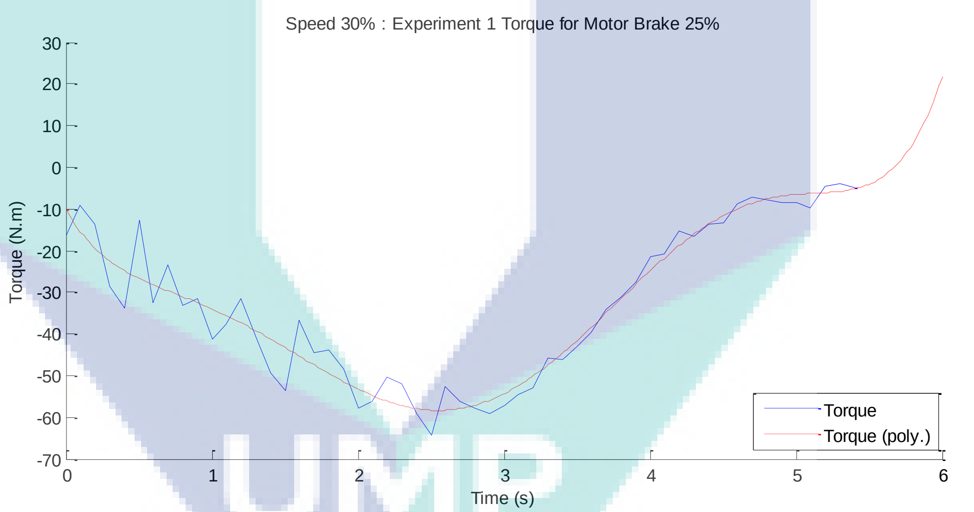

Figure **Error! No text of specified style in document.**.2.2 Torque for Speed 30% : Experiment 1 Motor Brake 25%.

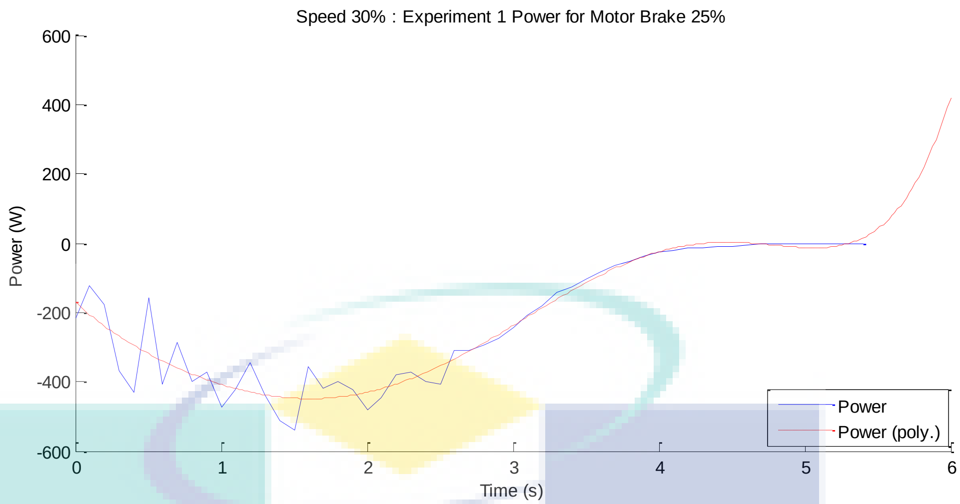

Figure **Error! No text of specified style in document.**.2.3 Power for Speed 30% : Experiment 1 Motor Brake 25%.

From Figure 4.2.4, the stopping time and distance are shorter compared to experiment 1 in Figure 4.2.1. The recorded stopping time is 2.3 s, and the stopping distance is recorded at 4.34 m. However, the pitch recorded is high, which hiked up to 4.163°. The pitch was expected to be the highest for experiment 2 due to the usage of only front brakes to conduct the experiments.

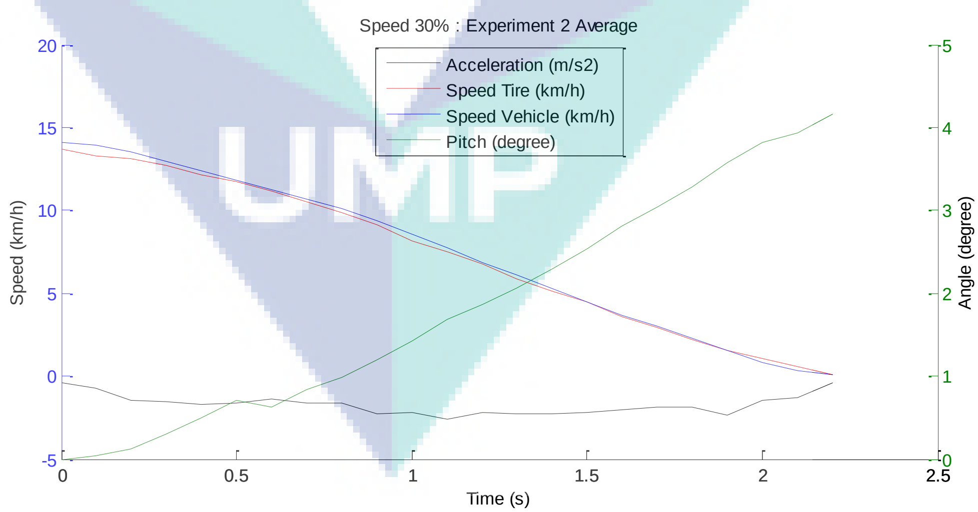

Figure **Error! No text of specified style in document.**.2.4 Experiment results for the average of Speed 30%: Experiment 2.

From Figure 4.2.5 above, the braking method used is the combinations of motor brakes with the front disc brakes. There are improvements recorded for experiment 3.

The stopping time was recorded at 2.2 s, and the stopping distance is recorded at 2.7 m. The pitch of the EV recorded is relatively lower than the previous experiment, which could accumulate until only 3.564°. The average pitch recorded is expected to be lower than Experiment 2.

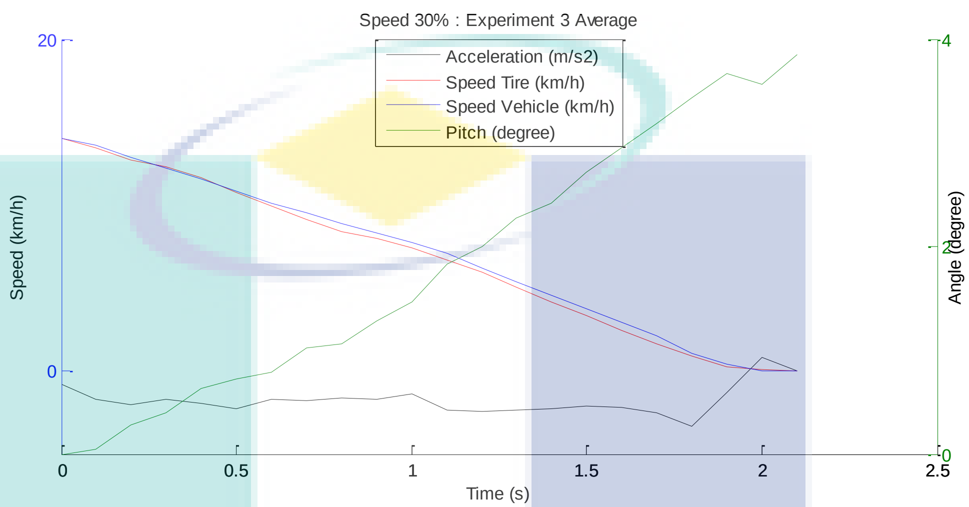

Figure **Error! No text of specified style in document.**.2.5 Experiment results for the average of Speed 30%: Experiment 3.

From Figure 4.2.6, the method of the experiment is a combination of front and rear disc brakes. To perform the experiment, the hydraulic lines of the front and rear disc brakes must be connected to the same master cylinder pump. The stopping time, stopping distance and pitch recorded are lower than the previous experiments. The stopping time is 1.6 s, stopping distance is 3.2 m, and the pitch is recorded to be only up to 3.237°.

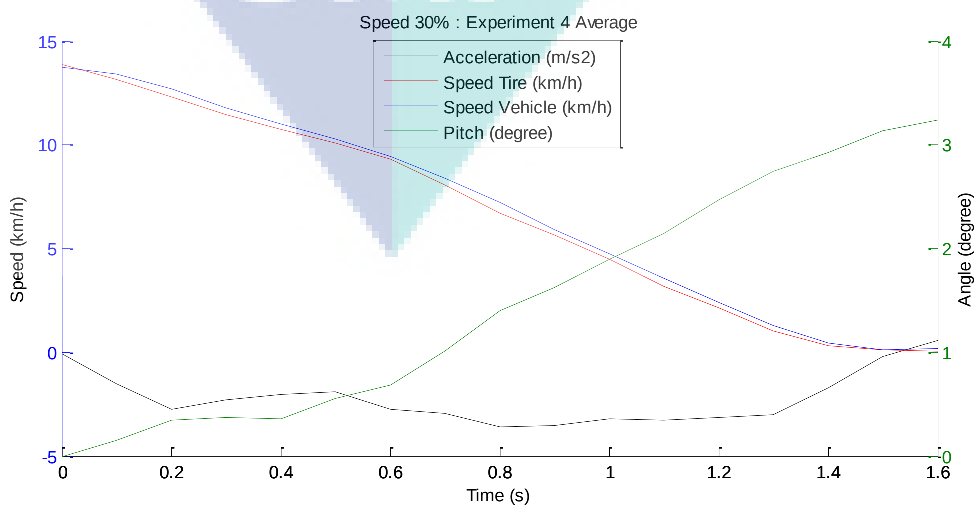

Figure **Error! No text of specified style in document.**.2.6 Experiment results for the average of Speed 30%: Experiment 4.

From the Figure 4.2.7, there are combinations of front and rear disc brakes, as well as motor brakes, are implemented. The stopping time and stopping distance are recorded to be the best, compared to the previous experiments conducted for the same speed. The stopping time is recorded to be only at 1.5 s, the stopping distance is 2.05 m, and pitch is recorded at only 2.86°.

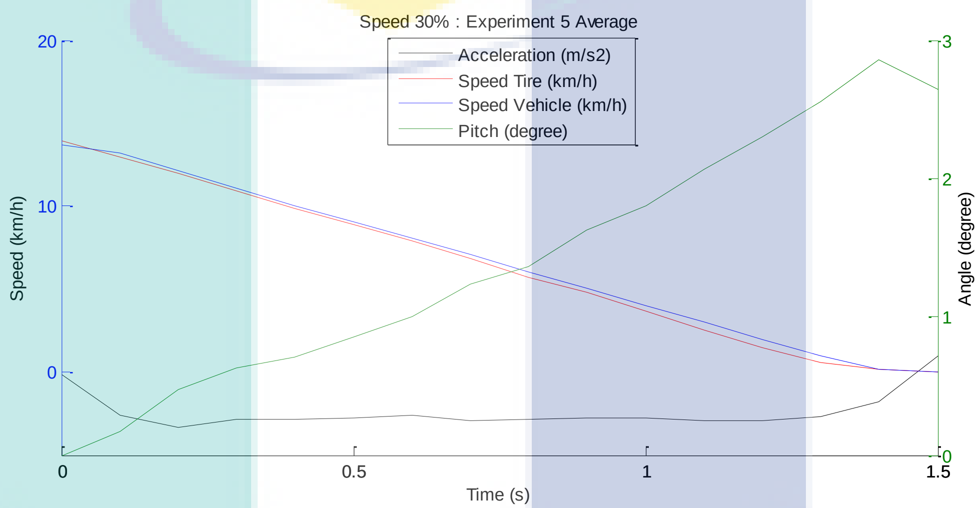

Figure **Error! No text of specified style in document.**.2.7 Experiment results for the average of Speed 30%: Experiment 5.

As can be seen from Fig 4.2.8, it took more than 5 sec for the vehicle to come to a complete stop in Experiment 1. This is due to only motor brakes are applied for this experiment. The motor brake effort is directly proportional to the load (speed) to the motor. The lower the speed of the vehicle, there will be lower motor brakes effort and up to a point, no more motor brakes effort because B-emf<supplied voltage. Beyond this point onwards, there would be only free rolling of the EV.

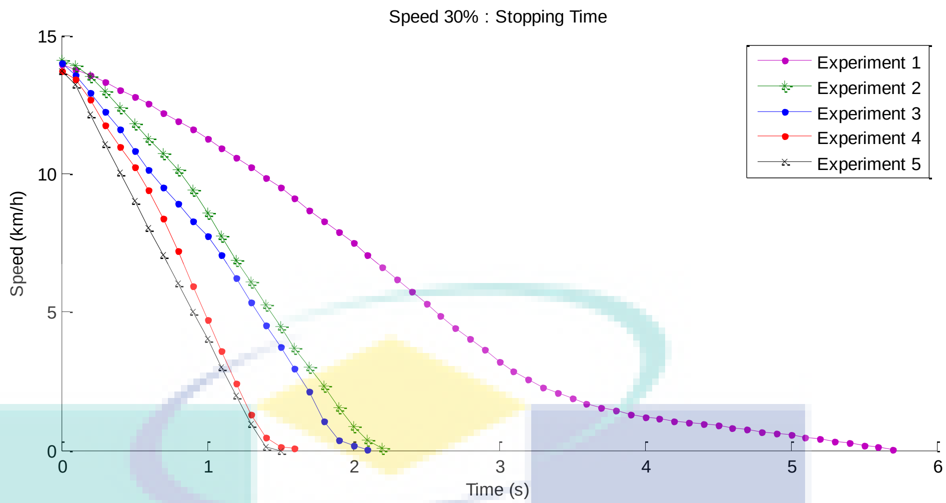

Figure **Error! No text of specified style in document.**.2.8 Results for the average stopping time in Experiment: Speed 30%.

In Fig 4.2.9, the highest pitch recorded is for Experiment 2. This is due to, only front disc brakes are applied during the experiment. The lowest pitch recorded is for Experiment 5, which applied the entire front and rear disc brakes as well as motor brakes. From Table 4.2, the highest distance is recorded at 14.6 m for Experiment 1. The shortest distance recorded is only 2.05 m for Experiment 5. With the lowest braking distance in Speed 30%, Experiment 5 has the highest braking performance compared to the other four braking methods.

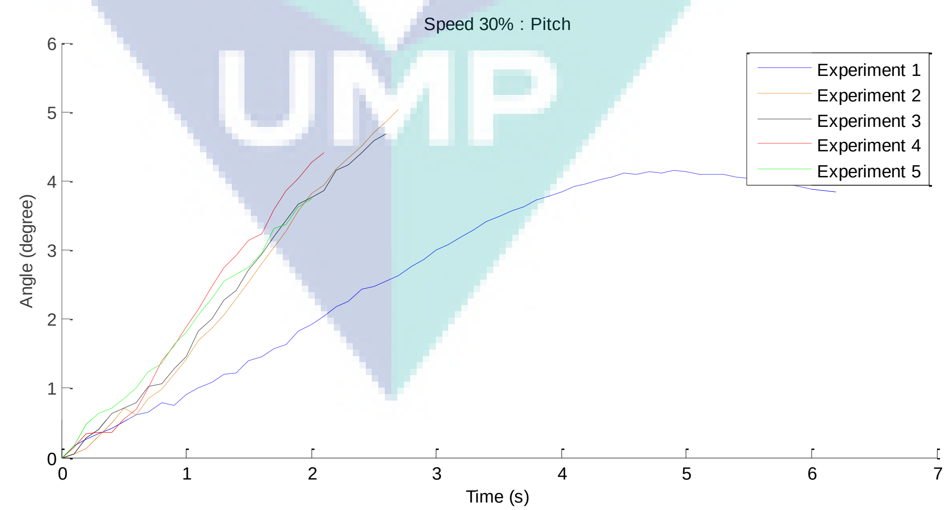

Figure **Error! No text of specified style in document.**.2.9 Results for the average pitch in Experiment: Speed 30%.

In Figure 4.2.10, the lowest deceleration rate is recorded for Experiment 1. From Table 4.2, the rate of deceleration for Experiment 1 is calculated at 0.707 m/s^2. The highest deceleration rate is recorded for Experiment 5, at 2.778 m/s^2.

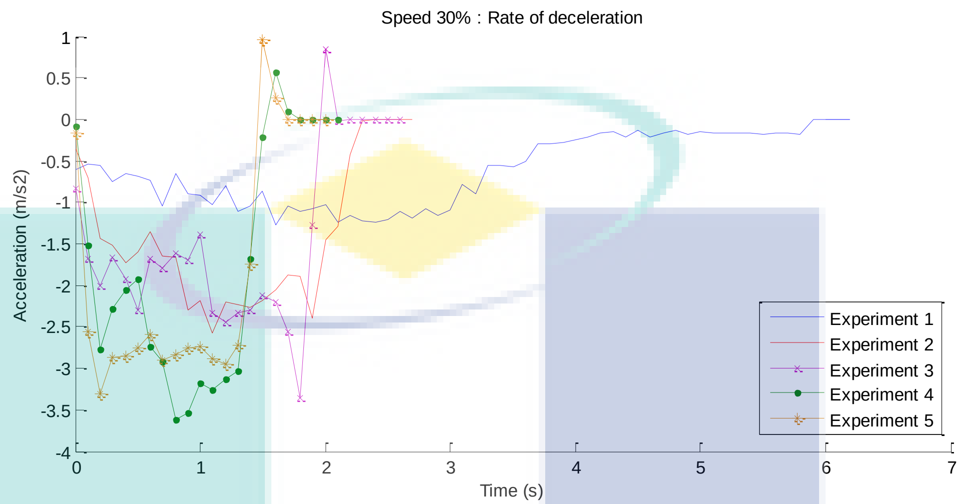

Figure **Error! No text of specified style in document.**.2.10 Rate of deceleration in Experiment: Speed 30%.

For Figure 4.2.11, the highest stopping distance is recorded for Experiment 1, which at 14.6 m. For Experiment 3 and 4, the stopping distance is almost identical. This is due to the effect of 25% motor brakes are insignificant. The stopping distance of Experiment 5 is recorded at 2.05 m, which is the lowest.

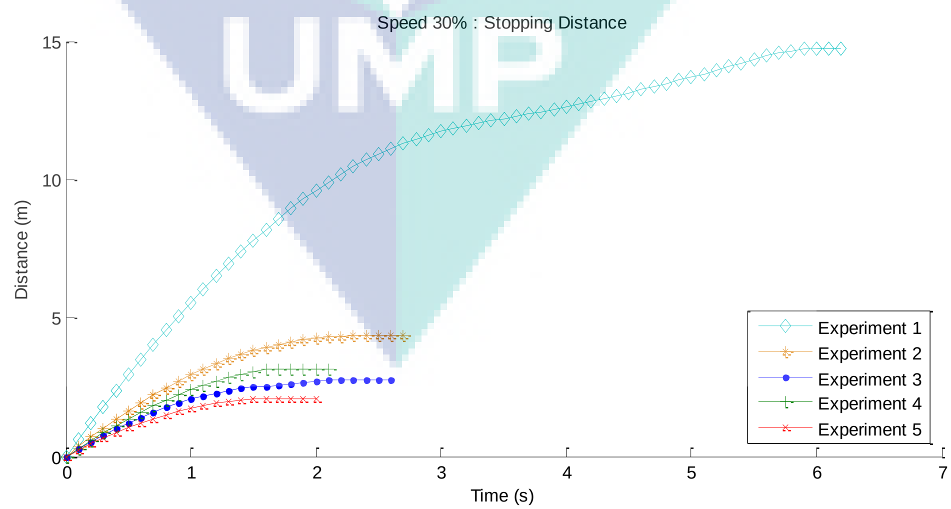

Figure **Error! No text of specified style in document.**.2.11 Stopping distance in Experiment: Speed 30%.

Table **Error! No text of specified style in document.**.2 Summary of experiments for speed: 30%

Type of Experiments	Stopping Time (s)	Stopping Distance (m)	Pitch (°)	Deceleration Rate (m/s^2)
Experiment 1	5.8 s	14.6 m	3.99°	0.707 m/s^2
Experiment 2	2.3 s	4.3 m	4.16°	1.852 m/s^2
Experiment 3	2.2 s	2.7 m	3.57°	2.047 m/s^2
Experiment 4	1.6 s	3.16 m	3.24°	2.593 m/s^2
Experiment 5	1.5 s	2.05 m	2.86°	2.778 m/s^2

4.3 Speed 30% @ 14 km/h with 50% Motor Brake

The experiments are repeated only for the Experiment1 and Experiment 5. This is due to only motor brake percentages are changed. The improvement of result shows that there are differences in the motor brake torque applied. Experiment 1 is conducted again to shows that the motor brake method is dynamic brake, which can change their braking torque percentage. Experiment 5 is conducted again to study the improvements for the highest performance of the mode of braking. Experiment 3 is not conducted again because the braking performance has already proved in the previous experiment, and even though the experiment is conducted again with 50% Motor Brake, it will not get to the higher performance compared to the Experiment 5. Experiment 2 and 4 are not conducted because they involved only on hydraulic mechanical brakes.

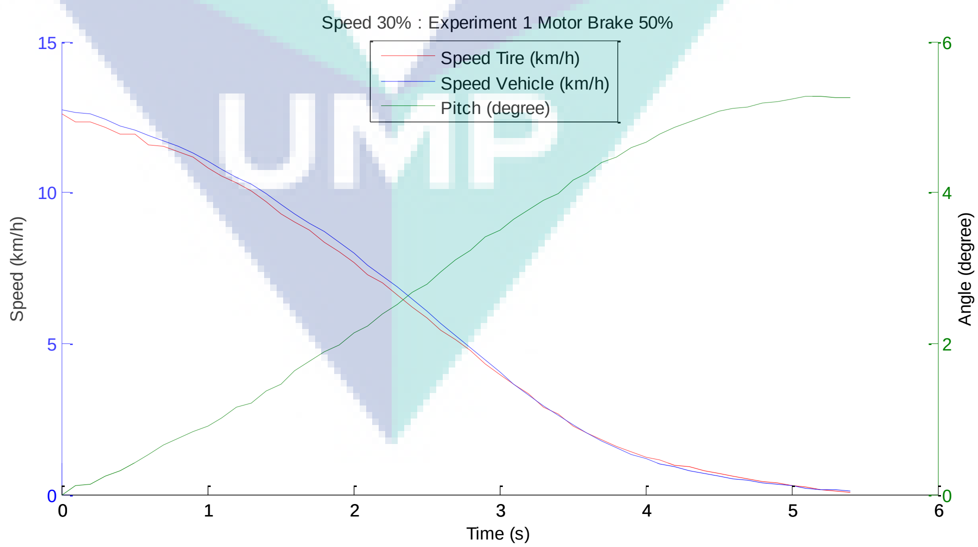

Figure **Error! No text of specified style in document.**.3.1 Average Experiment 1: Speed 30% Motor Brake 50%

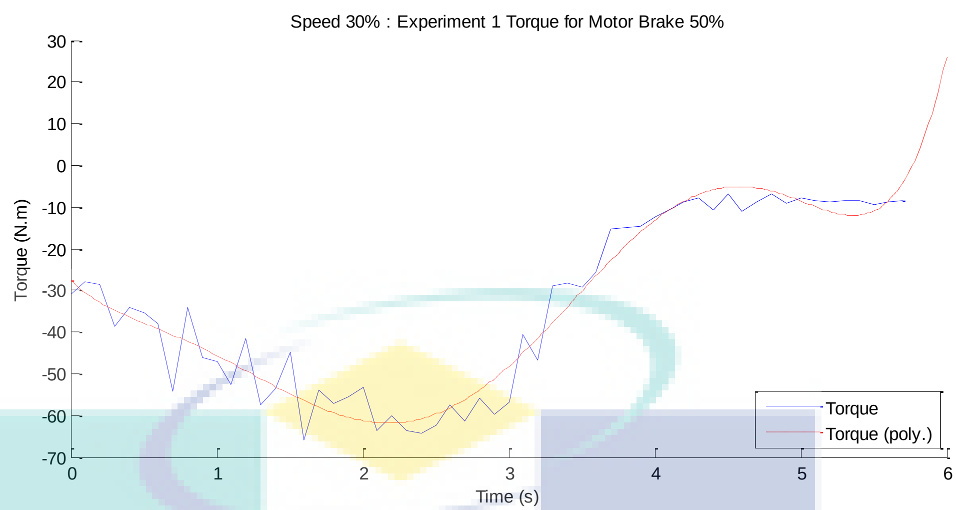

Figure **Error! No text of specified style in document.**.3.2 Torque for Experiment 1: Speed 30% Motor Brake 50%

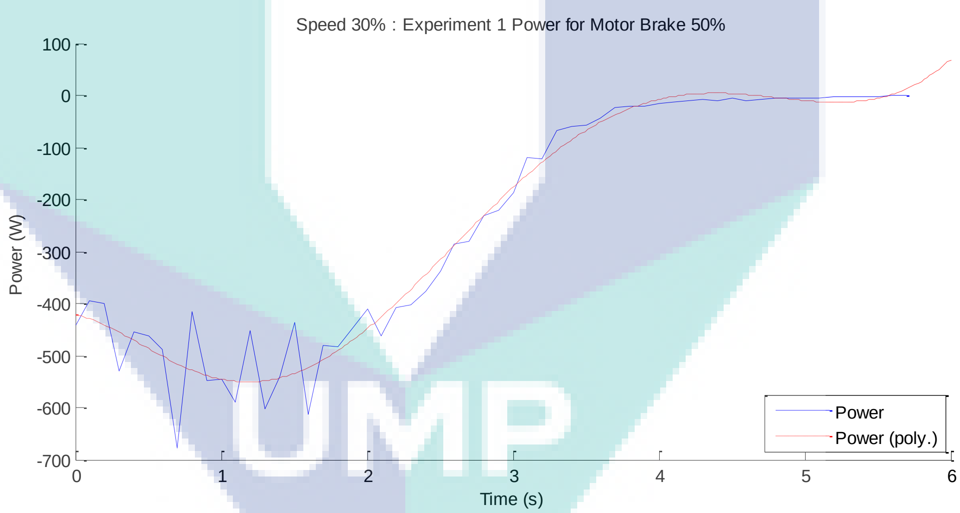

Figure **Error! No text of specified style in document.**.3.3 Power for Experiment 1: Speed 30% Motor Brake 50%

From the Figure 4.3.1, the time taken for Experiment 1 Motor Brake 50% to a complete stop is 5.37 s averagely. The stopping distance is 9.4 m, while the pitch is recorded at 5.29°. The rate of deceleration is recorded at 0.724 m/s^2, which shows that the rate of deceleration has improved for Motor Brake 50% compared to Motor Brake 25%. From the Figure 4.3.2 and Figure 4.3.3, the highest torque is recorded at -61.82 Nm and highest power produced is at 550.8 W. Table 4.3 shows the comparison of the Experiment 1 Motor Brake 25% and 50% as well as the improvements in percentage.

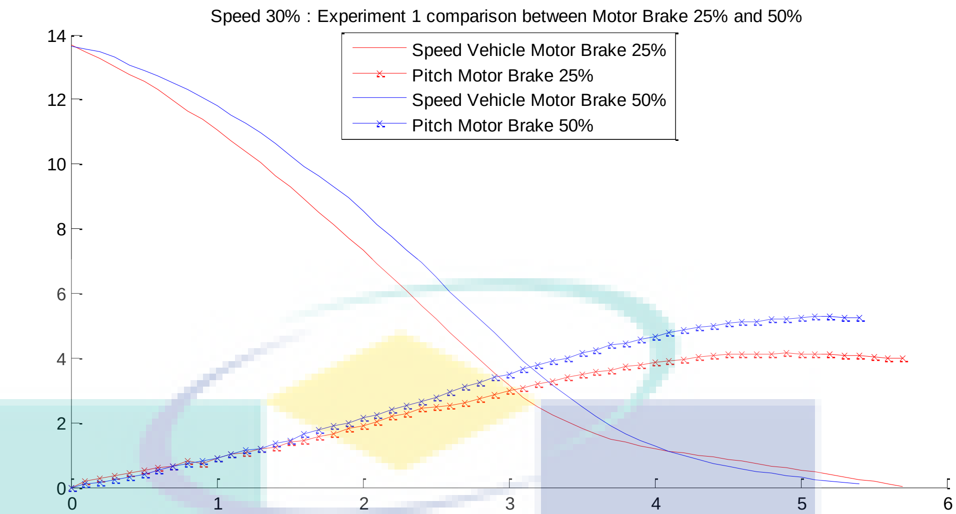

Figure **Error! No text of specified style in document.**.3.4 Experiment 1: Speed 30% comparison between Motor Brake 25% and 50%.

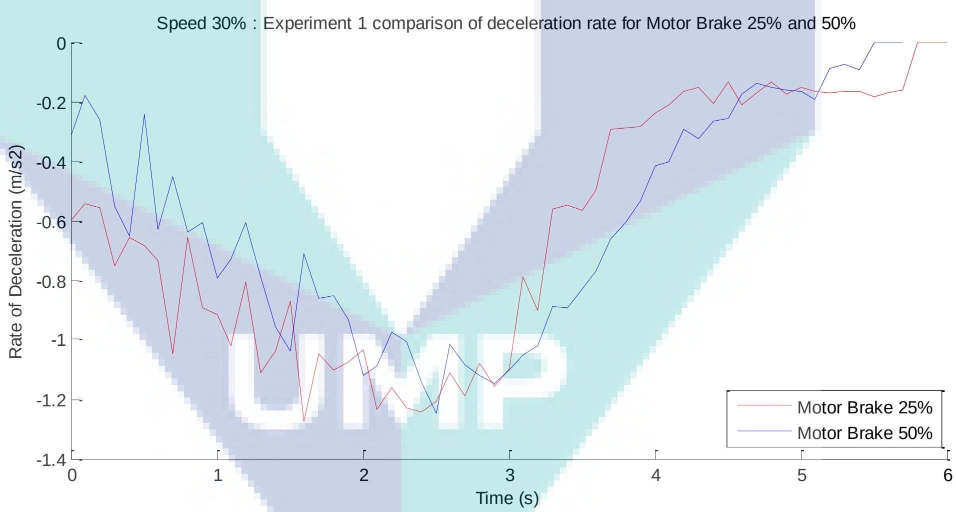

Figure **Error! No text of specified style in document.**.3.5 Experiment 1: Speed 30% deceleration rate comparison between Motor Brake 25% and 50%.

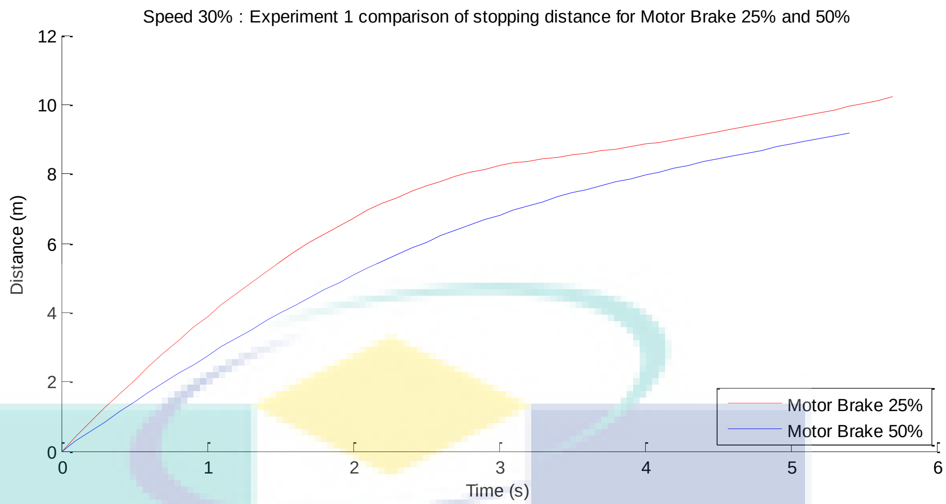

Figure **Error! No text of specified style in document.**.3.6 Experiment 1: Speed 30% stopping distance comparison between Motor Brake 25% and 50%.

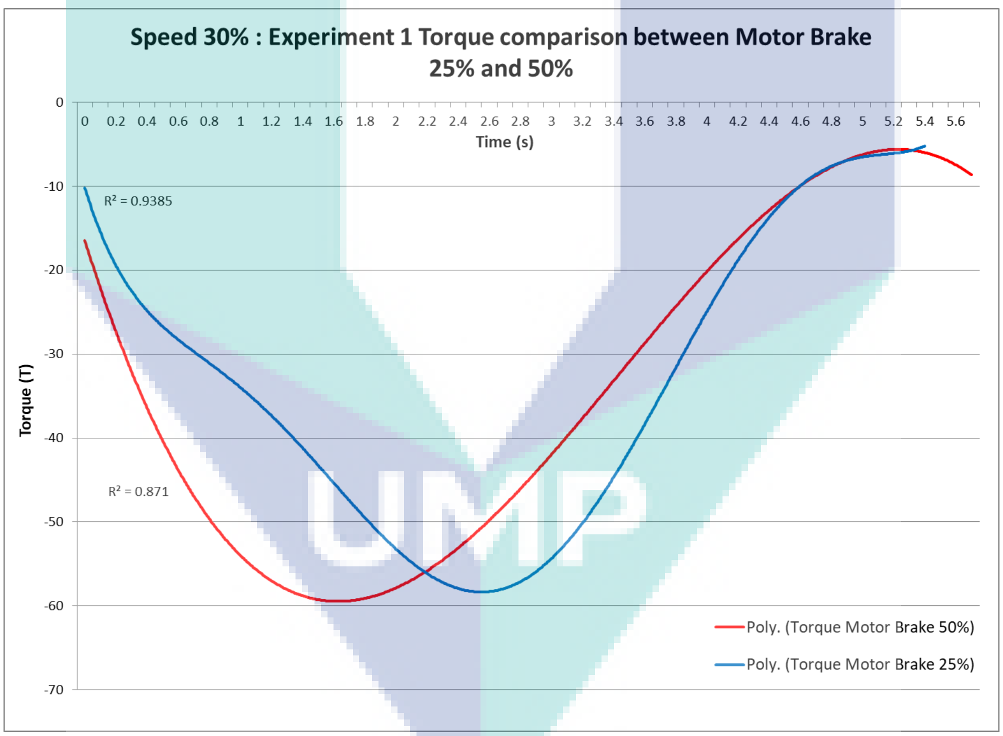

Figure **Error! No text of specified style in document.**.3.7 Torque comparison for Experiment 1: Speed 30% Motor Brake 25% and 50%.

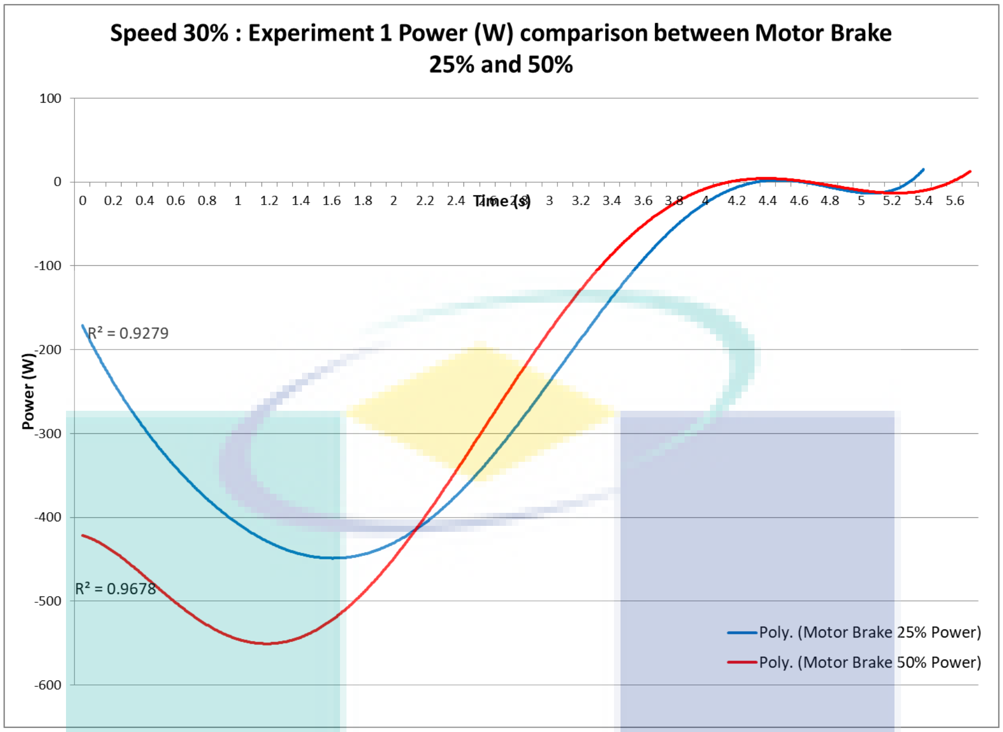

Figure **Error! No text of specified style in document.**.3.8 Power comparison for Experiment 1: Speed 30% Motor Brake 25% and 50%.

From the Figure 4.3.7 and 4.3.8, there are comparisons for the torque and power produced of Motor Brake 25% and 50%. The patterns for the torques produced in Figure 4.3.7 are almost identical to each other. However, the Motor Brake 50% (red line) shows that the torque produced is in earlier rate compared to Motor Brake 25% (blue line). In Figure 4.3.8, the power produced for Motor Brake 50% is higher compared to Motor Brake 25%. The higher power is due to increase of Motor Brake from 25% to 50%. Only Experiment 1 have the torque and power comparison because it is not affected with the hydraulic mechanical brakes.

Table **Error! No text of specified style in document.**.3 Results comparison for Speed 30%: Experiment 1 with Motor Brake 25% and 50%

Motor Brake	25%	50%	Improvement (%)
Time	5.8 s	5.37 s	7%
Distance	14.6 m	9.4 m	35%
Pitch	3.9°	5.29°	-26%
Deceleration Rate	0.707 m/s^2	0.724 m/s^2	2.3%
Max. Torque	-58.35Nm	-61.8Nm	5.6%
Max. Power	-448.6W	-550.8W	18.5%

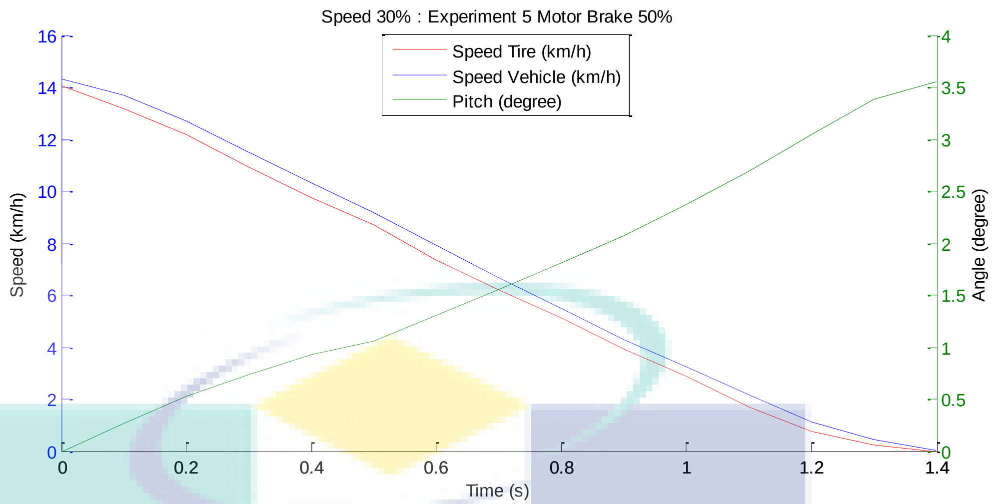

Figure **Error! No text of specified style in document.**.3.9 Result for Speed 30% Experiment 5 Motor Brake 50%.

Figure 4.3.9 shows that the result for the Experiment 5 Motor Brake 50%. The stopping time is recorded at 1.4 s, and the stopping distance is recorded at 2.5 m. The pitch is recorded at 4.6°, and the deceleration rate is recorded at 3.06 m/s^2. Overall result shows the improvements if compared to the Experiment 5 Motor Brake 25%. Figure 4.3.10, 4.3.11 and 4.3.12 shows the other comparison. In the Table 4.3 below shows the detailed results as well as improvements.

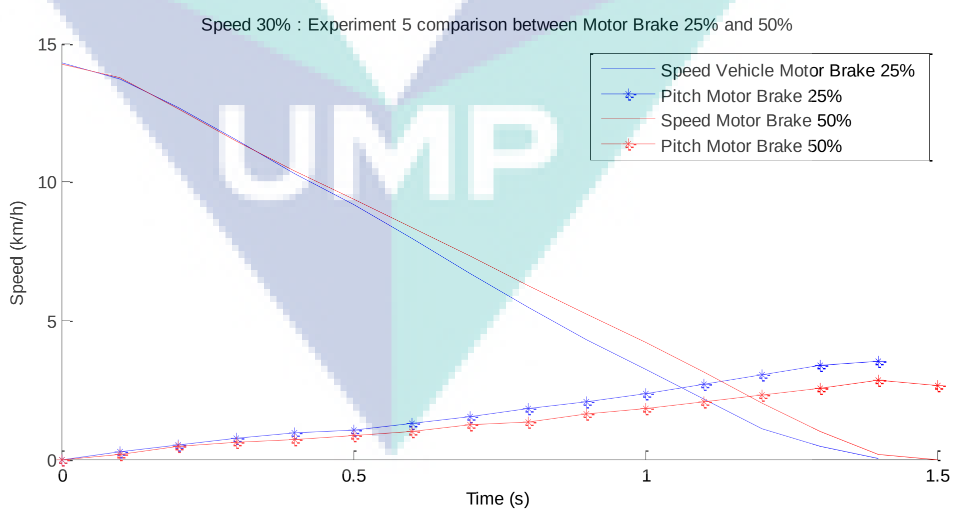

Figure **Error! No text of specified style in document.**.3.10 Speed comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

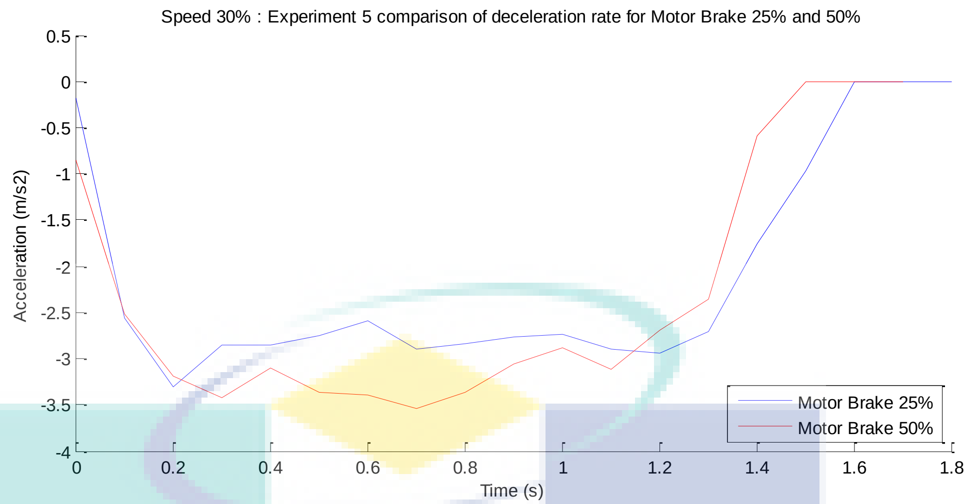

Figure **Error! No text of specified style in document.**.3.11 Deceleration rate comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

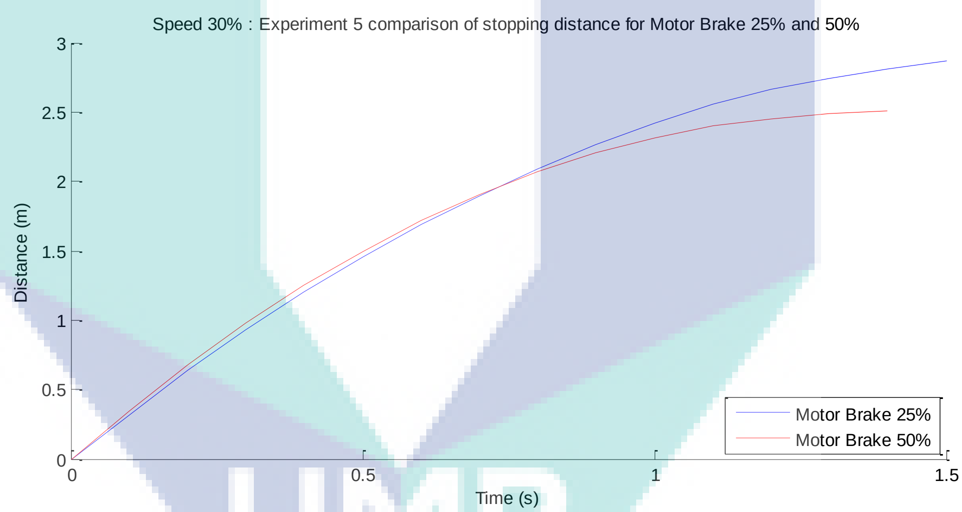

Figure **Error! No text of specified style in document.**.3.12 Distance comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

Table **Error! No text of specified style in document.**.3 Results comparison for Speed 30%: Experiment 5 with Motor Brake 25% and 50%

Motor Brake	25%	50%	Improvement (%)
Time	1.5 s	1.3 s	13%
Distance	2.86 m	2.5 m	12%
Pitch	2.86°	4.6°	-37%
Deceleration Rate	2.778 m/s^2	3.06 $/s^2$	9%

From the Table 4.7 above, there are improvements for the Motor Brake 50%. However, the pitch recorded shows increase of the degree if compared to the Motor

Brake 25%. This is due to there are an increase of motor brake efforts as well as human behaviour also affect the pitch recorded.

4.4 Speed 60% @ 28 km/h with 25% Motor Brake

For this speed, there were five experiments of different braking methods used, and the braking methods are the same as the previous experiments for Speed 30%. Thus, experiment results are expected to be the same pattern with the results from Speed 30%.

From Figure 4.4.1, the stopping time for the average of Experiment 1 is 7.2 s. Moreover, the stopping distance is the highest too, travelled up to 24.5 m long. This is due to only motor brakes are applied for this experiment. At an earlier stage, the supplied voltage<B-emf, thus the energy will be able to be stored back into the battery. Over time, the tire speed will be decreased, and the supplied voltage>B-emf. Beyond this point, no more motor brake forces applied because the load (speed) experienced to the motor is too low. The pitch is recorded at 6.7°. In Figure 4.4.2 and 4.4.3, there shows the torque and power produced during braking. The highest torque is recorded to be at -112.5 Nm and the highest power is recorded at -1894.48 W.

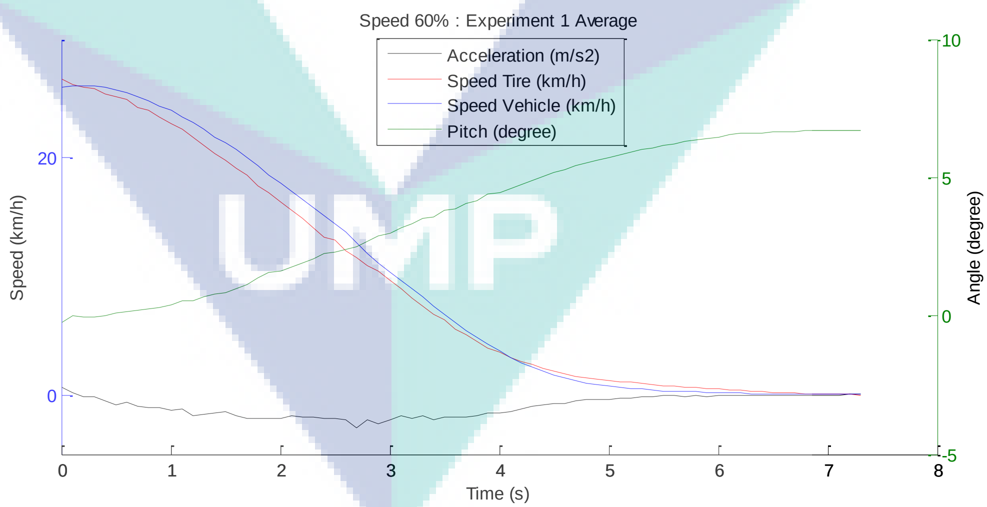

Figure **Error! No text of specified style in document.**.4.1 Experiment results for the average of Speed 60%: Experiment 1.

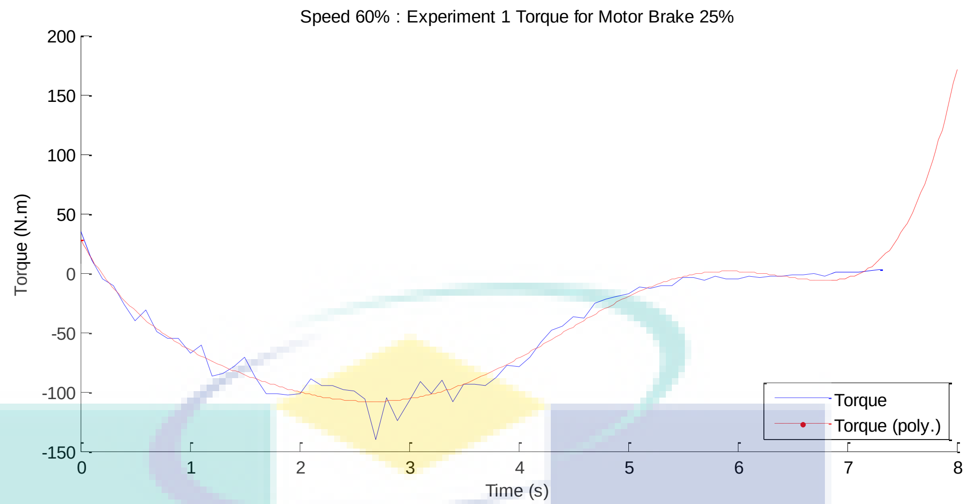

Figure **Error! No text of specified style in document.**.4.2 Torque for Speed 60%: Experiment 1 Motor Brake 25%.

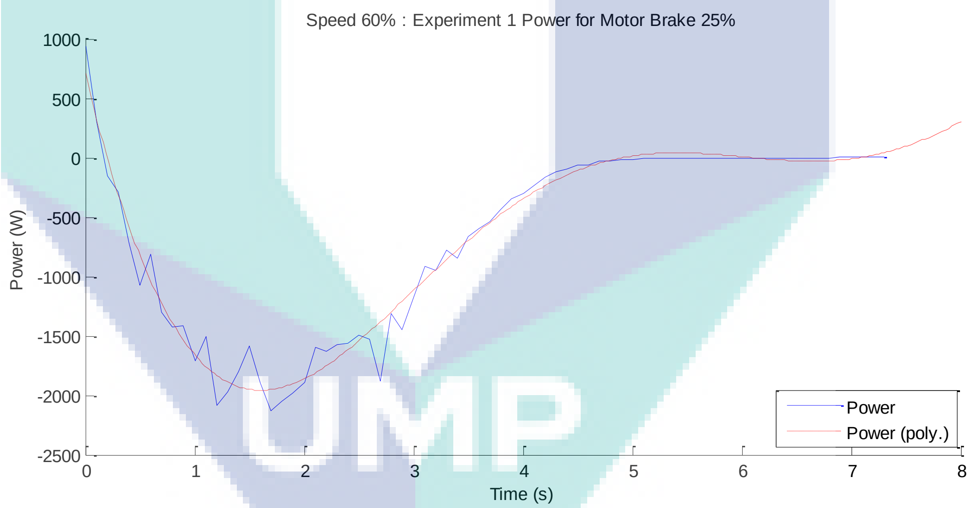

Figure **Error! No text of specified style in document.**.4.3 Power for Speed 60%: Experiment 1 Motor Brake 25%.

From Figure 4.4.4, the stopping time for Experiment 2 is 3.5 s. The pitch recorded is 9.6°, which is the highest if compared to the overall experiments. The pitch is high because only front disc brakes are applied for this experiment. The stopping distance recorded is 12.05 m, shorter compared to Experiment 1.

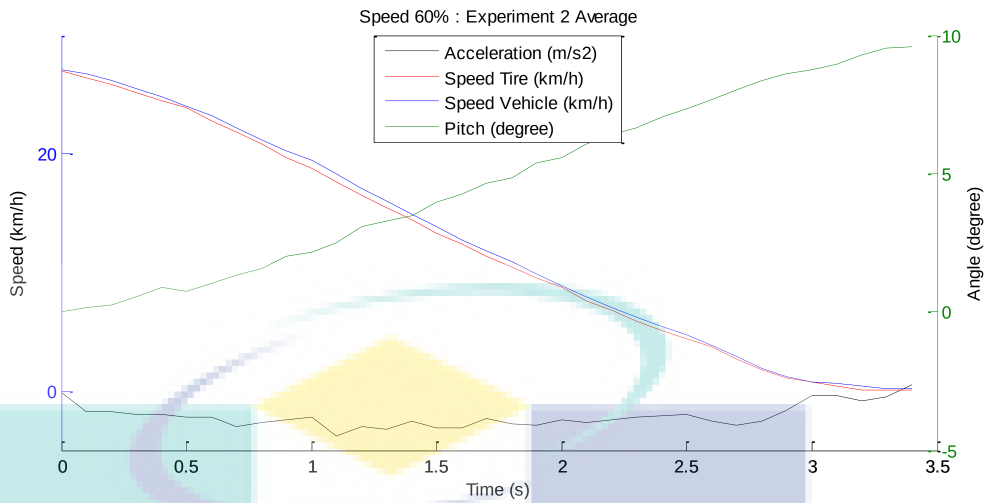

Figure **Error! No text of specified style in document.**.4.4 Experiment results for the average of Speed 60%: Experiment 2.

In Figure 4.4.5, the stopping time recorded is 2.5 s, whereas the pitch is recorded at 9.2°. There are only small improvements of the pitch if compared to the experiment from Figure 4.4.4. For the stopping distance, it is recorded at 11.6 m.

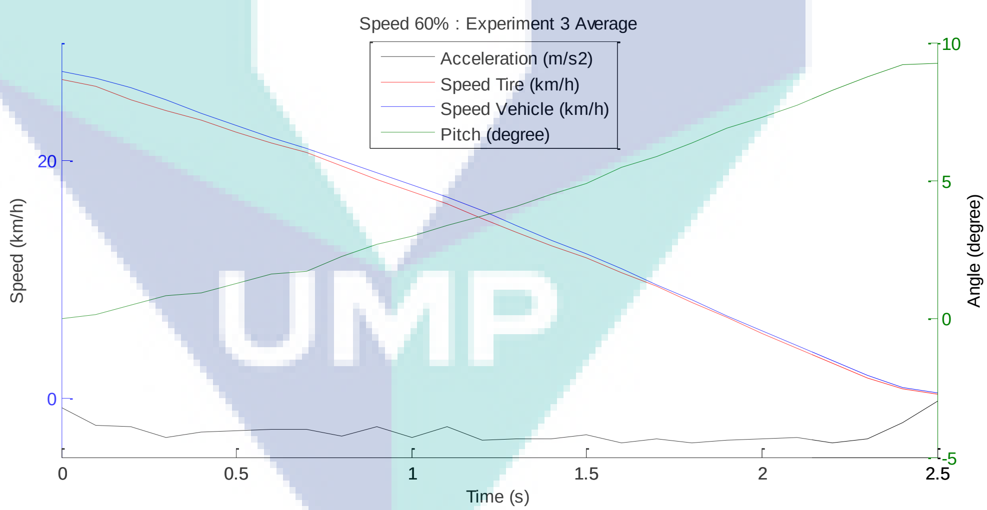

Figure **Error! No text of specified style in document.**.4.5 Experiment results for the average of Speed 60%: Experiment 3.

In Figure 4.4.6, the stopping time recorded is 2.7 s, and the pitch is recorded at 9.37°. It is relatively lower than the pitch produced for the experiment in Figure 4.4.5. The stopping distance recorded is 9.7 m.

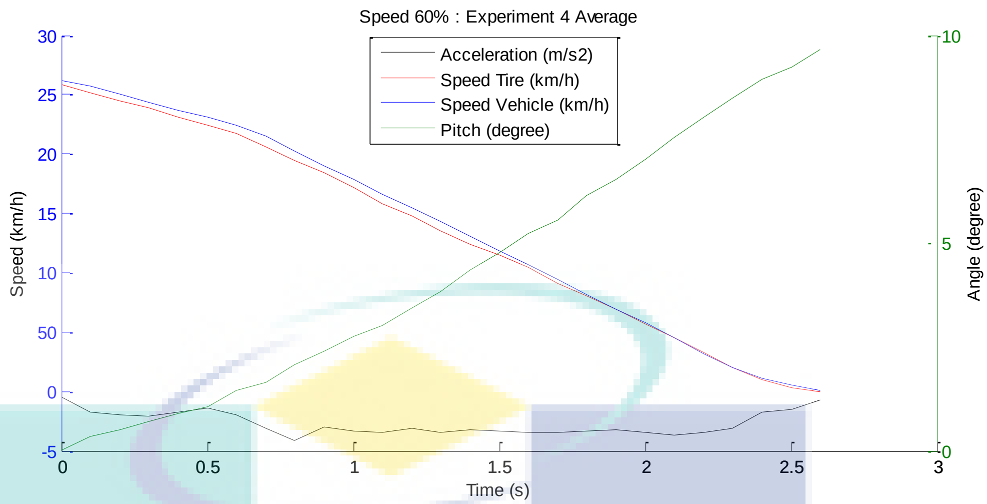

Figure **Error! No text of specified style in document.**.4.6 Experiment results for the average of Speed 60%: Experiment 4.

From Figure 4.4.7, there are improvements compared to the previous experiments for Speed: 60%. The average stopping time recorded was 2.5 s, whereas the highest pitch was recorded at 8.8°. For the stopping distance, it was recorded to only 9.34 m. For easier explanation, Figure 4.4.8 and 4.4.9 have summarised the results for the experiments of Speed: 60%.

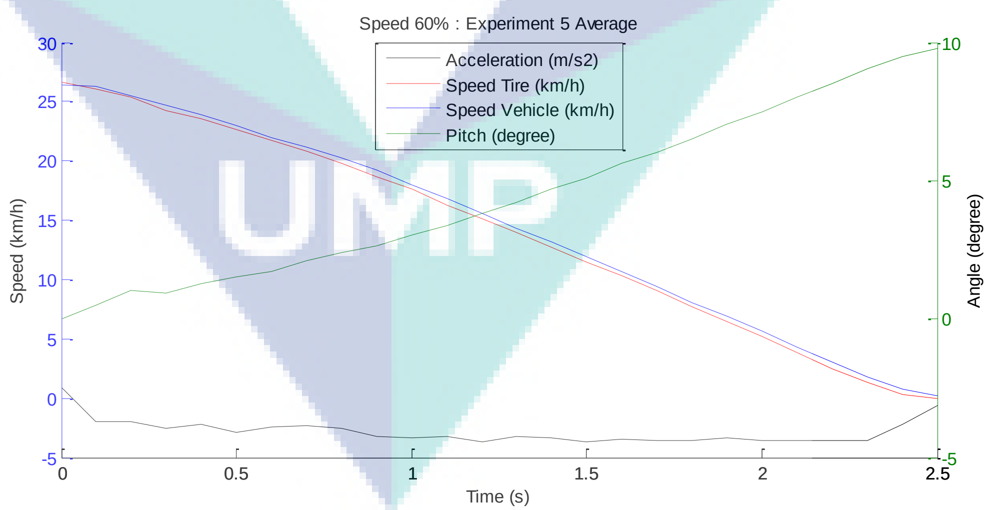

Figure **Error! No text of specified style in document.**.4.7 Experiment results for the average of Speed 60%: Experiment 5 Motor Brake 25%.

From Figure 4.4.8, it could be seen that the stopping time of Experiment 1 is the highest, whereas both Experiment 4 and 5 have almost identical stopping time. This is due to the 25% motor brakes are insignificant for the short duration of stopping time.

There are significant improvements for the stopping distance of the experiments for Speed: 60%. The shortest stopping distance recorded is 9.34 m, which is for Experiment 5, while the longest stopping distance is recorded at 24.5 m.

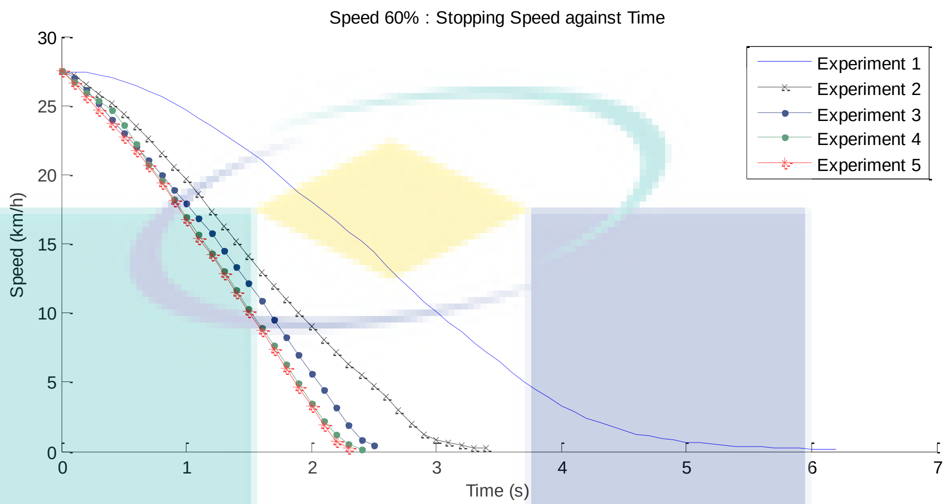

Figure **Error! No text of specified style in document.**.4.8 Experiment results for the average of Speed 60%: Stopping Time.

From Figure 4.4.9, the highest pitch recorded was for Experiment 2, which recorded to a whopping of 9.6°. This is due to only front disc brakes are used for this experiment. The lowest pitch is only 6.7°, recorded for Experiment 1. The main reason for the low pitch is due to the usage of only motor brakes which are located at the rear wheels of the EV.

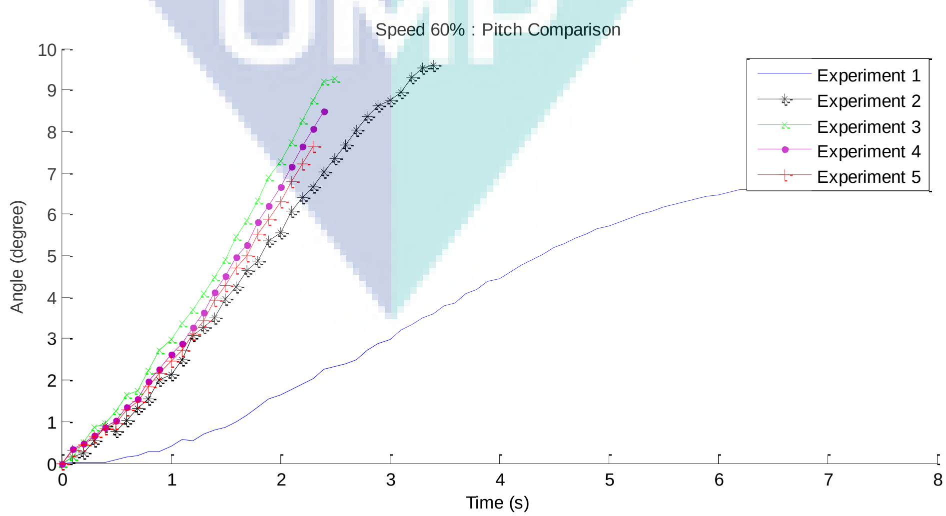

Figure **Error! No text of specified style in document.**.4.9 Experiment results for the average of Speed 60%: Pitch.

In Figure 4.4.10 and 4.4.11, there are significant improvements for the stopping distance with the deceleration rate. The higher the deceleration rate, the shorter time it is required for the vehicle to come to a complete stop. This can be proved with the values of deceleration rate in Table 4.4. The shortest distance was recorded to be at 9.5 m, while the longest distance was recorded to be at 24.5 m. By using the gyroscope sensor, the stopping distance can be calculated.

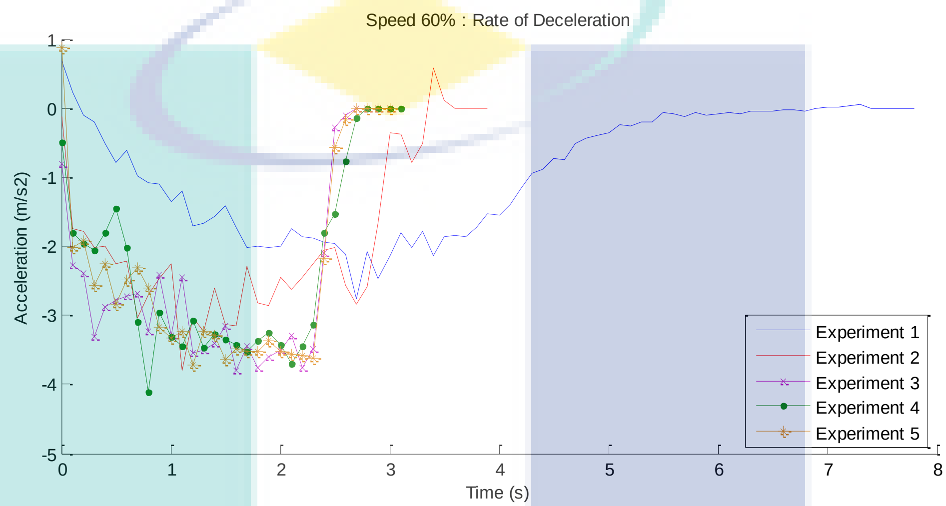

Figure **Error! No text of specified style in document.**.4.10 Rate of deceleration in Experiment: Speed 60%.

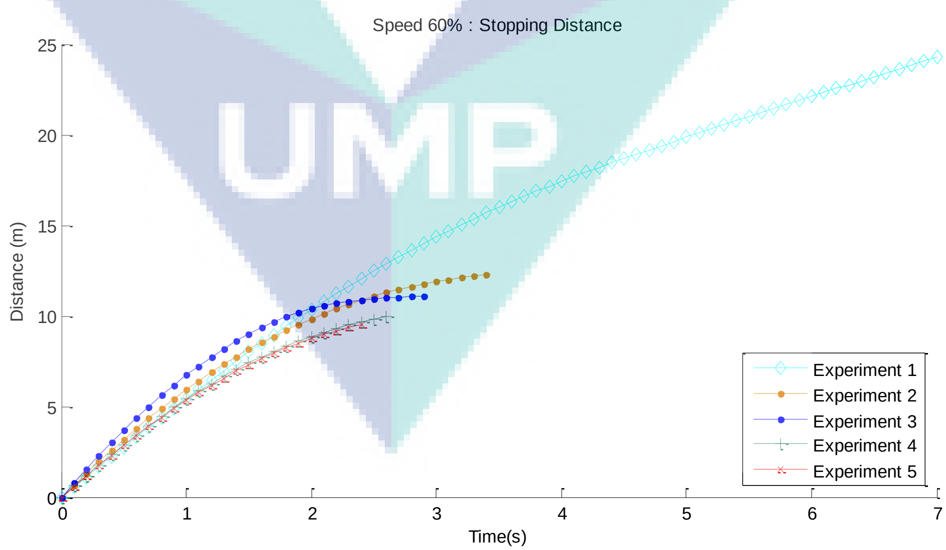

Figure **Error! No text of specified style in document.**.4.11 Stopping distance in Experiment: Speed 60%.

Table **Error! No text of specified style in document.**.3 Summary of experiments for speed: 60% Motor Brake 25%

Type of Experiments	Stopping Time (s)	Stopping Distance (m)	Pitch (°)	Deceleration Rate (m/s^2)
Experiment 1	7.2 s	24.5 m	6.7°	1.2346 m/s^2
Experiment 2	3.5 s	12.26 m	9.6°	2.509 m/s^2
Experiment 3	2.5 s	11.1 m	9.2°	2.5927 m/s^2
Experiment 4	2.7 s	9.93 m	9.37°	3.1112 m/s^2
Experiment 5	2.5 s	9.5 m	8.8°	3.2408 2

4.5 Speed 60% @ 28 km/h with 50% Motor Brake

For the difference of motor brake to 50%, there are 2 experiments conducted. The experiments are Experiment 1 and 5. These experiments are conducted again due to the usage of motor brakes with hydraulic brakes. Experiment 3 is not conducted because it is proved that Experiment 5 shows highest braking performance. Even though Experiment 3 is repeated, it will not show the highest braking performance though the performances improved. Experiment 2 and 4 are not repeated due to no usage of motor brakes.

From Figure 4.5.1, the stopping time is recorded at 5.8 s, and the stopping distance is recorded at 22.03 m. It shows improvements if compared to the Motor Brake 25%. The highest pitch is recorded at 7.91°. From the results above, it shows that the percentage of motor brake significantly improved braking performance. Thus, the braking method for motor brake can be considered as dynamic braking as the braking effort can be changed.

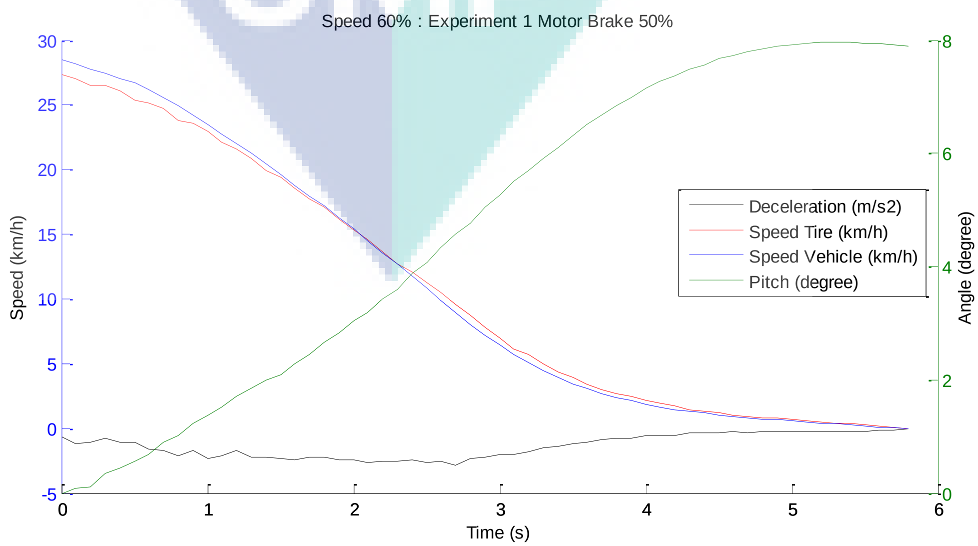

Figure **Error! No text of specified style in document.**.5.1 Average in Experiment: Speed 60% with Motor Brake 50%.

In Figure 4.5.2 and 4.5.3 shows the graph for the torque and power over time. Highest torque is recorded to be at -132.77 Nm while highest power is recorded at -2555.63 W. It shows a significant increase of the torque and power when compared to the motor brake 25% in Figure 4.4.2 and 4.4.3. The graph shows the actual results as well as the polynomial lines for an easier understanding. R^2 value for the torque is 0.9609 and 0.9718 for the power.

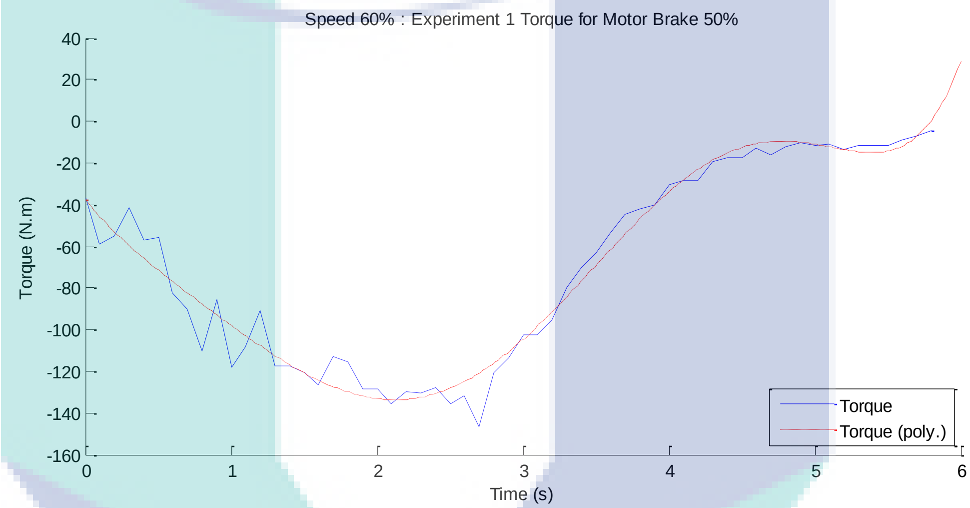

Figure **Error! No text of specified style in document.**.5.2 Torque for Speed 60%: Experiment 1 Motor Brake 50%.

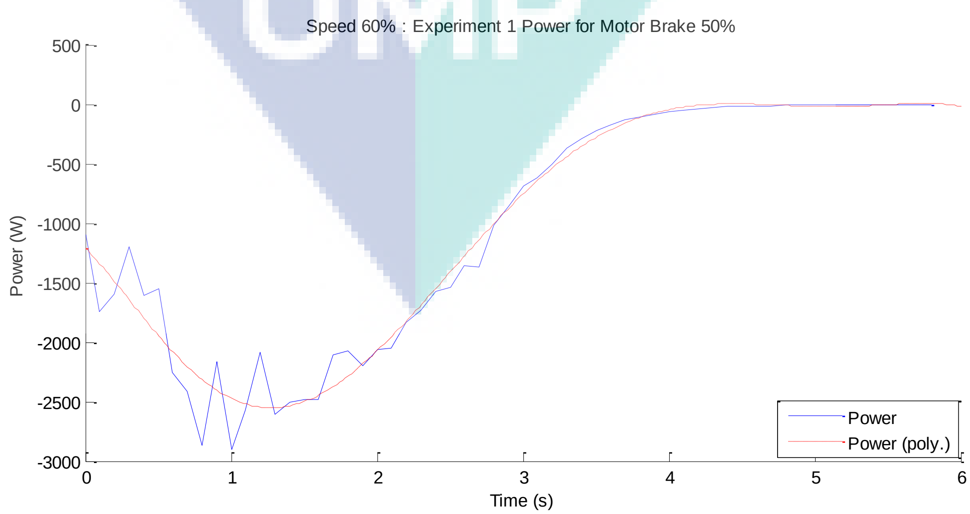

Figure **Error! No text of specified style in document.**.5.3 Power for Speed 60%: Experiment 1 Motor Brake 50%.

From Figure 4.5.4, 4.5.5 and 4.5.6, shows the comparison for the Motor Brake of 25% and 50%. For the deceleration rate in Figure 4.5.5, Motor Brake 50% shows a higher deceleration rate, which is 1.325 m/s^2 compared to Motor Brake 25% which is 1.2346 m/s^2. This relation gives the higher braking performance for Motor Brake 50% that acquire shorter braking time and distance. As for the torque and power production, Motor Brake 50% produced a higher value of torque and power.

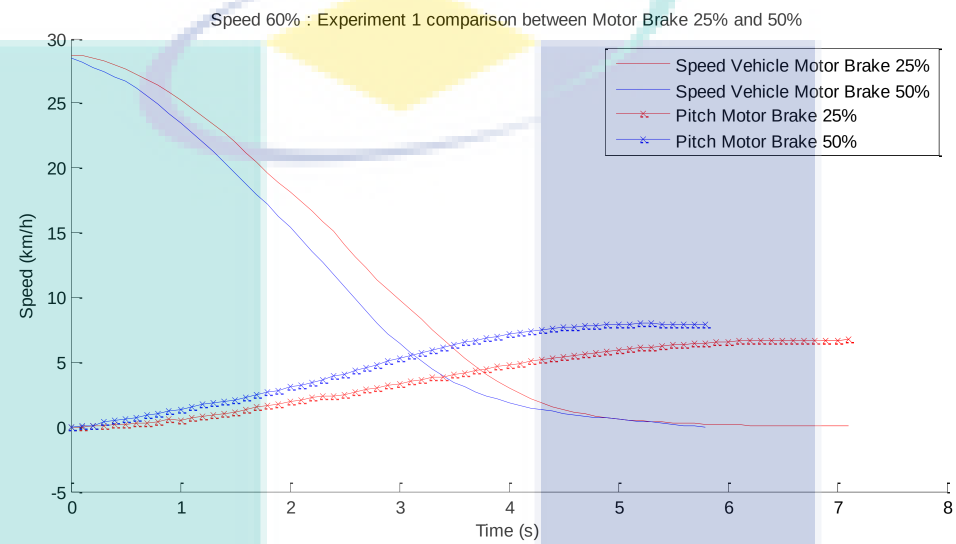

Figure **Error! No text of specified style in document.**.5.4 Comparison of stopping time for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

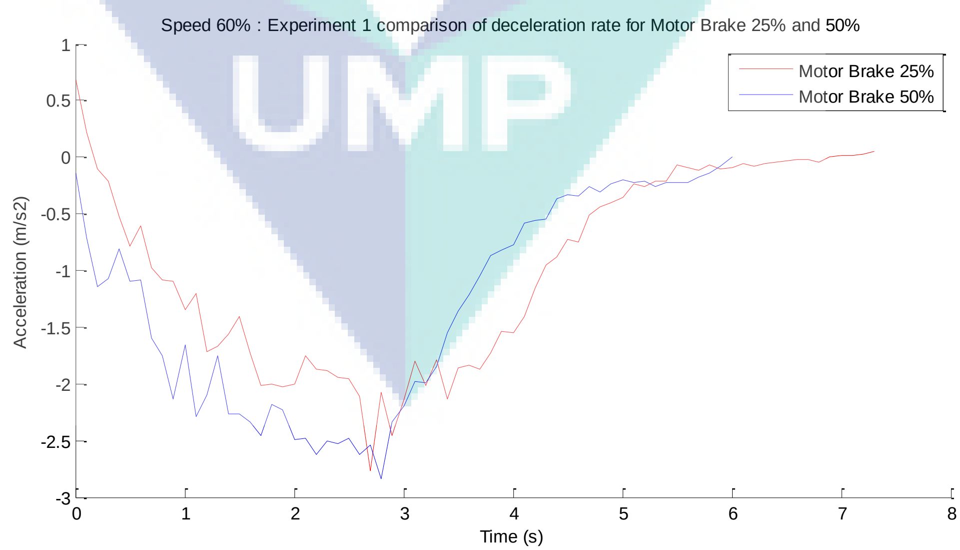

Figure **Error! No text of specified style in document.**.5.5 Comparison of deceleration rate for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

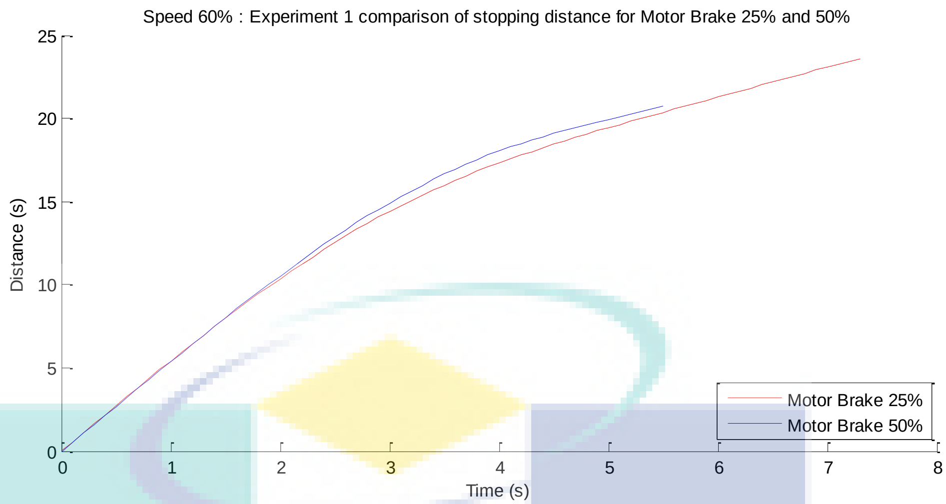

Figure **Error! No text of specified style in document.**.5.6 Comparison of stopping time for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

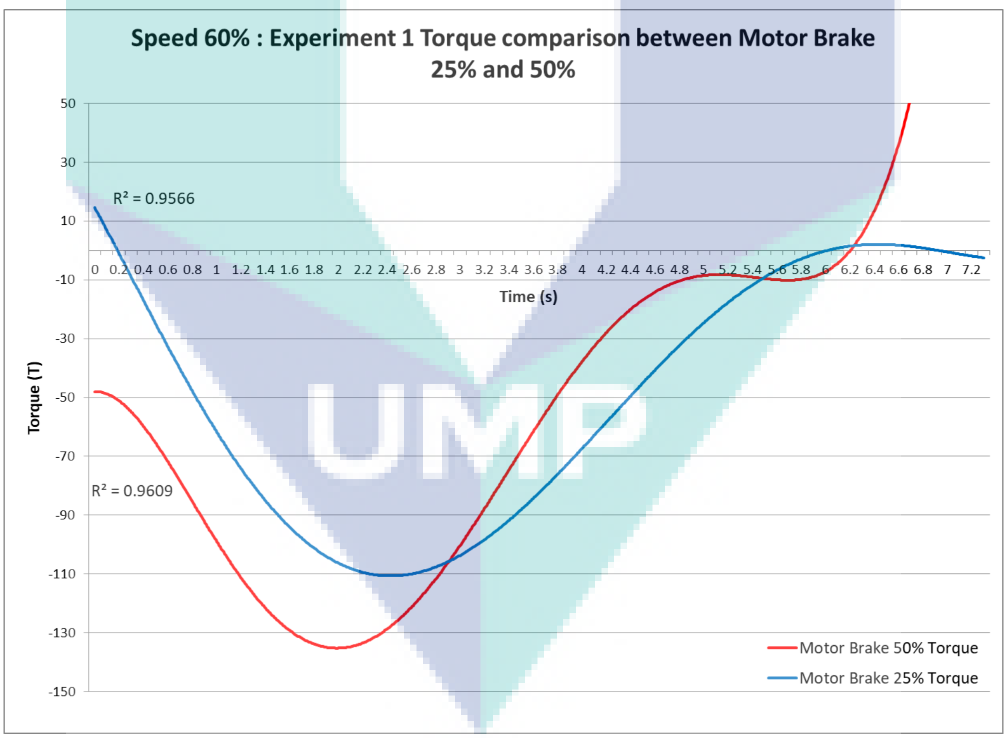

Figure **Error! No text of specified style in document.**.5.7 Comparison of torque for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

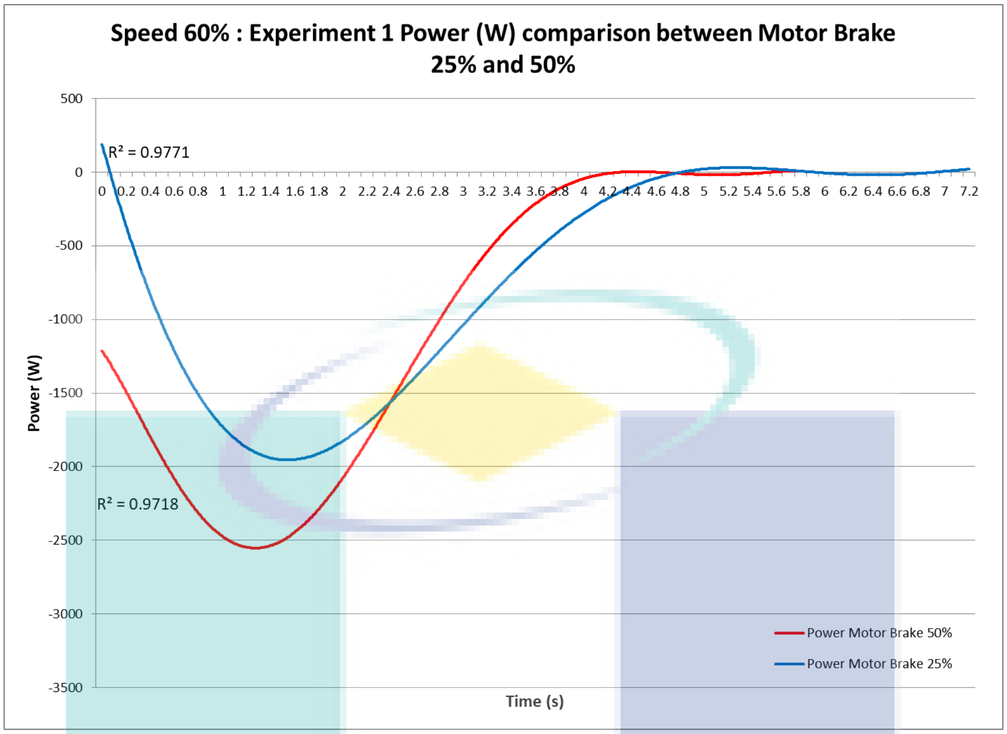

Figure **Error! No text of specified style in document.**.5.8 Comparison of power for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

Table **Error! No text of specified style in document.**.5 Results for Speed 60%: Experiment 1 with Motor Brake 25% and 50%

Motor Brake	25%	50%	Improvement
Time	7.2 s	5.8 s	22%
Distance	24.5 m	22.03 m	10%
Pitch	6.7°	7.91°	-18%
Deceleration Rate	1.235 m/s^2	1.325 m/s^2	6.8%
Max. Torque	-113 Nm	-133 Nm	15.3%
Max. Power	-1985 W	-2556 W	25.9%

In Figure 4.5.9, the stopping time is recorded at 2.27 s and stopping distance is recorded at 8.82 m. There are improvements if compared with the Motor Brake 25% in Figure 4.4.7. As for the deceleration rate, it shows that the Motor Brake 50% achieved the highest deceleration rate so far in the whole experiments, which is 3.456 m/s^2. Thus, from the deceleration rate as well as stopping time and distance, it proved that the higher rate of deceleration can improve the braking performance. Plus, from Figure 4.5.9, there are no tire-locking effects, as the forces applied to the pedal force during experiments are still not huge enough to lock the tires. Depending only to the human force would not be enough, and the pedal forces should be increased to achieve better stopping performance.

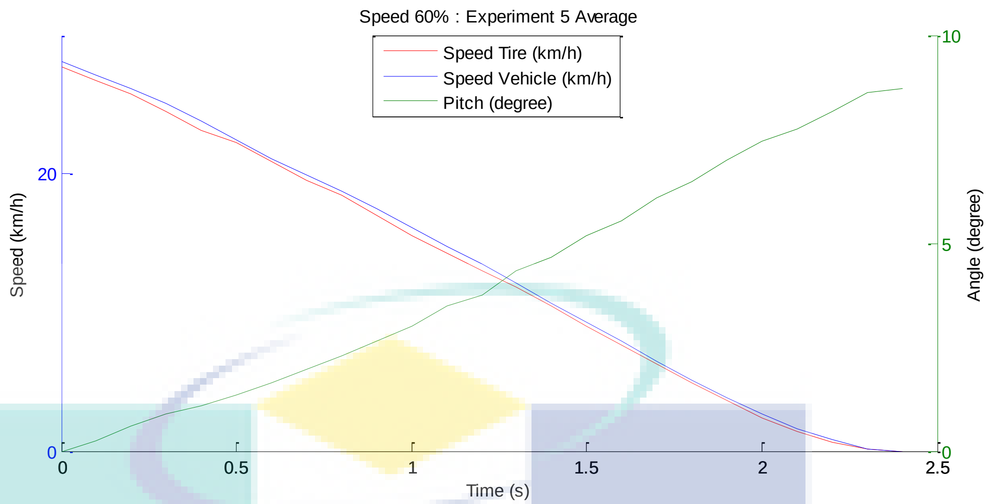

Figure **Error! No text of specified style in document.**.5.9 Average result for Experiment 5: Speed 60% Motor Brake 50%.

From Figure 4.5.10 and 4.5.11, there show the differences of deceleration rate as well as stopping time and distance. For the pitch, it shows that there only slight differences, from 8.8° for Motor Brake 25% to 8.4% for Motor Brake 50%. Human behaviour during braking could affect the pitch results. From Figure 4.5.12, there are slight improvements for the stopping distance. From 9.5 m to 8.8 m, it shows that there is an improvement of 0.7 m in stopping distance.

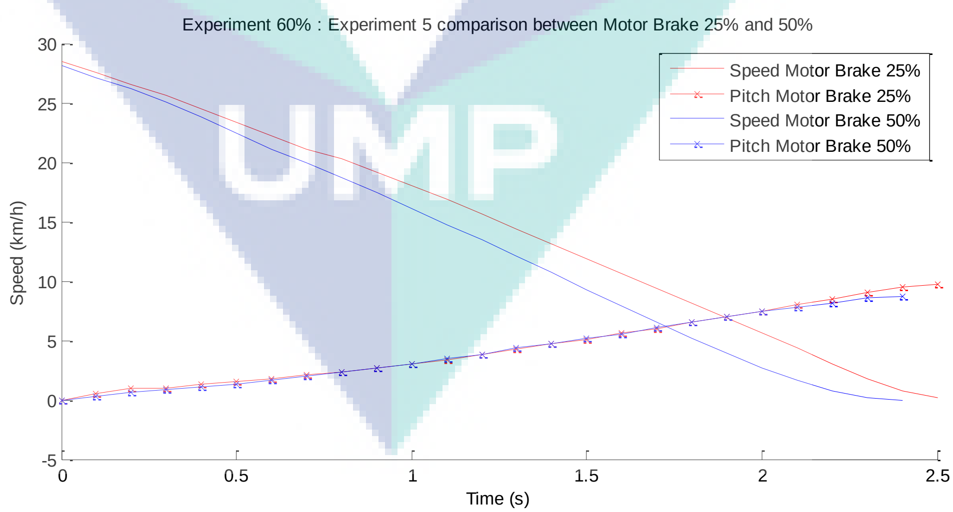

Figure **Error! No text of specified style in document.**.5.10 Results comparison for Experiment 5: Speed 60% Motor Brake 25% and 50%.

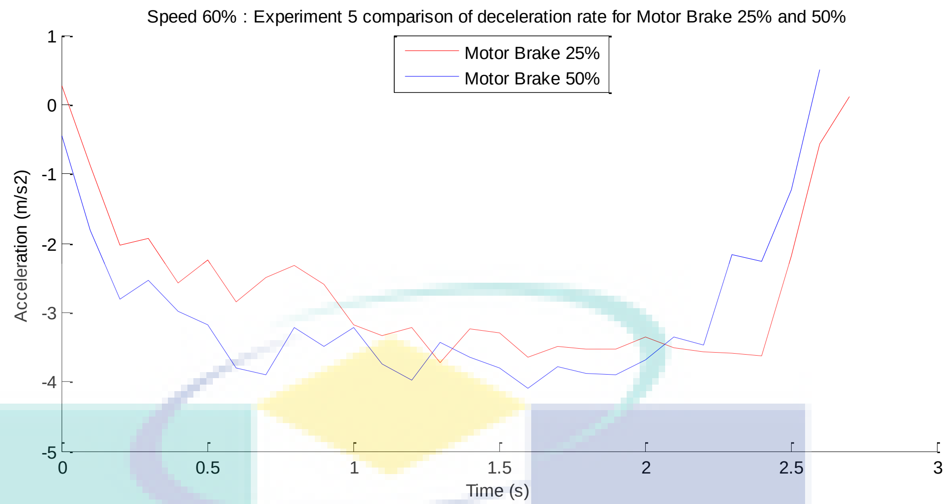

Figure **Error! No text of specified style in document.**.4 Comparison of deceleration rate for Experiment 5: Speed 60% Motor Brake 25% and 50%.

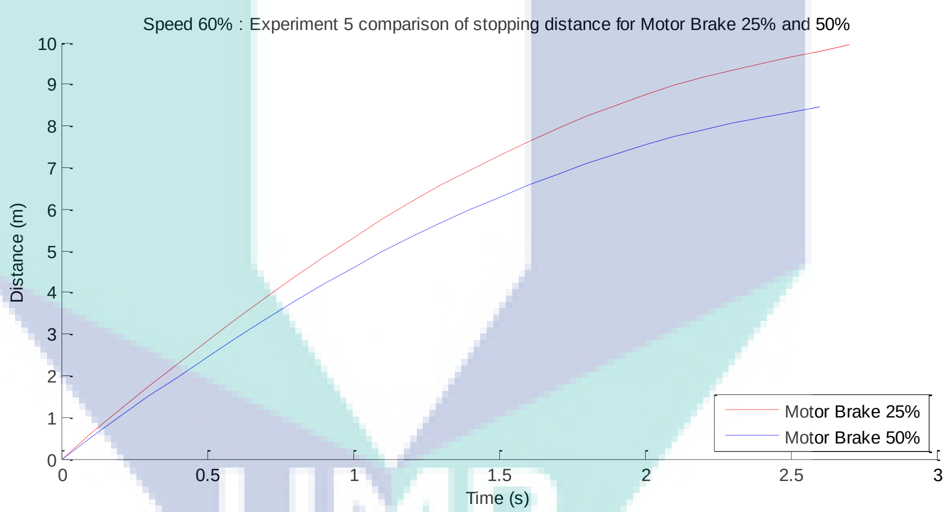

Figure **Error! No text of specified style in document.**.5 Comparison of stopping distance for Experiment 5: Speed 60% Motor Brake 25% and 50%.

Table **Error! No text of specified style in document.**.5.2 Results for Speed 60%: Experiment 5 with Motor Brake 25% and 50%

Motor Brake	25%	50%	Improvement
Time	2.5 s	5.8 s	19%
Distance	9.5 m	22.03 m	10%
Pitch	8.8°	7.91°	5%
Deceleration Rate	3.241 m/s^2	3.456 m/s^2	6%

Table 4.5.2 shows the summary results for Experiment 5 with Motor Brake 25% and 50%. It shows the improvements in all of the aspects, especially in the stopping time

and stopping distance. The deceleration rate is recorded as the highest for the whole experiments, which is 3.456 m/s^2 averagely. However, there is no torque and power graphs are evaluated as Experiment 5 is the combination of the whole methods of braking. Thus, the hydraulic mechanical brakes will affect a lot the results for the torque and power for the motor brakes. Due to that, the torque and power graphs are only evaluated for Experiment 1. As stated in the guidelines from the book of A Policy on Geometric Design of Highway and Streets 2001 by American Association of State Highway and Transportation Officials (AASHTO), a deceleration of 3.4 m/s^2 is recommended as the deceleration threshold for determining the stopping distance. It is recommended due to the capability of the drivers to be able to avoid unexpected objects or quickly changes lane during braking.

4.6 Validation of a Simulation Model

To validate the simulation according to the same data as in experiments, the results of experiments must be validated with results from the simulation using the conditions as from experiments (road condition, vehicle speeds). After the validation process has been made, the simulations will be made using different road conditions. The results from the validations must be at most only 10% difference with the results from the experiments. The experiment results are compared only for Speed 60% with Motor Brake 25%.

Table **Error! No text of specified style in document.**.5.1 Validation of simulation data for speed: 60%

Type of Exp.	Experiment		Simulation		Percentage Error	
	Stopping Time	Distance	Stopping Time	Distance	Stopping Time (%)	Distance (%)
Exp. 1	7.2 s	24.50 m	7.640 s	22.632 m	5.8%	7.6%
Exp. 2	3.5 s	12.056 m	3.072 s	11.610 m	12.2%	3.7%
Exp. 3	3.0 s	11.666 m	2.980 s	11.150 m	0.6%	4.4%
Exp. 4	2.7 s	9.7230 m	2.770 s	10.482 m	2.5%	7.3%
Exp. 5	2.5 s	9.3340 m	2.531 s	9.2860 m	1.2%	0.5%

In order to obtain the percentage error, Equation 4.6 is used. The normal percentage error between the experiments and simulation data will be within 10%.

$$Percentage\ Error, |\%| = \frac{Experiment - Simulation}{Experiment}$$

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From Table 4.5.1, the validation data of the experiments and simulations are identical to each other. The parameters of the simulation should be the same as the experiments (vehicle specs, friction, etc) so that identical data could be generated.

4.6 Simulation with Panic Braking Condition (ABS-OFF)

From the recent study of braking performance from the pedal force effect, it was recorded that the average pedal force exerted by the drivers are 400 N during a panic situation. There were around 599 correspondents involved during the experiments. Most of the drivers can exert at least 90 lbs of pedal force or 400 N in the SI scale.

From this, the average pedal force exerted is transmitted into the master cylinder by multiplying with the pedal force ratio. Then, the hydraulic line pressure is calculated, and the brake pressure applied to the brakes can be calculated too. Because there is no proportioning valve, the pressure in the hydraulic line would be the same for the front and rear brakes. The only difference is the disc brake piston size which will differentiate the brake force for the front and rear tires. There are no simulations involving panic braking for Experiment 1 because there are only motor brakes involved.

From Figure 4.6.1, the front tires are applied with the brake force, while there are no mechanical or motor brakes for the rear tires. Plus, the front tires are completely in a lock because the ABS function is turned off. The stopping time is recorded at 2.92 s, while the stopping distance is recorded at 10.9414 m.

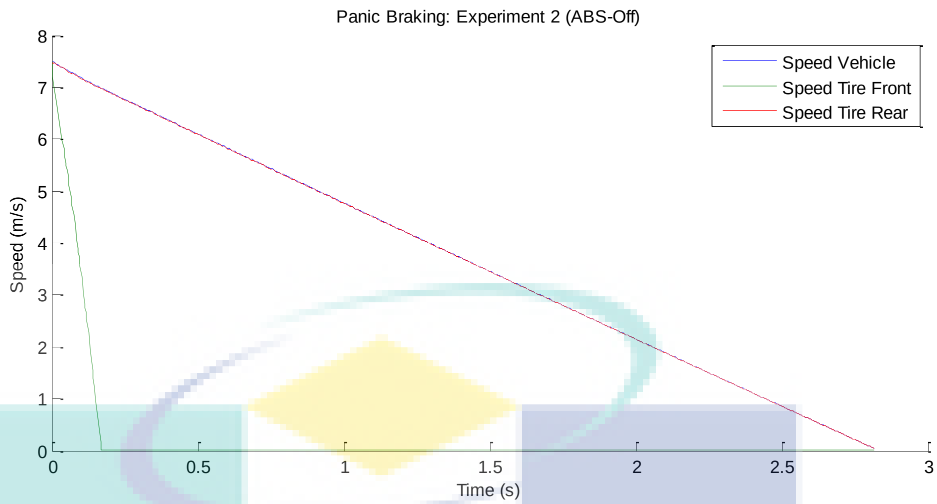

Figure **Error! No text of specified style in document.**.6.1 Simulation of panic braking for Experiment 2.

From Figure 4.6.2, the front tires are applied with the brake force, while rear tires are applied with the motor brakes force. However, there are no involvements of rear disc brakes. The front tires are completely in a lock, because the ABS function is turned off. The stopping time is recorded at 2.8422 s, while the stopping distance is recorded at 10.5576 m.

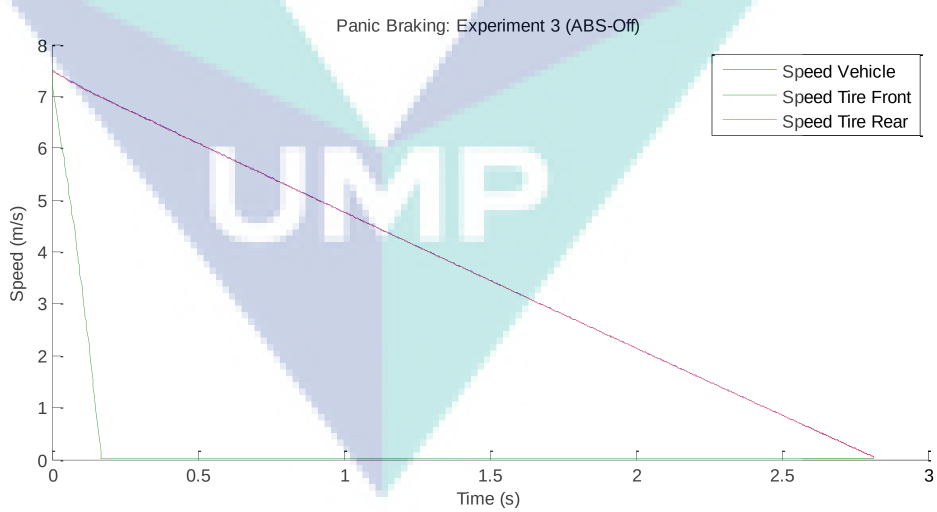

Figure **Error! No text of specified style in document.**.6.2 Simulation of panic braking for Experiment 3.

As in Figure 4.6.3, the front and rear tires are applied with the brake force, while no motor brakes force is applied to the rear tires. The front tires are completely in a lock because the ABS function is turned off. The stopping time is recorded at 2.3376 s, while the stopping distance is recorded at 8.7688 m.

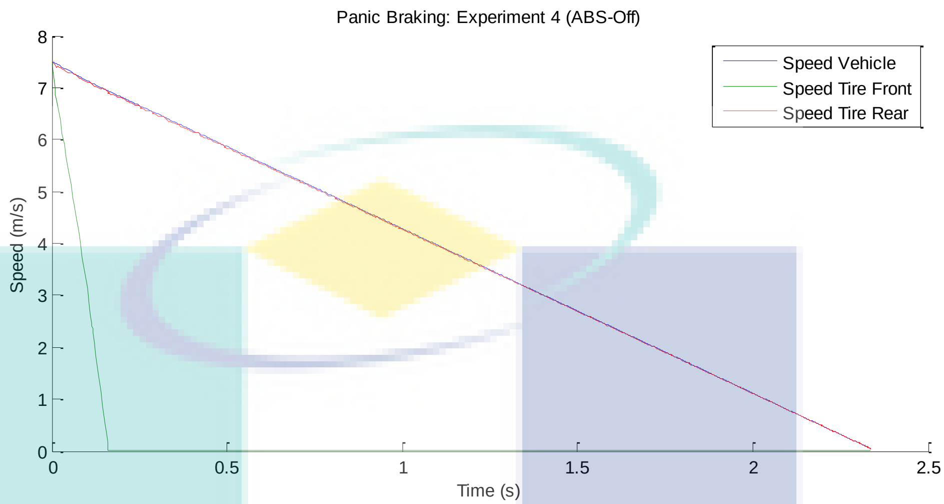

Figure **Error! No text of specified style in document.**.6.3 Simulation of panic braking for the Experiment 4.

As in Figure 4.6.4, the front and rear tires are applied with the brake force, while motor brakes force is applied to the rear tires. The front tires are completely in lock because the ABS function is turned off. The rear tires are not in the lock because the forces exerted are still low. The stopping time is recorded at 2.2886 s, while the stopping distance is recorded at 8.5273 m.

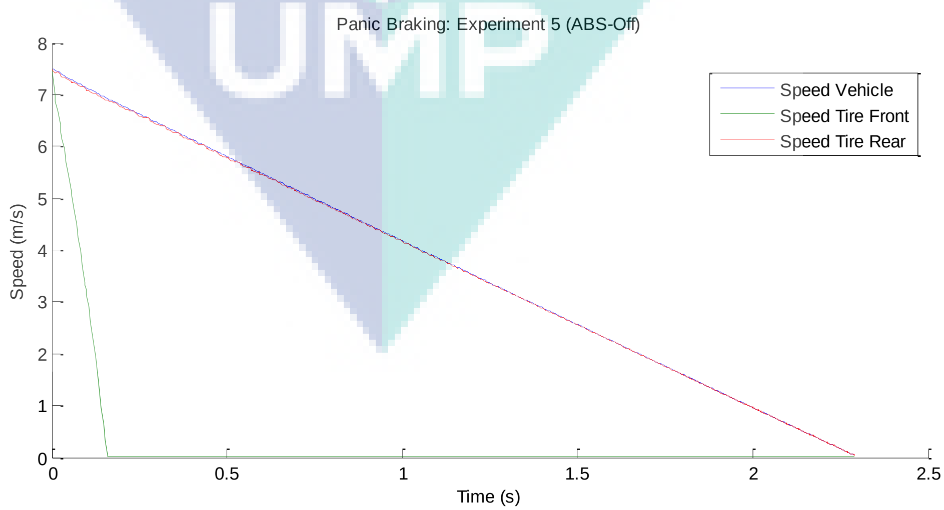

Figure **Error! No text of specified style in document.**.6.4 Simulation of panic braking for the Experiment 5.

Table **Error! No text of specified style in document.**.6.1 Simulation data for panic braking: (ABS-Off)

Type of Experiment	Stopping Time	Stopping Distance
Exp. 2	2.9199 s	10.9414 m
Exp. 3	2.8422 s	10.5576 m
Exp. 4	2.3376 s	8.7688 m
Exp. 5	2.2886 s	8.5273

4.7 Simulation with Panic Braking Condition (ABS-ON)

Using the same simulation blocks with the previous simulations, only the ABS function is added to the simulation. The ABS will prevent the wheels lock as well as avoid the vehicle from accidents. The ABS will improve braking performance, especially in terms of stopping time and stopping distance.

Figure 4.6.1 shows the simulation for only front disc brake forces is applied. On the rear tires, there are no mechanical brakes forces as well as motor brakes force. The stopping time recorded is 2.3869 s, while the stopping distance is recorded at 9.0249 m. As from the graph, the speed of the front tire is fluctuating, showing that the ABS has taken action against the slip ratio differences which would lock the tires during hard braking. For the simulation of panic braking using the braking method of Experiment 1, there are no possibilities of conducting the simulations because there are only motor brake forces applied to the EV. Thus, there will be no relation of pedal force to the motor brake forces.

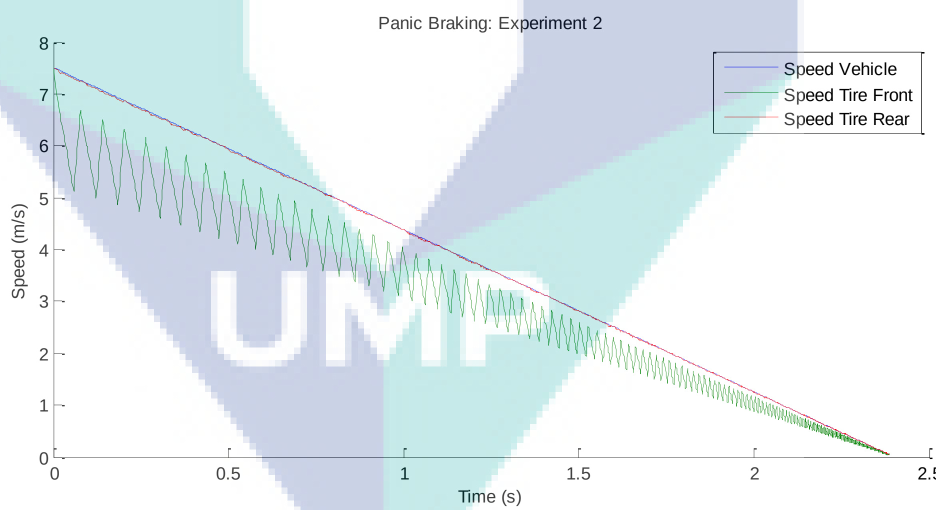

Figure **Error! No text of specified style in document.**.6.1 Simulation of panic braking for Experiment 2 (ABS-On).

From Figure 4.6.2, there are combinations of front disc brakes with the rear motor brakes. Only rear disc brakes forces are not applied to the simulation. ABS has taken effect to the front wheels due to the high braking forces during panic braking. The stopping time is recorded at 2.3253 s, and the stopping distance is recorded at 8.7187 m.

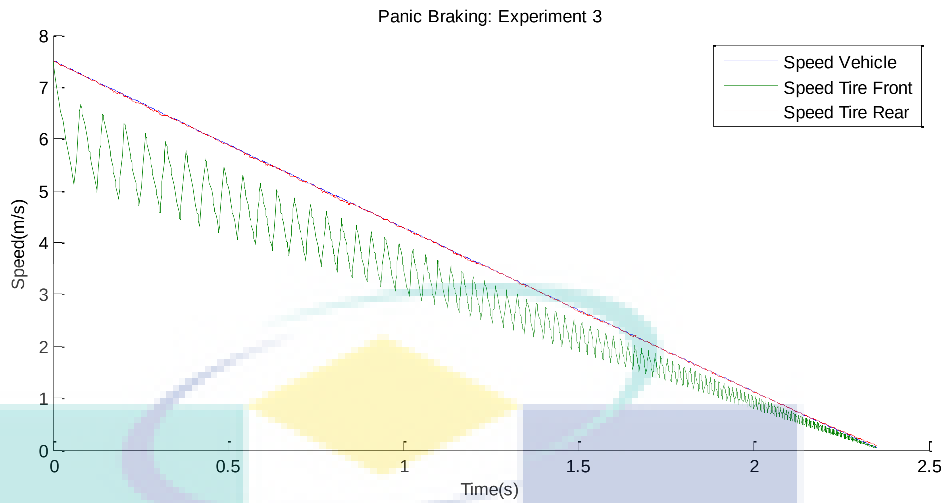

Figure **Error! No text of specified style in document.**.6.2 Simulation of panic braking for Experiment 3 (ABS-On).

For the simulation of Experiment 4 as in Figure 4.6.3, the stopping time recorded is at 2.0015 s and stopping distance is recorded at 7.5585 m. The improvement of stopping time and distance is due to the brake forces are applied to both front and rear disc brakes. Only motor brakes are not applied during the simulation.

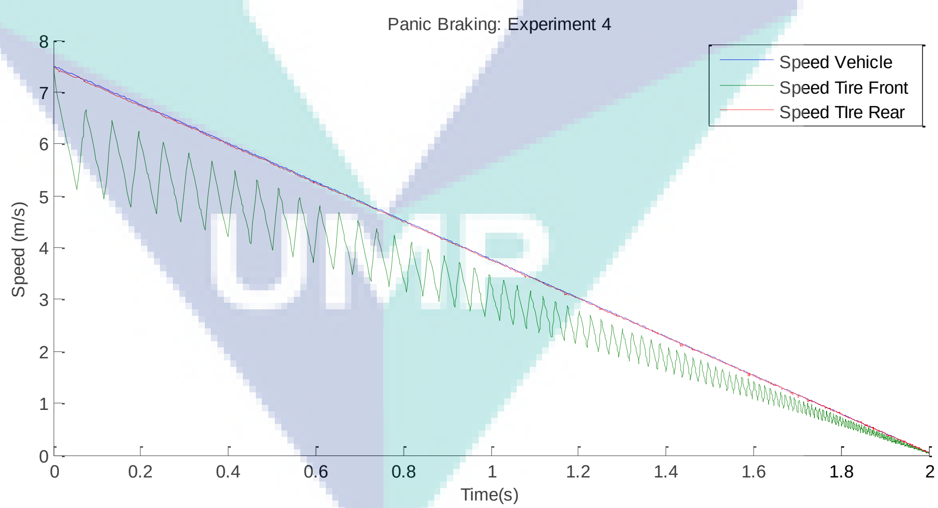

Figure **Error! No text of specified style in document.**.6.3 Simulation of panic braking for Experiment 4 (ABS-On).

From Figure 4.6.4, the front and rear disc brakes are applied to the simulation. Plus, the motor brakes are applied too at the rear tires of the EV. For the result, the stopping time is recorded at 1.9654 s, and the stopping distance is recorded at 7.3811 m.

From all the simulations above, it could be concluded that the fifth method of braking is the best braking method in terms of improving the braking performances.

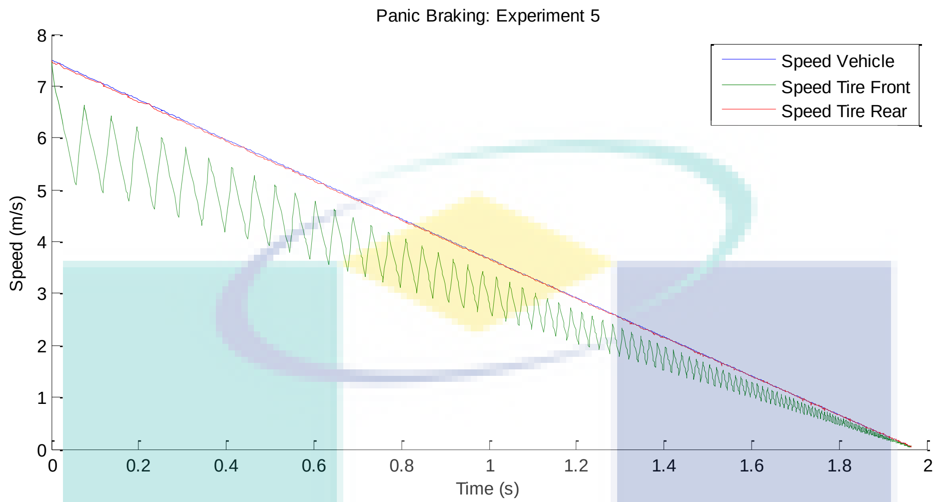

Figure **Error! No text of specified style in document.**.6.4 Simulation of panic braking for the Experiment 5 (ABS-On).

Table **Error! No text of specified style in document.**.6.1 Summary data for the simulation of Panic Braking.

Type of Exp.	ABS-OFF		ABS-ON	
	Stopping Time	Distance	Stopping Time	Distance
Exp. 2	2.9199 s	10.942 m	2.3869 s	9.025 m
Exp. 3	2.8422 s	10.558 m	2.3253 s	8.719 m
Exp. 4	2.3376 s	8.769 m	2.0015 s	7.559 m
Exp. 5	2.2886 s	8.528 m	1.9654 s	7.381 m

5. CONCLUSION

In this study, we analyzed the vehicle dynamics behaviour during emergency braking without ABS. The comprehensive analysis considered the longitudinal, lateral and vertical motions of the vehicle. The effect of an emergency braking to the longitudinal motion can be seen from the car’s velocity, the tire rotational speed and course travelled. Meanwhile, the effect at the lateral motion can be seen from the pitch angle. The longitudinal and lateral motions are the general motion that is used in the development of the ABS. However, this study extended to the effect at the vertical motion on each wheel. During emergency braking, the longitudinal deceleration of the car changed abruptly. As a result, more load is transferred from rear wheels to the front wheels, which caused the vehicle to dive forward. Besides analysis on vehicle behaviour during emergency braking, this study also can contribute to the development of anti-dive suspension. From the comprehensive study on the effect of the emergency braking without ABS to the vehicle dynamics behaviour, the essential of ABS can be acknowledged. In addition, the results also can be as a guideline for the validation of the full vehicle model and contribute to the development of anti-dive suspension.

After analysed the vehicle dynamic behaviour without ABS, a simulation model has been developed in MATLAB-Simulink. The simulation conducted to understand the dynamic behaviour of the vehicle during panic braking under dry condition. The simulation is set with two conditions; ABS and without ABS activated. The simulation results show that due to the sudden and large amount of braking torque, the tire is locked-up when ABS is not applied to the vehicle. In this situation, the vehicle is skidding and as a result, the stopping time and distance become longer. However, when ABS is applied to the vehicle, the optimum friction force is created between the tire and road surface. Therefore, the tire is not locked up and the vehicle is more stable than without ABS. It can be concluded that ABS can prevent the tire from locking up during panic braking and improve the safety of the vehicle.

A simulation model on a combination of ABS and regenerative brake control to prevent the small electric vehicle from skidding during braking on an icy road also has been developed. From the numerical analysis, during braking on an icy road, ABS is crucial because it can prevent tyre lock. The in-wheel motor can be an actuator of ABS to control the regenerative braking force produced from the in-wheel motor. From the simulation result, it is approved that our proposed model, ABS and regenerative brake control can improve the braking performance and safety of the small EVs.

ACHIEVEMENT

i) Name of articles/ manuscripts/ books published

1. International Journal of Automotive and Mechanical Engineering (IJAME), Investigation on Vehicle Dynamic Behaviour During Emergency Braking at Different Speed, 2019

2. IEEE Explore, 2018 SICE International Symposium on Control Systems (SICE ISCS), Skid control enhancement for small electric vehicle by using sliding mode control strategy, 2018
3. IOP Conference Series: Materials Science and Engineering, Comparison of braking performance between mechanical and dynamic braking for Electric Powered Wheelchair, 2019
4. AIP Conference Proceedings, Parameters estimation and calibration of BLDC motor for electric powered wheelchair, 2019

ii) Title of Paper presentations (international/ local)

1. 2018 SICE International Symposium on Control Systems (SICE ISCS), Skid control enhancement for small electric vehicle by using sliding mode control strategy, 2018
2. 1st International Postgraduate Conference on Mechanical Engineering (IPCME2018), IOP Conference Series: Materials Science and Engineering, Comparison of braking performance between mechanical and dynamic braking for Electric Powered Wheelchair, 2018
3. 3rd International Conference on Automotive Innovation Green Energy Vehicle, AIP Conference Proceedings, Parameters estimation and calibration of BLDC motor for electric powered wheelchair, 2019

iii) Human Capital Development

1. Muhammad Asyraf Bin Shahrom
2. Muhamad Sollehudin Bin Ibrahim

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