INVESIGATION ON DIFFERENTIAL BRAKING TORQUE CONTROLLER TO IMPROVE THE STABILITY OF SMALL IN-WHEEL ELECTRIC VEHICLE

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter will discuss the project that being conducted including project background, problem statement, objectives, scopes, project planning and thesis outline in detail.

1.2 Project Background

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 vehicles (EVs) become the alternative-design automobile to replace internal combustion engine vehicles (ICEVs). The driving system of EV is an electric motor where the electricity is supplied by batteries. It produces zero emission and the system operate smoothly and quietly. Thus, these advantages bring impact to the environment as well as human being. Compared to the ICEVs, electric automobiles are ninety-seven cleaner and producing no tailpipe emissions that brings negative impact to air.

1.3 Problem Statement

Although EVs can improve the environmental problem, the safety system of the EVs still need to be improved. During braking, the electric motor will generate the electric braking torque to reduce the speed as well as to stop the vehicle. The amount of electric braking torque from the electric motor need to be controlled to prevent the excessive braking torque to the wheels. Without braking control, the tire can be lock-up and the vehicle will be skidding.

In addition, the steer performance of small EV with in-wheel motor will decrease during accelerating and braking at the cornering. Due to the load that was concentrated at the in-wheel motor, the load distribution will become unbalance, especially when make a turning. To improve the steer performance, the braking torque at in-wheel motor need to be controlled.

1.4 Objective

1. To analyse the braking performance between hydraulic and electrical braking.
2. To develop the motor braking controller for small EV with two in-wheel motors
3. To investigate the steer performance during cornering with difference speed.

1.5 Scope of Project

- The experiment of braking performance between hydraulic and electrical will be conducted at difference electrical braking load.

- The electric braking controller will be developed in the MATLAB-Simulink, and the performance of the controller will be simulated.

- The performance of the electric motor braking controller will be analysed while braking at difference road condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The highlighted purpose of this chapter is to deliver a review of past research effort on EV and vehicle braking system. EV can be categorised into three types which are battery electric vehicle, plug-in hybrid electric vehicle and hybrid electric vehicle.

Besides that, braking systems can be divided to electrical and mechanical braking. Dynamic braking, plugging braking and regenerative braking are the three main types of electrical braking whereas mechanical braking includes disc brake and drum brakes.

Lastly, brake performance of an automobile plays an important role in the safety feature of vehicle. Therefore, performing braking test can determine the brake performance of vehicle whether it meets the criteria of good brake performance or it is not.

2.2 Electric Vehicle

As humanities realised how serious it is for the issue of climate change, everyone is trying to save the environment and natural resources. In the automotive industry, the awareness of the environmental problem has led to the development of energy efficient vehicles (EEVs). Nowadays, many countries actively promote electric automobiles to their citizens. The government also plays a big role by giving several privileges and provide the infrastructure for the electric vehicles (EVs). 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 Electro mobility Development Plan” that promoted by Germany encourage the industries for technology development and infrastructure construction with the gaol 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% and US 0.8%. 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. [1, 2]

EV is an automobile that uses an electric motor as the primary source of propulsion and the motor is run by electrical energy that stored in the rechargeable batteries. History of EV is much longer than people recognised. EVs were seen soon after Joseph Henry introduced the first DC-powered motor in 1830. The first known electric car was a small model built by Professor Stratingh in the Dutch town of Groningen in 1835. [3]

After a long era of research and experiment carried out by scientist and researchers, EV has become future trend of automobile world to replace the usage of gasoline engine vehicles. In 2018, there are three common types of electric vehicles selling in the market which are battery electric vehicle (BEV), hybrid-electric vehicle (HEV) and plug-in hybrid-electric vehicle (PHEV).

BEV generate through an electric motor and battery. BEV works without the need of a traditional internal combustion engine, all the power source generated purely from electrical energy. Besides that, BEV store electricity in high-capacity battery packs and the power from the battery is used to power up all electronics parts as well as the main-drive electric motor. Since BEV can only be powered by electricity, it must be plugged into an external source of electricity like electrical outlet or specialty electric vehicle charging stations to recharge its battery.[4]

HEV performs using two complementary drive system. It is a combination between gasoline engine and electric motor. Transmission will be turned when both engine work at the same time and wheels will be rotated as well after it receive the energy from transmission. HEVs are not same with BEV where its battery can be recharged in charging station. All energy of HEV come from gasoline and regenerative braking. Regenerative braking system in HEV generate electric power to help keep the batteries charged. When the driver applies the brakes, the electric motor turns into a generator, and the magnetic drag slows the vehicle down. [4]

PHEV is slightly different compare to HEV. It uses an electric motor with a battery that can be plugged into the power supply like high voltage wall plug to charge the battery whereas internal combustion engine still being used to drive the car when the battery of electric motor is running low. PHEV has a good feature where the battery can be charged at any ordinary 110-volt electric socket. Hence, it can extend the capacity of electric motor and bring the cars farther without the need of using ICE engine. With this great advantage, vehicle's fuel efficiency will be increased and PHEV users realize this type of EV have more saving in fuel cost compare to traditional hybrid vehicle. Nowadays, many car manufacturers focusing on plug-in-hybrid technology due to its high saving of fuel efficiency and lower emission of carbon dioxide (CO2), carbon monoxide (CO) and nitrogen oxide (NOx) gases. [4, 5].

2.3 Main Components of Electric Vehicles

Electric vehicle is propelled mainly by electric motors, motor controllers and rechargeable batteries. These three components work correlate with each other and if one of them is missing or faulty in the system, electric vehicles would not be started and driven smoothly. Batteries as the power source of electric vehicle will distribute current and voltage to the motor controller whereas electric motor received current and voltage from the controller and generates the electric energy to kinetic energy and rotates the wheels.

2.3.1 Electric Motors

Electric motor plays an important role of enabling electric car to work. It is a mechanical part which converts electrical energy to mechanical energy. For high performance electric car, driving motor should have a high speed, large starting torque and a wider speed range. In addition, in order to ensure the electric motor is working in the vehicle running form, electric motor should have a light weight, smaller volume, high efficiency and good energy feedback performance. [5]

There are two main types of electric motors which there are direct current (DC) motors and alternating current (AC) motors. DC motor is commonly used in electric vehicles compare to AC motors and it can be categorised to two types as brushed direct current (BDC) motors and brushless direct current (BLDC) motors. The working principle of BDC and BLDC motors are different and each of them has their own advantages and disadvantages will be discussed on following topic.

2.3.1.1 Brushed Direct Current (BDC) Motors

BDC motor is a long-established product and it is broadly used in a wide area from toys to push button adjustable car sears. It sells at a reasonable price, easy to use and available in various size and shapes. Thus, it is suitable for a low budget project. All BDC motors contain four basic components with a stator, rotor, brushes and a commutator. Structure of BDC motor is shown in Figure 2-1.The following paragraph will further explain the function of each components. [6]

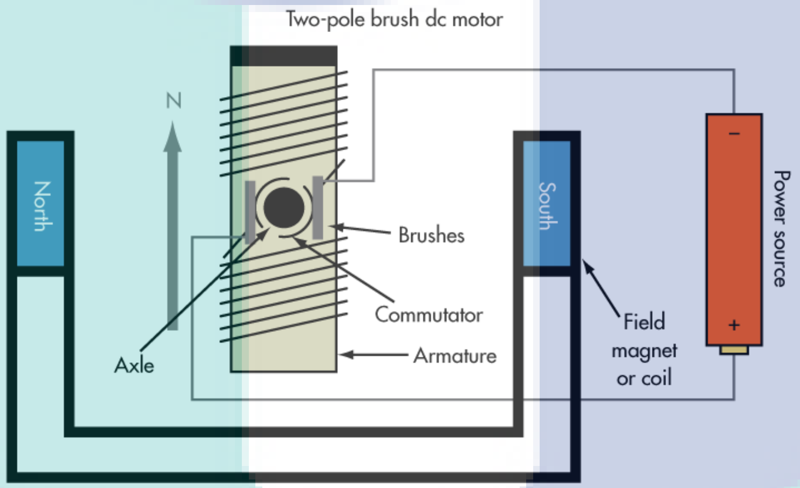


Figure 2:1 Structure of BDC Motor [6]

Stator creates a stationary magnetic field that loops the rotor. The magnetic field is formed by either electromagnetic windings or permanent magnets. Then, types of BDC motors can be distinguished by structure of stator or the way of electromagnetic windings connected to the power source.[6]

The rotor usually called as the armature is made up of one or more windings. Then, this winding in the rotor are energised by current and produce a magnetic field. Opposite poles that generated by the stator will attract the magnetic poles of rotor and enable the rotor to turn. As the motor is turning, the windings are being energised continuously in different sequence so that the magnetic poles formed by the rotor do not overrun the opposite poles generated in the stator. This switching of the field in the rotor windings is called commutation.[6]

BDC motor is different with other type of motor. It does not need controller to switch current in the motor windings. Instead, BDC motor use a segmented copper sleeve located on the axle of motor, called a commutator to commutate the windings of motor mechanically. When the motor turns, commutator will be slid over by carbon brushes coming in contact with different segment of the commutator. This segment will be attached to different rotor windings and enable the motor to generate a dynamic magnetic field when a voltage is applied across the brushes of motor. Moreover, brushes and commutator play an important role in the working mechanism of BDC motor and they can be wore since they are sliding past each other. A clear structure for parts of BDC motor is shown in Figure 2.2.[6, 7]

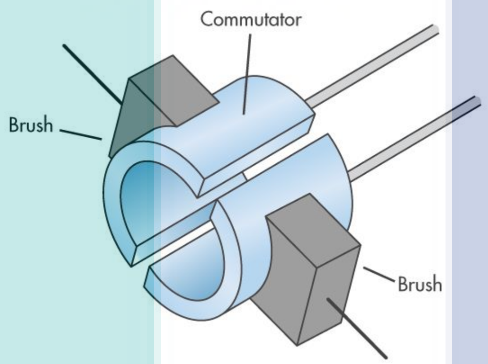


Figure 2:2 Parts of BDC motor [6]

2.3.1.2 Brushless Direct Current (BLDC) Motors

Brushless direct current motors shown in Figure 2-3, also called Permanent Magnet Brushless DC Motors (PMBLDC), do not contain brushes in its design. Stator of BLDC motor consist of electromagnet that does not rotate while the rotor contains rare earth magnets. In order to make the motor spin, changing of polarity is controlled by a motor controller and it makes BLDC motor more precise and efficient. Without the brushes, BLDC motor has less variable motor constants and properties and most importantly reduce frictional losses. Moreover, when the electromagnets locate in the stator, it makes the motor much easier to cool and thus motor is able to run at a higher power without overheat the motor's component.[7]
Then, for BLDC motors, mechanical switching that used in BDC motors is replaced with electronic switch and controlled by electronic circuit. Hence, it enhances the reliability of

product and give a longer operating life to the users. BDC motors in practice give more disadvantages to the users such as noise created by brush friction, generation of sparks and it has a limited life due to brush wear.[7]

Besides that, stator's winding circuit in BLDC motors drive magnetic force to enable the rotation of permanent magnet rotors. Next, for current switching of BLDC motors, hall sensors have to be matched up with electronic circuit to complete the current switching process. On the other hand, BLDC motors can be controlled by sensor or sensor-less mode. Sensor-less mode brings advantages to the user by omitting the sensing part and thus operating cost will be cheaper. However, sensor-less mode needs a higher requirements on controlling algorithms and it needs more complex electronic circuit parts to drive the motor.[7]

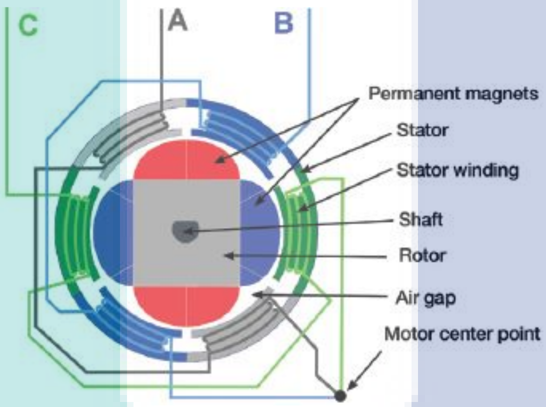


Figure 2:3

2.3.2 Motor Controller

A motor controller is a device that acts as intermediary between motor and batteries and help in regulating the manner in which a motor works. When it receive the supply voltage from battery, it will provide signals to motor drives and runs the motor. It can be used to start, stop and run motors in a programmed manner. Besides that. Speed of motor, torque can be increased gradually and rotational direction can be reverse when motor controller is applied.

Working principle of motor controller basically use the Hall Effect sensors to decide the orientation of rotor and magnetic field is applied perpendicular to the rotor magnets. For controlling the speed of motor, Pulse Width Modulated (PWM) concept is used. Speed of the motor can be accomplished by measuring the time for hall sensors to go through full rotation which equivalent to one revolution of motor. [8]

2.4 Braking System of Vehicle

Brakes are the most essential mechanism on any automobiles because the safety and lives of driver and passengers depend on the adequate operation of the braking system. For a light vehicle, it is predictable that brakes can be applied on average 50,000 times per year.[9]

All braking system are used to lower the speed and stop a moving vehicles or to avoid the vehicles from moving if the car is stationary. Nowadays, electrical braking and mechanical braking are two main kind on braking system use in automobiles. For modern cars like hybrid or battery electric vehicle, both electrical and mechanical braking system are applied in the vehicle braking system to optimum the brake efficiency and stop the car within shortest period. Electrical braking is effective on reduce the speed and mechanical braking is used to fully stop the automobile. If only electrical braking applied in the system without mechanical braking, emergency braking or parking braking cannot be achieved and this is the reason why mechanical braking are still employed in the modern vehicle. Detail explanation on electrical and mechanical braking system will be discussed on the subchapter below.

2.4.1 Electrical Braking System

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. Paragraph below will further explain each type of electrical braking on their working principle as well as advantages and disadvantages.

2.4.1.1 Dynamic Braking

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 raking 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. [10]

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 Fig 2.4 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. This is the main working mechanism of dynamic braking but actually there are four different techniques of dynamics braking where they are discussed in detail below.[11]

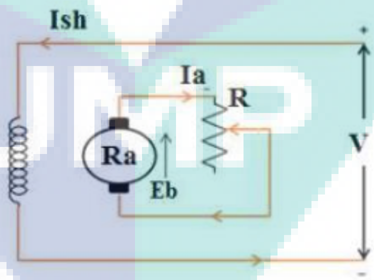


Figure 2:4 Concept of Dynamic Braking [11]

For this type of dynamic braking, when the three phase induction motor is cut off from the supply, rotor at the motor will continue to spin due to inertia and stator windings will induce emf. During this stage, if there is a capacitor with suitable value is linked across with the stator terminals, excitation stage will be continued by the terminal capacitor. However, magnetic saturation will limit the induced emf and the whole process is known as capacitor self-excitation. In this phenomenon, rotor magnetic circuit will produce energy and the capacitor will store the energy. Hence, the motor are now act as a generator. Electric power that generated from the generator will be dissipated in the inherent resistance of the windings. When the whole process is completed, braking can be performed. For this type of dynamic braking, kinetic energy is lost more rapidly when brake is applied. A circuit diagram of capacitive braking is shown in Fig 2.5. For enabling the machine to be self-excited, a minimum capacitance is needed and under usual cases, value excitation capacitance must be larger than a specific capacitance only can run this capacitance braking.[10]

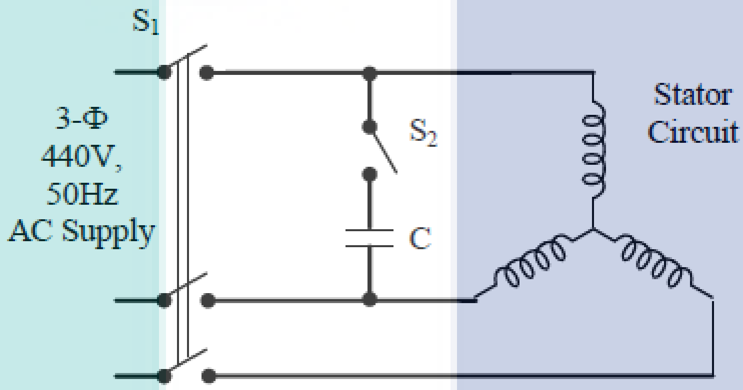


Figure 2:5 Capacitor Braking [10]

2.4.1.2 DC Injection Braking

The second type of dynamic braking is known as dc injection braking. For this type of braking, zero-frequency current as input transfer to the stator winding and produce zero air-gap power. Braking torque can be produced at poly-phase induction motor by replacing the ac voltage on the stator winding with dc voltage as shown in Fig 2:6. During this stage, when the dc voltage is supplied to the stator windings of induction motor, induction motor will be inverted after two of the three stator has been supplied by dc voltage. Now, the rotor of induction motor becomes a rotating armature and the stator becomes the field. At that instant, the braking torque and rotor current become zero. This phenomenon is known as DC injection braking and it is suitable to stop a rotating object at high speed and braking torque is small.[10]

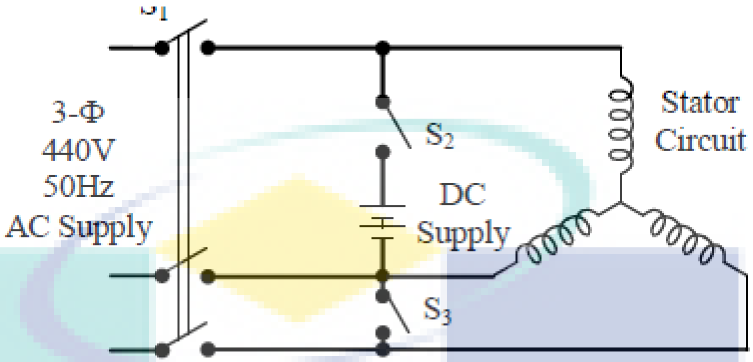


Figure 2:6 DC Injection Braking [10]

2.4.1.3 Magnetic Braking

Magnetic braking can be performed by shorting two or three stator lead after the magnetic field has been assured and the main ac supply has been cut off. The circuit diagram of magnetic braking can be seen in Fig 2:7. For this type of dynamic braking, no additional input energy is needed and thus it generates less heat energy because it only need kinetic energy to rotate the drive shaft. Magnetic braking works based on induced current and Lenz's law. A small example of relating the concept of Lenz's law is when a metal plate is connected to the end of a pendulum and let it swing, the speed will be significantly declined when the pendulum enters the poles of magnet. This phenomenon can be occurred because the electric field is induced when the plate entering the magnetic field and eddy current is created during this phenomenon. The current produced used to oppose the change of magnetic flux through the plate and in turn will reducing the object once the current dissipate the energy from the plate.[10]

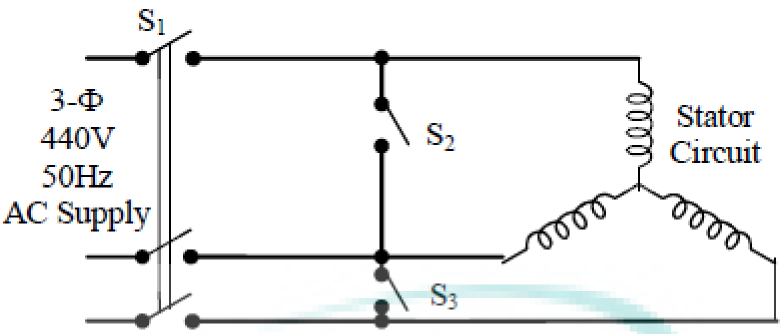


Figure 2:7 Magnetic Braking [10]

2.4.1.4 Zero-Sequence Dynamic Braking

Circuit diagram of zero-sequence dynamic braking is shown at Fig 2.8. This type of dynamic works when three stator windings of the electric motor linked in series and either ac or dc voltage is supplied to two stator terminal and thereby a resultant stationary field will be created. Such connection is named as zero-sequence connection because the current in all stator windings are co-phasal. There is a creation of magnetic field caused by current of zero sequence which the number of poles are three times greater than the actual magnetic poles in the machine. However, zero-sequence dynamic braking cannot return the kinetic energy at the rotor to the electric supply which meant the kinetic energy produced in zero-sequence braking cannot be converted into a useful electrical energy. [10]

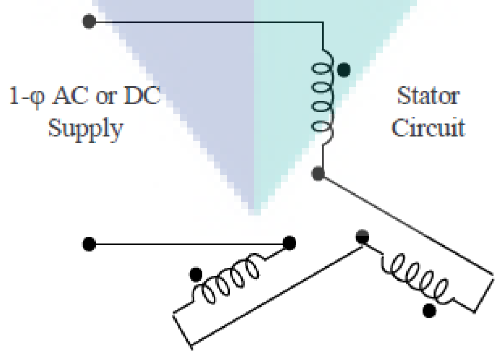


Figure 2:8 Zero-sequence Dynamic Braking ([10]

From all four types of dynamic braking stated above, dynamic braking is well-known because of its high performance and efficiency in any speed, regardless of boosting. However, it has a disadvantage when the speed of motor is low due to high braking torque is required to stop the vehicle or in other words, the amount of electrical braking is insignificant in slower speed and this braking system is not possible to stop a slow-running vehicle.

2.4.1.5 Plugging Braking

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. Working mechanism of plugging braking will be explained in detail on paragraph below.[12]

For traditional plug braking, shown in Fig 2:9, 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.[10]

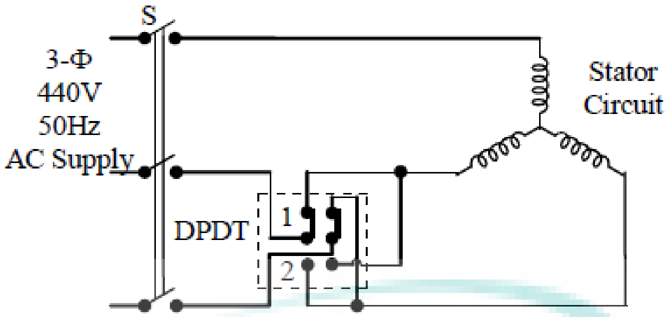


Figure 2:9 Plugging Braking [10]

2.4.1.6 Regenerative Braking

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". [13]

Instead of wasting the kinetic energy from the automobile and dissipate as heat, regenerative braking convert the kinetic energy into electrical energy and store 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 Fig 2:10. 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. These two type of regenerative braking will be discussed in detail on the following paragraph.

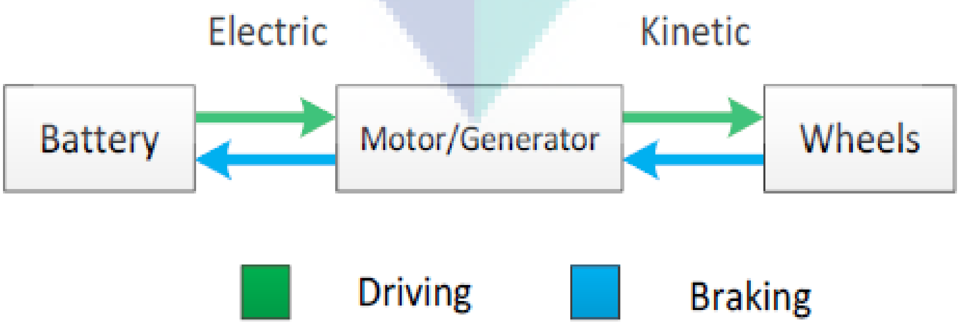


Figure 2:10 Flow of energy using regenerative braking [13]

Motor based regenerative braking system commonly used in electrical or hybrid automobiles. Electric motor in the EV connect the drive shaft and when current is delivered to the electric motor, it start to runs and in turn rotates the drive shaft of cars. On the other hand, when the driver tends to slow down or stop the vehicle, brake pedal is pressed and the current supply to the motor will be disconnected. At that instant, electric motor is no longer supplying torque to the drive shaft, instead, inertia and momentum properties that remain during accelerating will drive the motor. Now, electric motor act as a generator opposing the inertial rotational motion and slow down the car. In this phenomenon, electricity is generated and it can be stored in battery or capacitor and it is shown in Fig 2:11.[14]

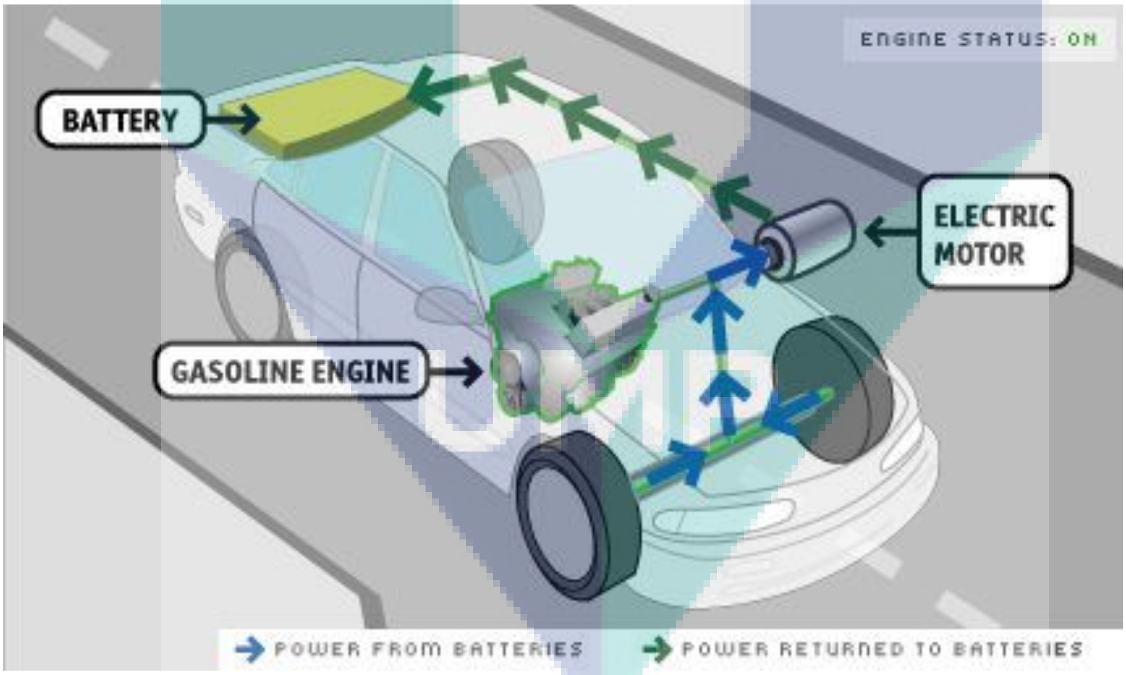


Figure 2:11 Energy flow diagram for Motor Based Regenerative Braking [14]

Next, for the operation of electric motor shown in Fig 2:12, it runs in one direction at an instant, when it run one direction, current from electric motor to wheel generate electrical energy to mechanical energy, it accelerate the vehicle. When the direction change to opposite direction, the current flow from wheel to electric motor, the motor is now act as a generator and convert mechanical energy to electrical energy. The regenerating electrical energy will store in battery and it can use for braking purpose or recharging the battery [14].

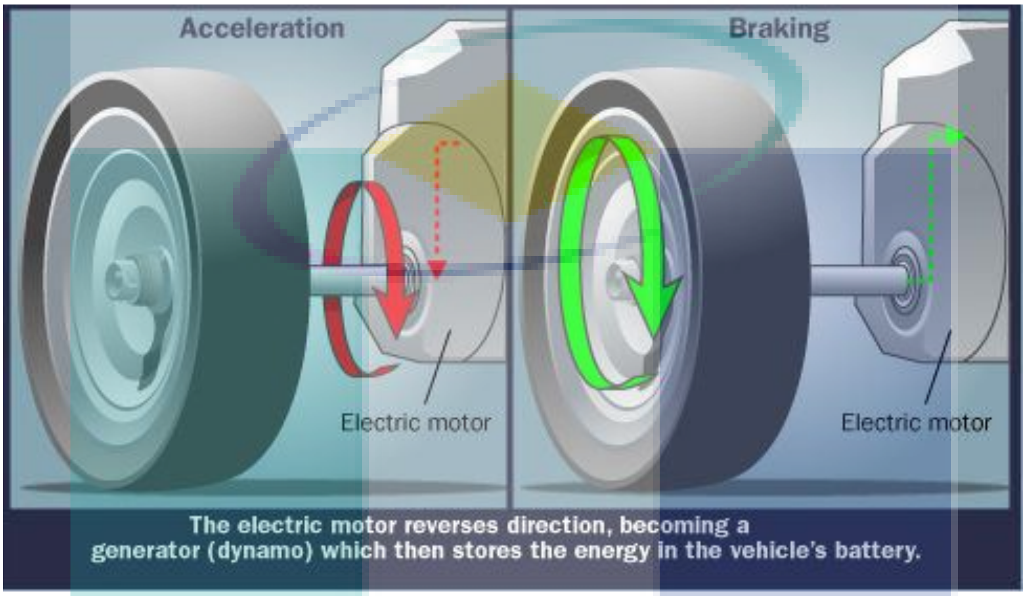


Figure 2:12 Operation of Electric Motor on Regenerative Braking [14]

Flywheel use to store mechanical energy and the stored energy is used when it is needed during acceleration. It is a heavy, high speed rotating disc that produce kinetic energy when it spins. Next, volume of energy stored by flywheel depends on how fast it spins and how heavier it is. Faster rotating speed and heavier weight can create higher energy storage.

Operation of flywheel based regenerative braking shown in Fig 2:13 occur when the driver presses the brake pedal, flywheel is engaged with the drive shaft and produce an engaged power. The engaged power is then divided between drive shaft and flywheel. With this power, there is a large amount of inertia on flywheel absorb the power from engine in the form of kinetic energy and stop the vehicle. Besides that, this kinetic energy can be further use for accelerating the vehicle. [14]

By using flywheel based regenerative braking, the transmission of energy is directly transmitted to the vehicle. Thus, vehicle has better performance than the energy generates from battery because it need conversion of energy to move the automobiles. This kind of regenerative braking has no transmission losses because the energy stored in the flywheel is directly shifted to the car in its original form. Hence, this kind of braking system is commonly used in F-1 cars due to its high efficiency and continuous energy supply.[15]

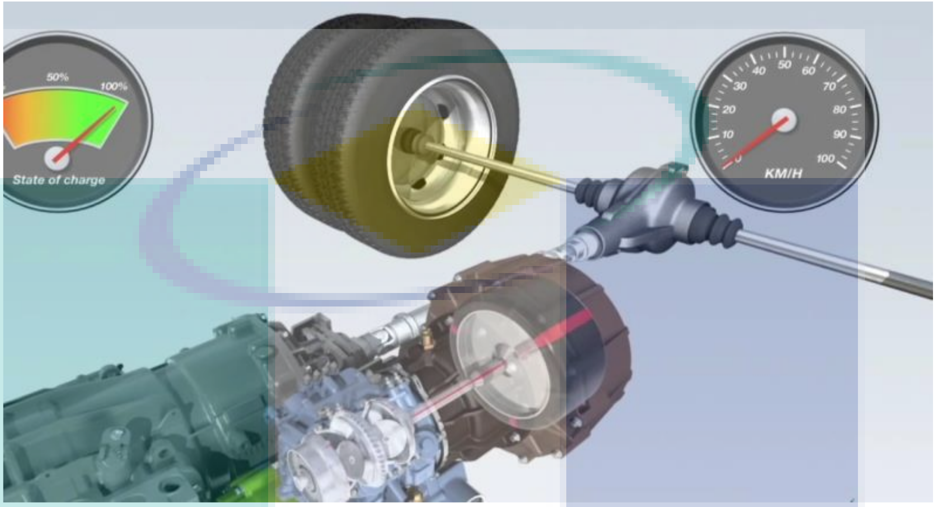


Figure 2:13 Flywheel Based Regenerative Braking [14]

2.4.2 Mechanical Braking

Mechanical brake consists of mechanical components which generate frictional force and make surface contact between two surface to slow down or stop a vehicle. It convert the vehicle movement to heat while stopping the rotation of wheels. A clear image of mechanical brake system components is shown in Fig 2:14 Mechanical brake system use lever or linkages to transmit force from on point to another. When driver exerts a force on brake pedal, brake fluid in the master cylinder is pressurised by the brake pedal force. The hydraulic force is transmitted through brake lines to each wheel cylinder or callipers. Then, hydraulic pressure at each wheel cylinder or callipers will be compressed by the hydraulic pressure and enable the friction material like brake drum of brake disc to slow down or stopped a moving vehicle. [9]

There are several types of mechanical brakes and the most common types are disc brakes and drum brakes. Both disc brakes and drum brakes will be discussed in detail on following subchapter. Besides that, hydraulic braking principle will be further discuss on subchapter below as well.

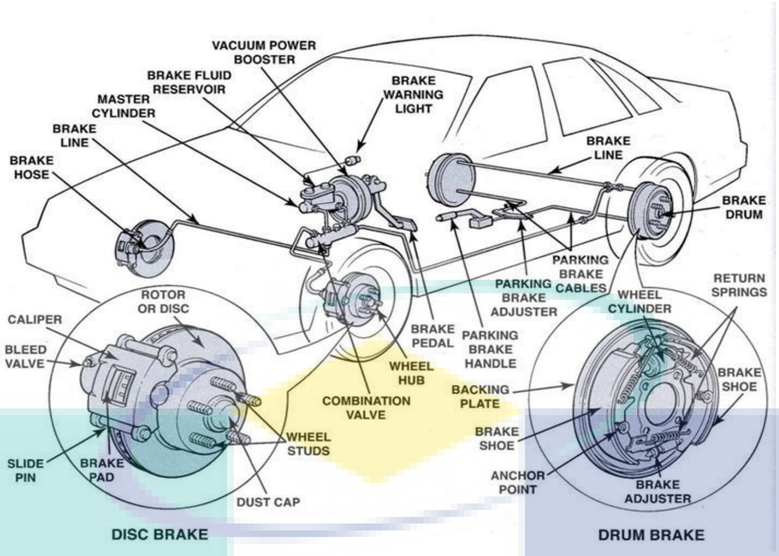


Figure 2:14 Mechanical components in mechanical brake system [9]

2.4.2.1 Disc Brake

Disc brake is a mechanical wheel brake which slow down the wheels by friction. It works based on compressing the brake pad against a brake disc with a set of callipers. Disc brakes are commonly used on the front of modern vehicles while some high performance automobiles manufacturer like BMW who emphasis on the driving performance will use both front and rear disc brakes because it can bring the vehicle to halt in a shorter period. Brake disc is usually made of cast iron but there are disc brakes made of composited such as carbon-carbon or ceramic matrix composite. [16]

For the operation of mechanical disc braking, brake disc is connected at the wheel or axle and when the driver tends to stop the wheel, the brake pad which mounted on brake calliper is forced mechanically, hydraulically, pneumatically or electromagnetically against both side of disc to slower or stop the automobiles. Moreover, in order to achieve mechanical disc braking, there are a few components work together to achieve the braking process and there will be discussed on paragraph below.[17]

A disc braking system as shown in Fig 2:15 consists of a rotor, a hub, a calliper set, two brake pads on each wheel and mounting bolts.

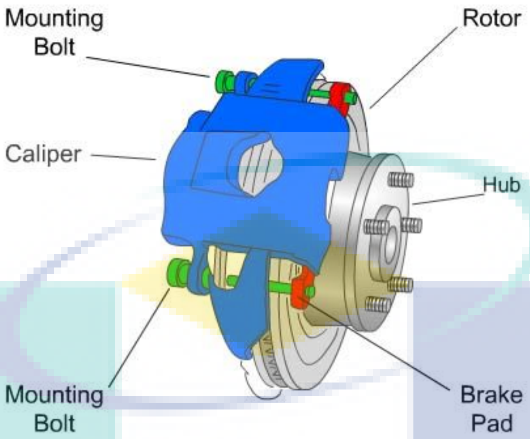


Figure 2:15 Components of disc brake [17]

The disc brake calliper used to transform hydraulic pressure from master cylinder to a mechanical force and compress the brake pads against the rotor. The calliper which made of iron or aluminium has a U-shaped casting mounted over the rotor. Floating calliper and sliding calliper shown in Fig 2:16 and 2:17 respectively are the most common type of calliper use on disc brake. Both of them provide the same function and the difference between them is only mounting way. All type of callipers contain housing, internal hydraulic passages, pistons, piston seals, dust boots, bleeder screw, inboard and outboard disc pads and mounting bolts.[17]

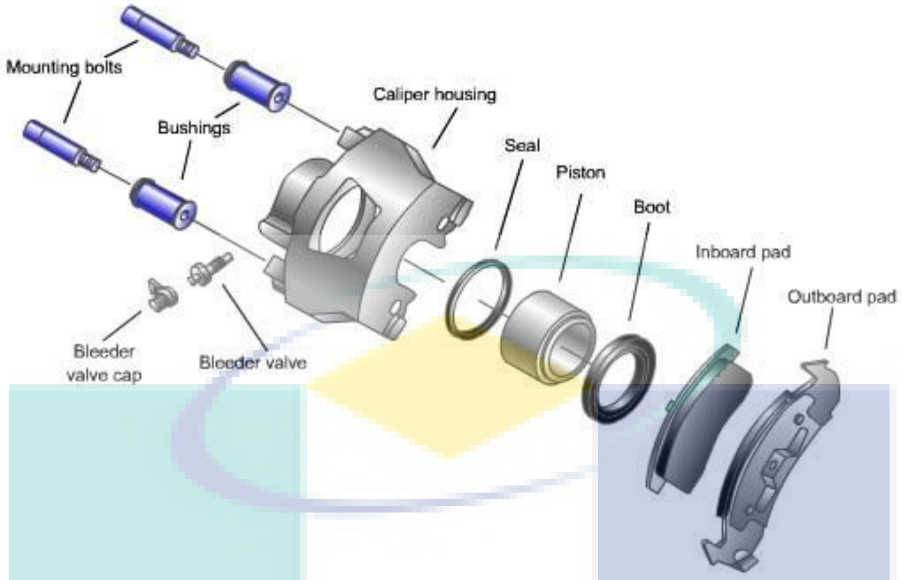


Figure 2:16 Floating Calliper on Mounting Bolts and Bushings

Source: [17]

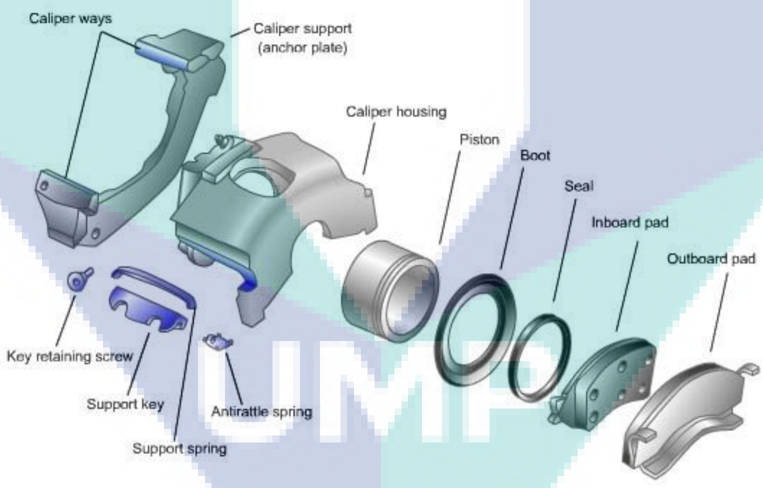


Figure 2:17 Machined Guide Sliding Calliper [17]

Furthermore, the next important component for disc brake is brake rotor with attach to the wheels. The rotor act as a friction surface that clamp against the disc brake pad to slow down or stop a car. Besides that, the rotor must be fabricated and maintained to a close tolerance. This is because excessive lateral runout or the thickness around the rotor is uneven can cause vibration and shutter during braking. A clear image of disc brake rotor is shown in Fig 2:18. [17]

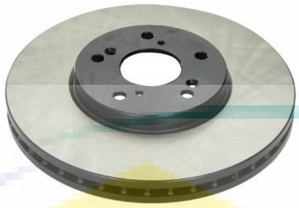


Figure 2:18 Disc brake rotor [17]

2.4.2.2 Drum Brake

According to [16]: 'A drum brake is a brake that uses friction caused by a set of shoes or pads that press against a rotating drum-shaped part called a brake drum. The term drum brake usually means a brake in which shoes press on the inner surface of the drum.'

Drum brake consists of two brake shoes attached on a stationary braking plate. When driver presses the brake pedal, wheel cylinder which has hydraulically activated pushes the shoes out to contact a rotating drum which creates friction and slow the car. Then, when the brake pedal is released, return spring retract the shoes to their original position. In recent years, most vehicles use drum brakes on their rear wheels and the most common types of drum brakes are duo-servo and leading trailing drum brakes which will be further discussed in following paragraph.[17]

Duo servo drum brake consists of brake drum, one primary shoe and one secondary shoe with friction linings, hydraulic wheel cylinder, anchor pin, backing plate, springs like return, hold down, connecting springs and adjustable linkage as shown in Fig 2:19 [17].

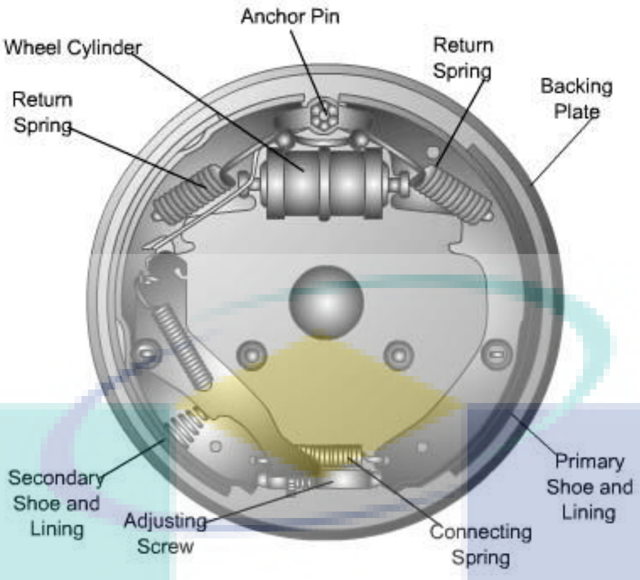


Figure 2:19 Duo servo drum brake [17]

Operation of duo servo drum brake started when driver presses the brake pedal, hydraulic pressure from the master cylinder force both wheel cylinder piston outward and the shoes are pressed against the drum. As the rotating drum get contacted from the brake shoes, frictional force causes both shoes to have a sight rotation. This action makes the secondary shoe to jam against anchor pin and this action generate braking force to slow or stop the vehicles.[17]

It is almost similar to duo servo drum brake and three major difference between leading-trailing and duo servo drum brake.

1. Anchor pin in leading trailing system is mounted at the bottom of the back plate while duo servo anchor pin locate at the top. Then,
2. There are no shoes push against each other in leading-trailing.
3. Leading-trailing drum brakes can be adjusted automatically when parking brake is applied and released.

A clear image of leading –trailing drum brakes is shown in Fig 2:20 [17]

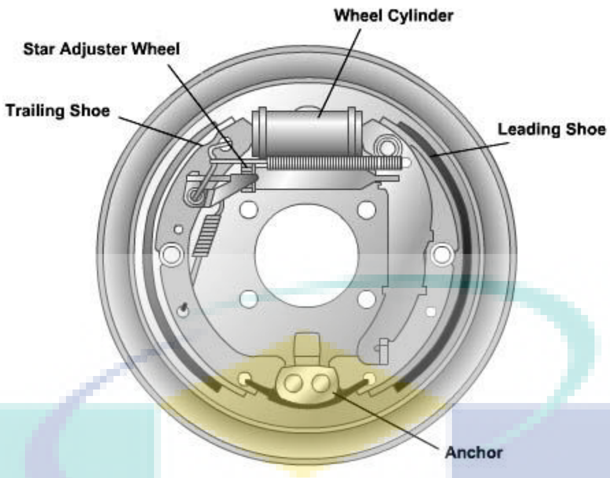


Figure 2:20 Leading-trailing Drum Brake [17]

For the operation of leading-trailing drum brake, its working principle simpler than duo servo drum brake. When driver presses the brake pedal, wheel cylinder is being pushed evenly on each brake shoe by hydraulic pressure. Then, each shoe in the drum brake is forced outward toward the drum. After that, the leading shoe is pulled by drum friction into tighter contact and provide a great braking force to the wheel cylinder and slow down the vehicle.[17]

2.5.1 Hydraulic Principle in Braking

The hydraulic principles that used in hydraulic braking is pascal law which discovered by a French physicist, Blaise Pascal. Pascal law state that "when force is applied to a liquid confined in a container or an enclosure, the pressure is transmitted equal and undiminished in every direction". In short, it means the pressure is applied on a fluid and it travels equally in all directions so that uniform braking action can be achieved on all four wheels. Pressure are dependent on the applied force and area of the container and the formula is shown below. [9]

$$P = \frac{F}{A} \tag{2.1}$$

As the formula of pressure is defined as force over area. The area of brake's piston will determine the force produce at the brake. Larger piston will create a greater force while smaller piston will in turn produce smaller forces. So, an example will be given in Fig 2:21, by using pascal law, when a smaller force is applied on the small piston, it can creates a larger force on a larger piston to lift up a car by using pascal law.

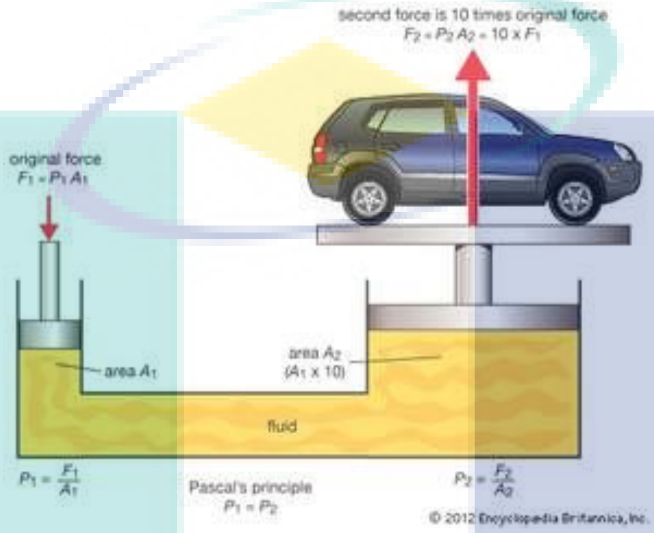


Figure 2:21 Pascal Law [9]

By applying pascal law in hydraulic brake system using brake fluid as the working mechanism, the braking force is exerted by a pushrod on the piston in the master cylinder. Then, brake fluid is flew into a pressure chamber through a compensating port from the brake fluid reservoir. In that instant, pressure of the entire hydraulic system is increased and forcing the fluid through hydraulic brake lines toward four wheel callipers. After that, all pressurised brake callipers will apply force to the brake pads and compress the brake pad against the spinning rotor. In this phenomenon, the friction between rotor and brake pads generate braking torque and slow the vehicle. [18]

On the other hand, when the brake brake pedal is released, it allows the spring in master cylinder assembly and return the master piston to its original position. This action will release the hydraulic pressure in each callipers and enable the brake pads to release the rotor. A diagram of hydraulic braking system is shown in Fig 2:22. [18]

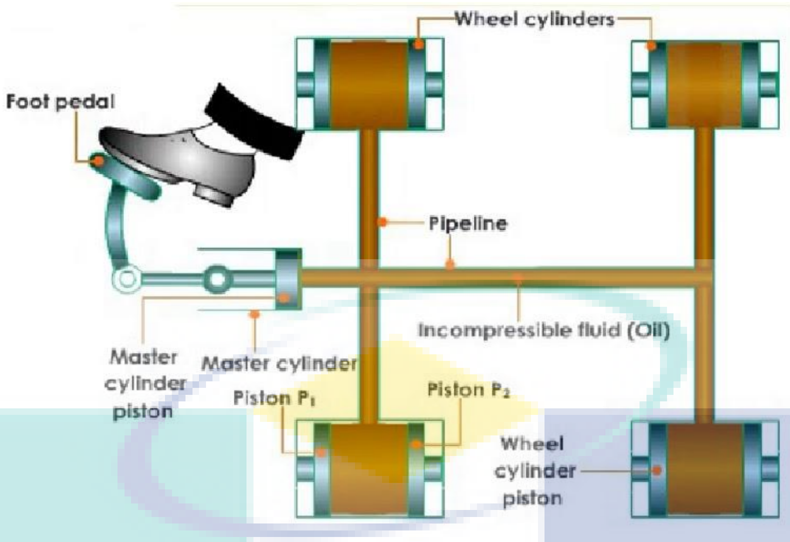


Figure 2:22 Hydraulic Brake System [18]

2.5.1 Braking Performance

Braking performance is one of the key aspect for automobiles because it directly impacts the vehicle and pedestrian safety. Driver brings the vehicle to halt in the shortest distance without losing control over vehicle is probably the most important safety requirement of any moving automobiles to avoid the occurrence of accidents. [19]

Technical condition of vehicles is one of the causes of traffic accidents. According to relevant statistics, for all the traffic accidents caused by the vehicle itself, about 45% are made by braking system's breakdown. Furthermore, for serious traffic accidents due to braking system, there are two main factors contribute to occurrence of accident. The first factor is insufficient braking distance and cause emergency braking cannot be performed completely. Sudden loss of direction stability of the rear wheel produced spinning effect is the second reason for serious traffic accidents. Brake system and effectiveness of its performance is the key characteristic of vehicle's technical condition. [20]

Braking system which compatible with great performance should consist of following characteristics:[21]

1. Stable Braking Performance

In order to achieve stable braking performance, brake force distribution on front and rear axles must be uniformed. Braking force on the left and right wheels must be same on the same axle to avoid any slide or slip phenomenon during emergency braking.

2. High working reliability

   A qualified braking system should have at least two independent brake lines for the driving brake. If one set of the brake line is not functioning, another set of brake line is able to use and stop the vehicle.

3. Good hysteretic nature

   The delay time should be as short as possible. If the delay time for depressing and releasing brake pedal is low. The braking efficiency will be increased.

4. Good brake thermal stability

   Brake pads should have good anti-heat fading capability.

5. Good water stability

   When the brake pad encountered water or sludge, brake pad's surface should resume normal parameters and did not affect its efficiency.

2.6.1 Method for Motor Braking Analysis

Nowadays, there are plenty of methods to test vehicle's braking performance. They can be categorised into two types which is road test method and bench test method. These two different methods require different conditions to carry out the experiment. Detailed explanation on both method will be discussed on following paragraph.

2.6.1.1 Road Test Method

This method is simple and straight forward. The dynamic change of the vehicle during braking can be recorded directly by testing instrument. At the same time, relationship between braking parameters can be reflected and compared throughout road test method. Besides that, braking parameters like braking distance, braking time, deceleration rate, and pitch angle can be taken during road test. On the other hand, instead of braking system, road test method can obtain other vehicle system parameters such as steering mechanism.[21]

2.6.1.2 Bench Test Method

Bench test is carried out indoors, so external conditions like raining or other factors do not affect the testing performance. Then, experiment for bench test can be performed many times and accurate and detailed experiment data can be achieved in this type of braking test.[21]

Braking testing bench can be categorised into four types which they are counter force type, inertia type, roller type and plate type. Nowadays, most researchers using single axle roller counter-force braking test system and plate type braking test system in their study.[21]

CHAPTER 3

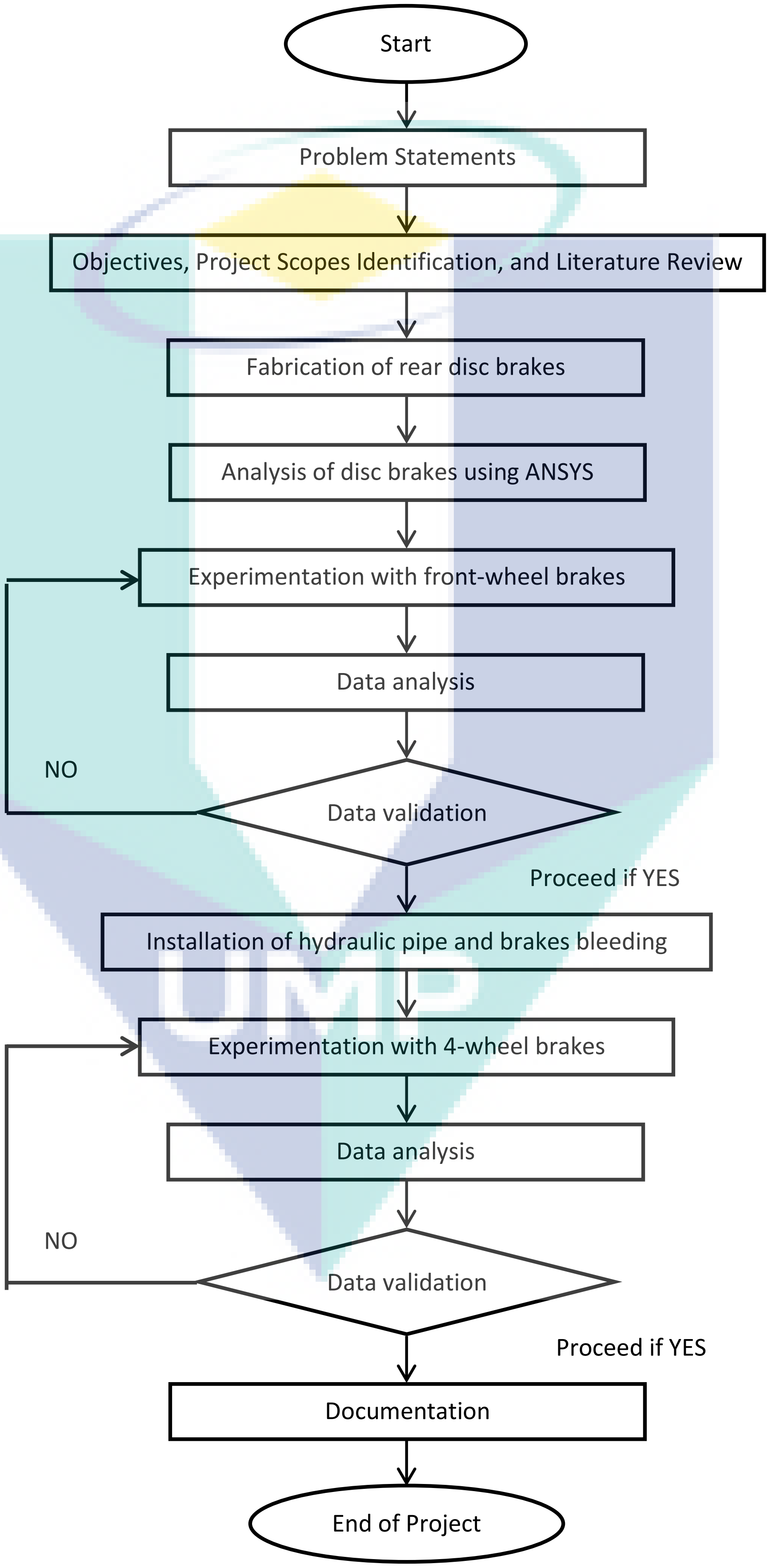
METHODOLOGY

3.1 Introduction

In this chapter, the detail explanations on every procedure have been made in order to solve the problem statement. This chapter will also clarify on the fabrication process for rear mechanical disc brakes including the installation of hydraulic pipe as well as brakes bleeding processes. The process flow chart is prepared to simplify and keep track on the project so that it becomes organized.

3.2 Flow Chart

Based on the project, the flow chart will be guides to overcome any problems arise during the progress. Project progress can be tracked according to the schedule, and any delays can be avoided. As soon as the objectives are set, the progress will be more focused on accomplishing the objectives during the timeframe. Several problems may occur, but can be overcome as long as they are systematically solved.


Start
Problem Statements
Objectives, Project Scopes Identification, and Literature Review
Fabrication of rear disc brakes
Analysis of disc brakes using ANSYS
Experimentation with front-wheel brakes
Data analysis
NO
Data validation
Proceed if YES
Installation of hydraulic pipe and brakes bleeding
Experimentation with 4-wheel brakes
Data analysis
NO
Data validation
Proceed if YES
Documentation
End of Project

3.3 Electric Vehicle

The current EV is already available from the lab. The EV is supplied by 4 units of 12V batteries which are connected in series. The EV is single seat vehicle, which follows the design from the formula SAE vehicle. The specifications of EV are provided in Table 3.1 below.

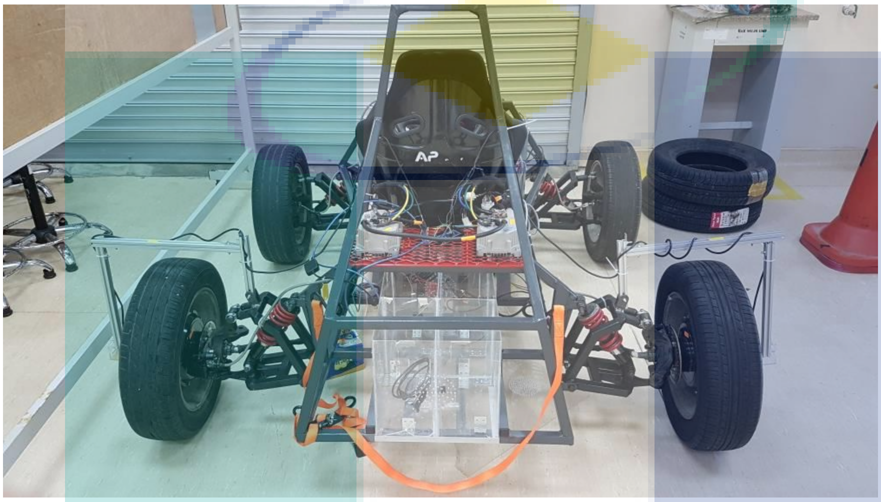


Figure 3:1 Back view of EV.

Table 3-1 EV specifications

Weight	241 kg
Battery	4 units of 12V batteries (connected in series)
Wheelbase	1.15m
Wheeltrack	1.43m
Motor Type	BLDC Motor
No. of Motor	2 units, attached to rear wheels
Motor Capacity	3000 W/unit
Maximum Speed	45 km/h

Even though the maximum speed of EV could reach up to 45 km/h with 48 V power supply, the experiments are capped to a maximum of only 28 km/h to ensure the driver's safety due to the unknowns of braking performance. The weight distribution for the EV is 55% for the rear and 45% for the front parts. By ratio, it will be 45:55 of weight distribution. The rear is heavier due to the batteries and in-wheel motors are placed on the rear parts of the EV. Plus, the EV is in rear drive mode, which follows with the standard criteria of formula SAE vehicle.

3.4 Hardware Components

The electrical components used in this project will include motors, motor controllers, rotary encoder sensors as well as gyroscope sensor. The overview of the electrical components is shown below.

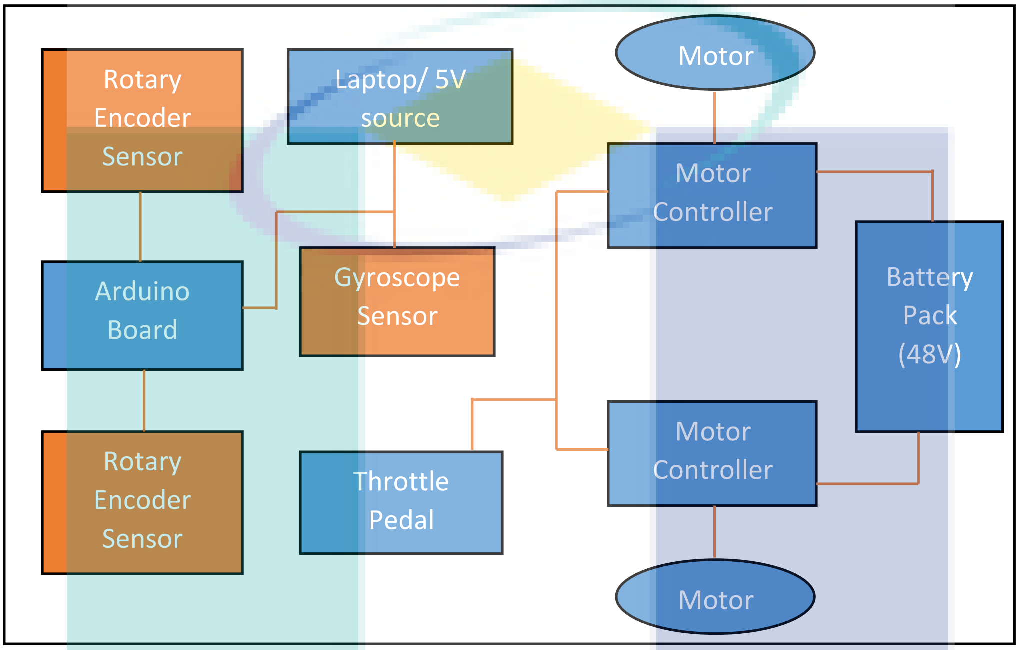


Figure 3:2 Block diagram for hardware components.

As shown in Figure 3.2 above, a battery pack which consisted of 4 units of 12V lead-acid battery are connected to the motor controller on each side of each motor. The motor driver and sensors consists of 2 units of rotary encoder, as well as a gyroscope sensor. The rotary encoder sensors are connected to the Arduino board, which is powered by 5V USB-powered from a laptop. The gyroscope sensor is powered by 5V USB laptop too.

3.4.1 In-wheel Motor

BLDC Motor is selected due to its maintenance free as well as less friction occurs in the motor during rotating motion. The inexistent of commutator as well stator will reduce the heat produced because no more friction produced on the stator. Plus, the BLDC Motor which would be fitted into the in-wheel tires will free up spaces of the vehicle, and thus able to utilize the large space for batteries bay. The specifications of BLDC Motor used are as in Table 3.2 below.

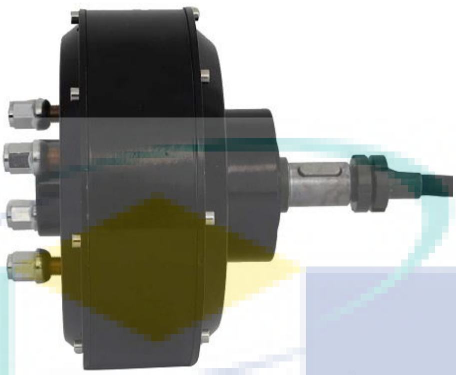


Figure 3:3 BLDC Hub Motor. [22]

Table 3-2 QS 3000W 205 50H V3 E-Car Hub Motor specifications [22]

Motor Type	BLDC Outer Rotor In-Wheel Hub Motor With 3-Hall Effect Sensors
Motor Design	Single axle without wheel 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

3.4.2 Motor Controller

In order to control the speed of the motor, the motor controller is used. Plus, the batteries will be connected to the motor controller first before it connects to the motor. Thus, by using the PWM voltage control, the speed can be controlled too. The controller used is based on sinusoidal wave control method which could reduce the torque ripples inside the motor as well as reduce the vibration produced.

Figure 3:4 KLS7230H Sinusoidal Wave Controller. [23]

Table 3-3 KLS7230H Sinusoidal Wave Controller specifications [23]

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

The motor controller is sufficient to control the single motor on the rear wheels. With the waterproof grade of IP66, the controllers have the characteristics of waterproof and dustproof. Even though the controller is certified with IP66, there are no experiments in wet condition as the safety of the driver cannot be compromised. The water could go through the cable connection of the controller-battery, and electrical injury can happen if anything goes wrong.

3.4.3 Rotary encoder

The rotary encoders used are for recording the wheel rotational speeds. The shafts of rotary encoders are attached directly to the centre of the wheels. There are two units of rotary encoders used for the experiments; attached to the rear -left and -right wheels of the EV. By using the aluminium profile as a bracket holder, the rotary encoders could be easily adjusted to be centrally aligned with the wheels.

Figure 3:5Rotary Encoder C/W Coupling. [24]

Table 3-4 Rotary Encoder C/W Coupling specifications [24]

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

$$\text{RPM} = \left(\frac{\left(Pulse\ Frequency\ in \frac{pulses}{sec}\right).(60sec/min)}{(500\ Sensor\ pulses/revolution)} \right) = \frac{Rev}{min} \qquad 3.1$$

where rotary encoder sensor is 500 pulse/ revolution.

3.4.4 Gyroscope

The gyroscope sensor used for is to record the accelerometer data from the experiments. The gyroscope sensor is placed to the CoG of the EV, to get the accurate value of the data. There are multiple data recorded which consisted of acceleration data, gyroscope data, magnetometer data as well as roll, pitch and yaw data.

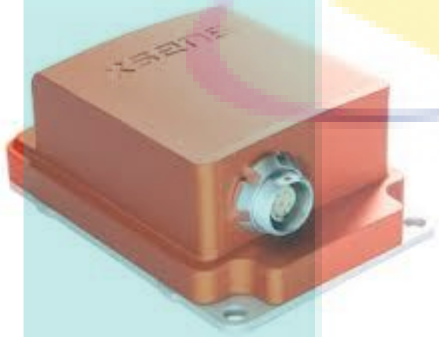


Figure 3:6 MTi-30 AHRS Gyroscope sensor. [25]

Table 3-5 MTi-30 AHRS Gyroscope sensor specifications [25]

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

As both of rotary encoder and gyroscope sensors only require 5V of voltage supply, they are directly connected to the laptop, which will record and saves data directly into the laptop.

3.5 Software Components

As the sensors only record the data, they would need software compliances to analyse the data. Plus, sensors which are in closed-source would need their own software applications to analyse the data. To analyse the disc brakes would need sophisticated software too, so that they will follow uniformity of the usual disc brake analysis should be.

3.5.1 Arduino IDE

With the usage both of the rotary encoders, they must be connected to the Arduino software by using the USB provided. The commands from the Arduino software would then able to records the data from the rotary encoders. The data from rotary encoder will then converted into MATLAB software for further analysis.

Figure 3:7 Graphical user interface of Arduino software.

3.5.2 Kelly Controller

The software is provided by the manufacturer for the motor controller. In order to adjust the speed of the wheels, the software must be connected to the motor controller by using the

USB drive. Without the configuration programmer, there will be no other ways to control the speed because the speed control of BLDC Motor is electronically controlled.

Figure 3:8 Graphical user interface of Kelly Controller User Configuration software.

3.5.3 Xsens Software

The software is used for recording the data from gyroscope sensor. As the sensor is a standalone sensor manufactured only from Xsens, the software compliance also comes from the same manufacturer too.

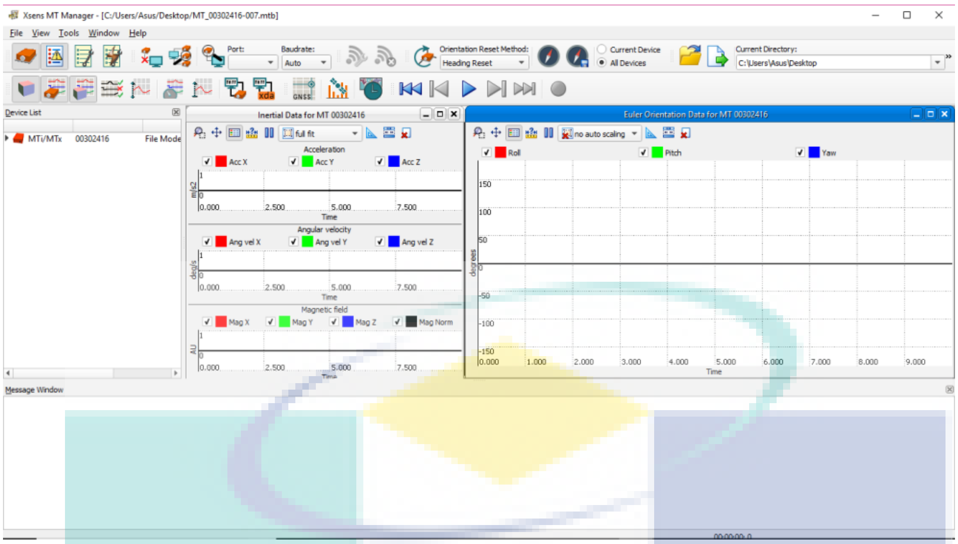


Figure 3:9 Graphical user interface of Xsens MT Manager 4.8 software.

3.5.4 Matlab-Simulink

The MATLAB software is used to analyse the data converted from the Arduino and Xsens MT Manager 4.8 software. After the conversion, the data will later on be plotted to the graphs.

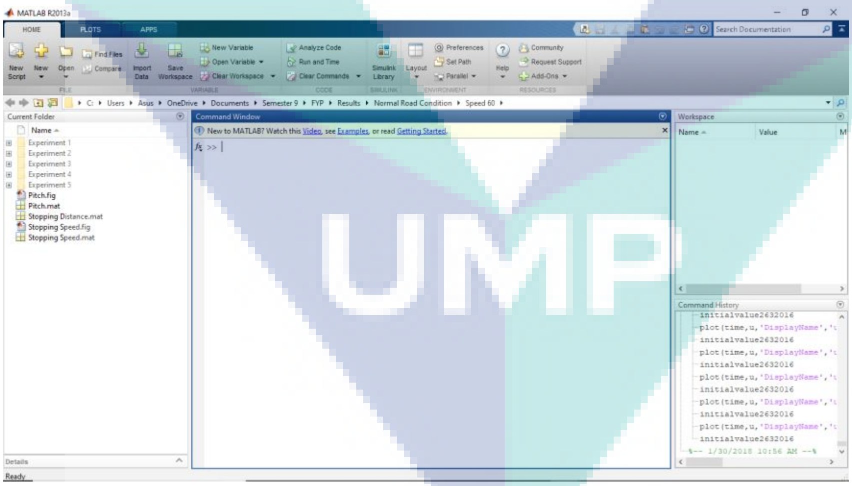


Figure 3:10 Graphical user interface of MATLAB Simulink software

3.5.5 ANSYS Workbench

In order to analyse the disc brakes, the ANSYS Workbench 18.1 is used. From the software, the analysis block diagram for the proper simulation is selected. Steady-state Thermal system and Static Structural system are selected because the disc brake that will be analysed is in static condition, and no fluids are considered in the analysis.

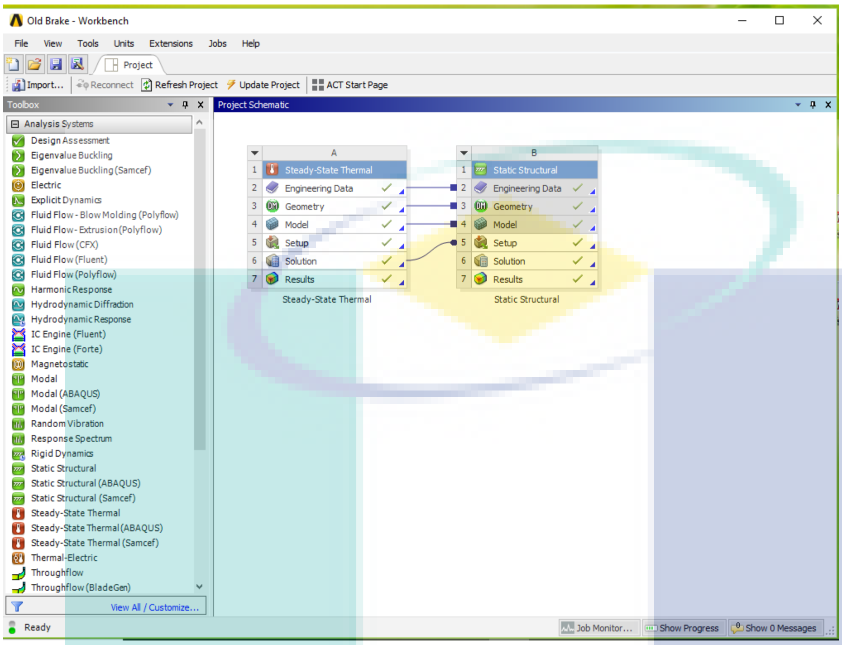


Figure 3:11 Graphical user interface of ANSYS Workbench 18.1 software

3.6 Disc Brake Analysis

In order to applying the custom disc brakes to the rear wheels, the custom disc brakes must be first analysed. The analysis of the disc brakes will know the maximum performance of the disc brakes fabricated. Plus, the performance of the original disc brakes to the fabricated disc brakes will be compared to get the percentage of performance reduction.

3.6.1 Technical Drawing

The technical drawing provides the original dimensions for the disc brake as well as the drilled disc brake. The disc brakes used is the cross-drilled type, to enhance the heat dissipation during braking. The drawing is important in order to explain about the modifications made. Plus, with the 3D drawings of the disc brakes, it could be imported into the ANSYS Workbench software for the further step.

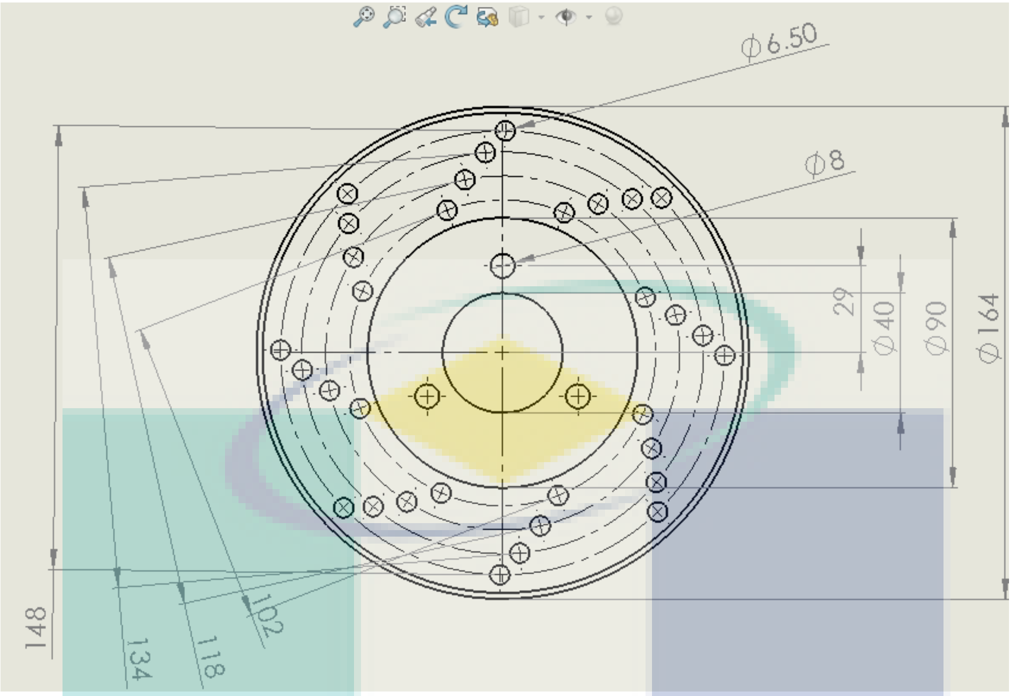


Figure 3:12 Drawing specifications for the original disc brake.

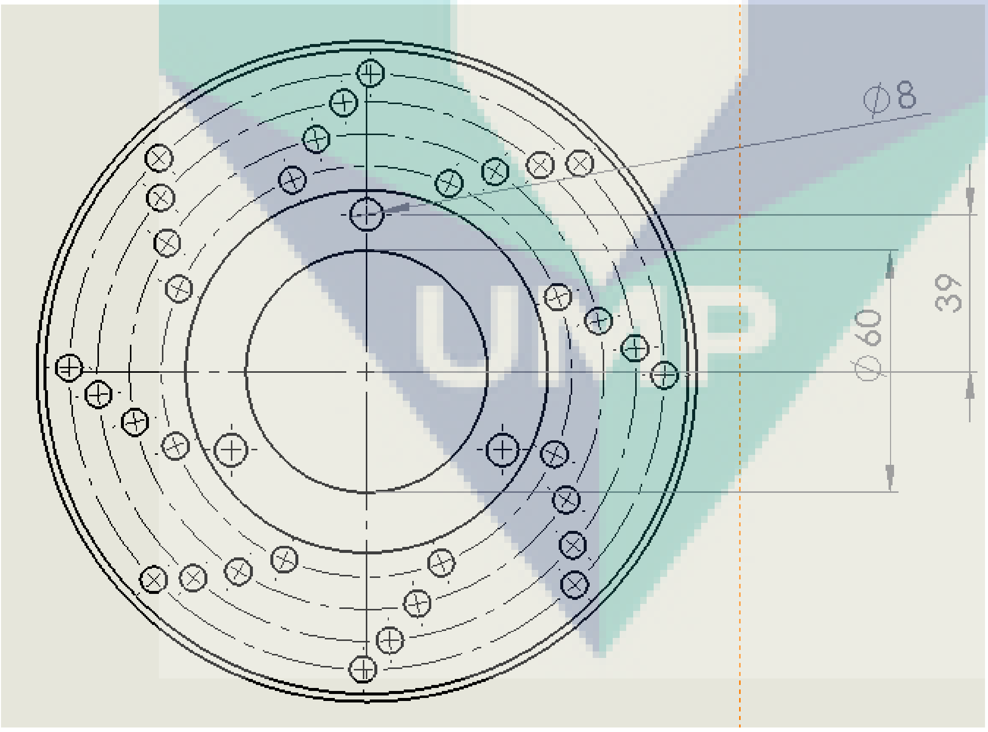


Figure 3:13 Drawing specifications for the custom-drilled disc brake.

Table 3-6 Comparison of disc brakes specifications

Type	Original	Custom-Drilled
Internal diameter	40 mm-D	60 mm-D
Radius to screw hole	29 mm-R	39 mm-R
Screw hole size	8 mm-D	8 mm-D

The internal diameter of the disc brakes must be drilled from 40 mm diameter to 60 mm diameter so that it could be fitted through the internal shaft casing of the in-wheel motor. The internal shaft casing diameter of the in-wheel motor is 58 mm diameter. Thus, there will be 2 mm extra of tolerance for the disc brakes.

3.6.2 Meshing Size

Meshing is one of the main criteria needs to be done first before proceeding to the next step of analysis. Meshing is used to render and demote the pre-processing phase of the FEA. The smaller the size of the meshing size of the design, the higher the details of the results produced later on. For a typical meshing size of a disc brake, a 1.0mm element size is used. However, smaller the size will require longer time for the computer to render the design.

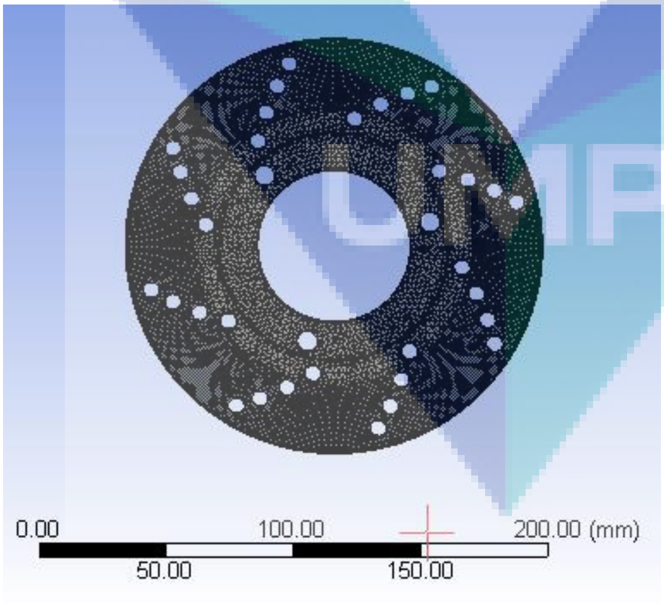


Figure 3:14 Meshing element for the custom-drilled disc brake.

Table 3-7 Comparison of meshing size of disc brakes

Type	Original	Custom-Drilled
Element size	1.0 mm	1.0 mm
Nodes	373467	514692
Elements	92371	131775

3.6.3 Boundaries Setup

There are a few steps in selecting the proper boundaries. In normal braking, the heat flux was generated and the brake disc consumes the most of the heat generated, which is usually greater than 90% [26]. In the modelling setup, thing that are less important and has less impact on the analysis is being ignored. The assumptions are always made based on the details and accuracy required for the modelling. Heat transfer analysis is only involve conduction and convection as the radiation can be neglected as it influence 5% to 10% of the heat transfer [27]. The disc material can be considered as homogenous and isotropic and the ambient temperature is set to 22°C.

$$\mathrm{Q} = M.g.V_0.\frac{\sin(1)}{12} \tag{3.2}$$

Where,

Q = Heat flux (W/m^2)

M=Mass of vehicle (kg)

G=Gravitational force (m/s^2)

V_0=initial velocity of vehicle (m/s)

$$T_b = 2.F_b.r.\mu \tag{3.3}$$

Where,

T_b=Braking Torque (Nm)

F_b=Braking Force (N)

r = Effective radius of the disc brake

μ = coefficient of friction of brake pad to the brake disc

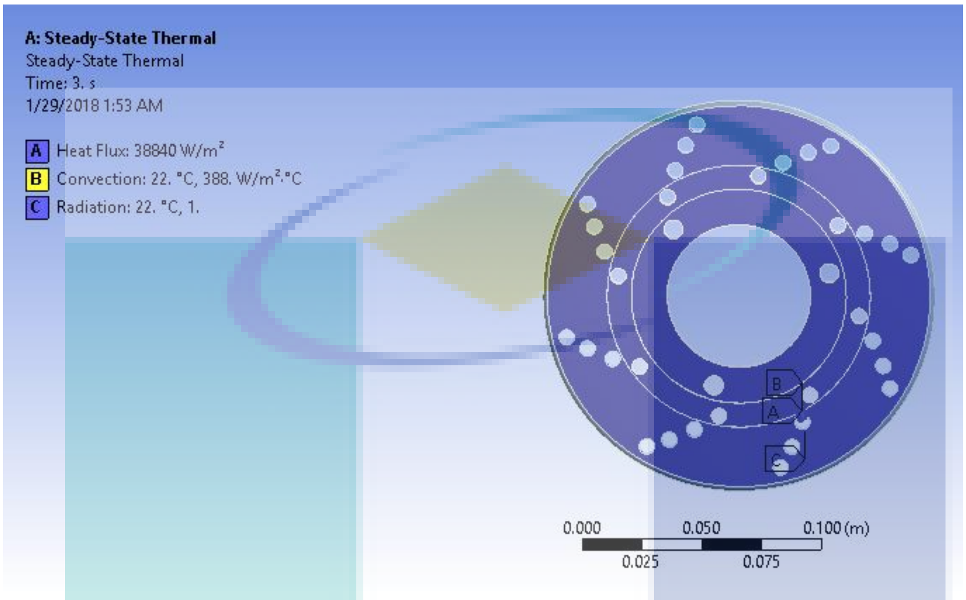


Figure 3:15 Steady state thermal boundaries for the custom-drilled disc brake.

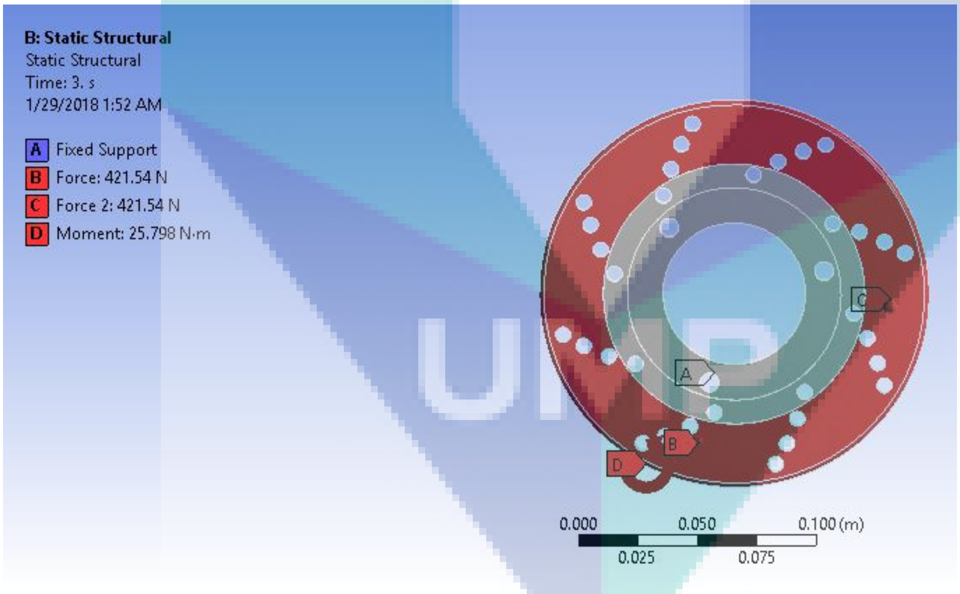


Figure 3:16 Static structural boundaries for the custom-drilled disc brake.

As can be seen in Figure 3:16, there are two sides of forces applied to the disc brakes. The direction both of the forces are directly applied to the disc. Time applied for the analysis is only 3 s, because most of the experiments are completed within 3 s.

3.7 Experiment

The experiments are the requirements in completing the objectives for this project. During the experiments, a lot of things must be considered, from the experimental procedure up to the safety of the driver and EV too. The experimental procedures must be followed to ensure that the data collected are valid enough. Misconduct during experiments would not only produce useless data, but also will brings hazard which could be happening anytime.

The motors for the EV are not only to drives forward, but will also be able to produce motor brakes. For this type of motor, it uses the method of dynamic braking for motor brake. Thus, the braking performance can be increased up to 50%. From this, it is decided to conduct the experiments using two different percentage of motor brakes, which are 25% and 50%. Even though braking solely using motor brakes are not choices for the car manufacturers, but experiments must be conducted too to study the performance of solely on motor brake. Most of car manufacturers would combine the motor brakes with the hydraulic brakes to improve the braking performance. During low speed, regenerative braking is not effective and may fail to stop the vehicle in the required time, especially in emergency. In the event of electrical or battery failure, the motor brakes will be malfunctioned. During this time, mechanical braking becomes critical [28]. As in Figure 3.17, only rear motor brakes are applied for the first experiments.

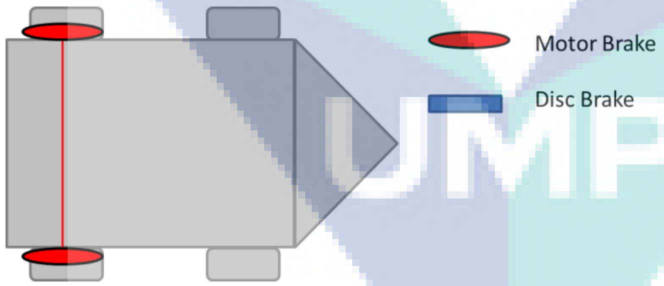


Figure 3:17 Experiment 1: Only rear motor brakes are used.

For the second experiments, only front brakes are used. As can be seen in Figure 3.18, the rear motor brakes are turned off so that the braking performances for only front disc brakes could be measured. For the third experiments as in Figure 3.19, front disc brakes with rear motor brakes will be combined together. Thus, the braking performance can be measured and could be compared with the previous experiments.

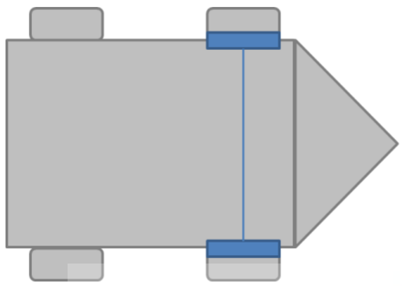


Figure 3:18 Experiment 2: Only front disc brakes are used.

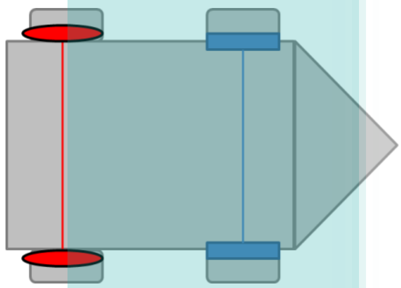


Figure 3:19 Experiment 3: Combination of front disc brakes and motor brakes are used.

As in Figure 3.20, the fourth method of experiments will be used are the combinations of front and rear disc brakes. In order to conduct the experiments, the hydraulic line for the front and rear disc brakes will be assembled together. Then, bleeding processes must be conducted to removes any excess air bubbles so that only brake oil is in the line. The excess air bubbles will reduce the braking performances if it is not removed. By using the right method, the brakes can be easily bled. During these experiments, motor brakes are turned off.

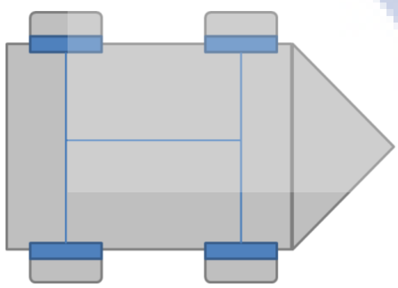


Figure 3:20 Experiment 4: Combination of front and rear disc brakes are used.

The last methods of braking for the fifth experiments are the combination of front-rear disc brakes with the rear motor brakes. It is expected to produce the highest braking performance compared to the other 4 methods of braking. The experiments performance will be analysed and compared in order to prove the improvements of braking by using multiple braking method.

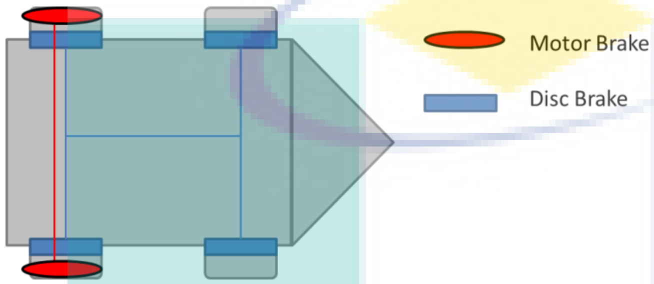


Figure 3:21 Experiment 5: Combination of front and rear disc brakes with motor brakes are used.

As for the experiment speed, there will be two different speeds will be applied for the experiments. First is the speed of 30% @ 14 km/h. For the second speed, it will be 60% @ 28 km/h. The lower speed is used due to the consideration of the safety for the driver in the event if the brakes are failed. Thus, the driver would still be able to control the EV to the complete stop and unfortunate accidents could be avoided. As an addition for the Experiment 1 and 5, there will be two different motor brake percentage will be applied, which are 25% and 50% respectively.

3.7.1 Location of Experiment

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. Due to this, the location has been selected to be inside of 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.

Figure 3:22 Experimental locations which have a 300 m straight line.

The location as in Figure 3:22 is considered as a proper location due to their long straight lines 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 can be seen in Attachment 2 is the request letter to the UMP Safety Department.

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.

3.7.2 Experimental Setup

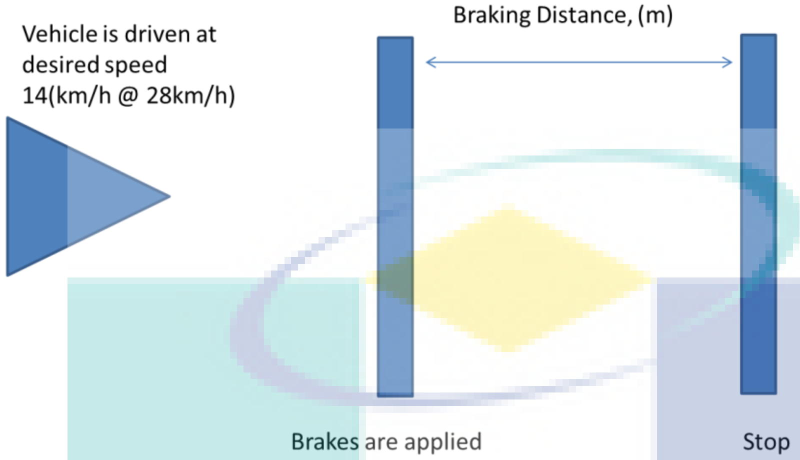


Figure 3:23 Illustration of experiments.

The experiments must be conducted in order so that the data from the experiments are valid for the experiments. Plus, the order of procedure is important so that no accidents will happen during conducting the experiments. The experimental setups are as below.

1. By using the gloves, the batteries are 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. After ensuring the road is clear from other road, the experiments will start.
5. After reaching the stopping line, the brakes are applied.
6. After complete stop, the vehicle is then turned off.
7. The data from rotary encoders and gyroscope sensor are then saved into the laptop.

3.7.3 Brakes Bleeding

Brake bleeding is removing any trapped air from the hydraulic system. When the air is trapped inside the hydraulic system, the brake pedal will feel “spongy” every time the forces exerted to it. Plus, the brake pedal will travel farther (more forces need to be applied) before the brakes start to apply. Air can enter through the leakage of brake lines or through the loose connection of the hydraulic line. A regular inspection is necessary to identify and locate the oil leakage to prevent accidents happened in the future. The oil reservoir also needs to be regularly inspected and refill the brakes oil until the recommended line. If the oil reservoir depletes their oil too frequently, leakage would be probably occurs.

There are several ways to bleed the brakes. There would be vacuum bleeding, gravity bleeding, and pressure bleeding as well as manual bleeding. However, manual bleeding is the most common method for the older vehicles as well as motorcycles. It is recommended to start the bleeding process at the rear wheel first, which is farthest from the master cylinder.

Before the bleeding starts, the reservoir must be refilled with the new brakes oil. The brake oil type must follow the recommendation from the vehicle’s manual. During the whole bleeding process, the reservoir must be regularly maintained their oil level, at least half full of the container. The plastic hose which should be at least 0.5 m long should be attached to the bleed screw valve. The bleed valve can be found at the inner side of brake calliper. The other end of the plastic hose should be submerged to another empty jar. This is due to the brake oil have the corrosive properties, and the oil can removes the body paint of vehicle.

Another assistant is needed to press the brake pedal a few times, and then the bleed valve is opened slowly (only one half turn). The excess brake will comes out through the plastic hose. Later, close again the bleed valve, and the assistant will release the brake pedal gently. This process is repeated several times. The air bubbles will be visible inside the plastic hose, and after a few repetition, there would be no more air bubbles inside the plastic hose. As reminder, the oil brake level inside the reservoir will be decreased, and it must be refilled repeatedly. If the reservoir is empty during the bleeding process, there would be extra air bubbles entering again the hydraulic line from the master cylinder. If this happens, the bleeding process should be repeated from the start again.

3.7.4 Calculations

In order to obtain the stopping distance, the GPS sensor is required to measure the distance. From the acceleration values, the distance can be determined too. However, due to the lacking of sensor, the mathematical calculations can be done to calculate the stopping distance. Due to the experiments are conducted in straight line, it is easier to calculate the stopping distance.

$$a = \frac{v_i - v_o}{t} \quad 3.4$$

$$d = v_o t + \frac{1}{2}at^2 \quad 3.5$$

where,

a = rate of deceleration (m/s²)

d = stopping distance (m)

v_i = *initial speed of vehicle (m/s)*

v_o = *final speed of vehicle (m/s)*

t = stopping time (s)

From the Equation 3.5 above, the sopping distance can be determined. From this, the braking force can be calculated by using the kinetic energy during braking.

$$W = E_k = F.d \quad 3.6$$

$$E_k = \frac{1}{2}mv^2 \quad 3.7$$

$$F = \frac{Mv^2}{2d} \quad 3.8$$

where,

W = Work done

E_k = *Kinetic Energy*

M = mass of the vehicle (kg)

v = velocity of the vehicle (km/h)

F = Force (N)

d = travelling distance

In the Equation 3.6, 3.7 and 3.8 above, it is used to determine the stopping forces. From the Experiment 2 which using only front hydraulic brakes, the braking force could be determined for the front brakes. In order to determine the rear brakes force, Experiment 4 is conducted. Experiment 4 which combines all the front and the rear mechanical disc brakes, will produce better braking performance compared to Experiment 2. Thus, braking force for Experiment 4 can be determined too. From that, brake force for rear hydraulic brakes can be determined by deducing the forces on Experiment 4 with the Experiment 2.

$$Angular\ velocity, \omega = \frac{v}{r} \tag{3.9}$$

$$Torque, \tau = \frac{M.r.a}{N} \times \frac{100}{\eta} \tag{3.10}$$

$$Power, W = \omega\tau \tag{3.11}$$

Where;

v = Speed of vehicle (m/s) = from gyroscope sensor

r = radius of tire (m) = 0.26585 m

a = acceleration (m/s^2) = from gyroscope sensor

η = motor efficiency (%) = 90%

N = Number of motor used = 2 units

M = Mass of vehicle (kg) = 343 kg

From the Equation 3.9, 3.10 and 3.11 above, it can be used to determine the torque and power produced from the motor braking. By using the formula by A.R. Hambley, the motor torque and power can be determined [29]. However, only experiments which using only motor brakes will be applied with these equations. Experiment 1 is suitable to be plotted with the torque and power graph, because the experiments are only involving the braking method of only motor brakes. In order to generate the graphs, the velocity and acceleration value must be obtained from the gyroscope sensor. On then, the graphs can be plotted over the time.

3.8 Numerical Analysis

In order to conduct the simulation, the parameters from the experiments must be determined first. The vehicle specifications, as well as the road friction and disc brake effective radius must be measure to gain the accurate data for the simulations. The accurate data would produce lower error percentage data during the validation process.

The Matlab/Simulink is suitable due to availability of multiple interconnecting block diagrams which will create one whole system which could be used to determine the accurate value of simulation. Plus, the simulation platforms provided by the author are ready to-be-use, thus only small changes need to be done to complete the simulation systems. For example, addition of motor brake coefficient, usage of different brakes for the front and rear tires (disc and drum brakes) as well as changes of braking force for the front and rear tires.

The simulation can be used to determine the stopping time and stopping distance during braking. Plus, because the experiments and simulations are conducted in a straight line, the parameters regarding y-axis direction can be neglected. Thus, only longitudinal forces are necessary. Speed of the tires and the vehicles can be determined in order to know the relations with the slip ratio formula. Plus, block diagram for ABS-function could be switched on or off, if necessary.

Initially, the ‘clock’ block must be created, so that the output results will be aligned with the time. Thus, results generated can be plotted over the time. The block function can be seen in Figure 3.24 below.

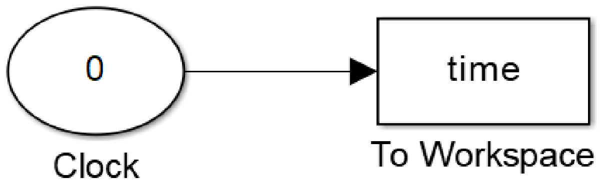


Figure 3:24 Time block diagram.

As for determining the exerted forces to the front and rear disc brakes, experiments must be conducted first. From Experiment 2 and 4, front and rear disc brakes forces can be determined. However, for the panic braking, there will be increase of pedal forces applied. From the vehicle specs, the master piston diameter size as well as brake piston sizes can be determined. Pedal ratio can be measured by using thread and ruler. Distance of pedal to pivot is represented as r_1, and distance of pedal to pushrod is represented as r_2.

$$R_p = \frac{r_1}{r_2} \quad 3.12$$

From the Equation 3.12 above, the pedal ratio, R_p can be determined. By multiply both the pedal force, F_p and R_p will produce the force at the master cylinder, F_m.

$$F_m = F_p . R_p \quad 3.13$$

As from Equation 3.13 above, force exerted in the master cylinder can be determined. After the master cylinder piston size is determined, the pressure exerted inside the hydraulic system can be determined.

$$P_{hydraulic} = \frac{F_m}{A_m} \quad 3.14$$

From the Equation 3.14, the master cylinder force, F_m is divided with the area of master cylinder piston, A_m. The pressure exerted is the same for the whole front and rear brakes because they share the same master cylinder, as well as no proportioning valves are used for rear tires. The only thing that makes the front and rear brakes force differs from each other is the size of brake piston that is used. Front tires use bigger brake piston size because they use the exact brake disc model as in Perodua Kancil vehicle. For the rear piston size, the vehicle uses brake disc model as in Suzuki V100, a scooter and the piston size is smaller. As both front and rear tires are using disc brakes, then there are no further explanation and modification needed inside the block diagram because both are the same system.

$$F_{brake} = P_{hydraulic} . A_{brake} \quad 3.15$$

However, there are several modifications to determine the braking torque applied to the tire.

$$F_{pad} = 2F_{brake} \quad 3.16$$

$$F_{friction} = \mu F_{pad} \quad 3.17$$

$$T_{br} = F_{friction} . r_{eff} \quad 3.18$$

$$T_{br} = 2\mu F_{brake} r_{eff} \quad 3.19$$

From the Equation 3.15, 3.16, 3.17, and 3.18 above, it can be used to determine the right forces exerted to the brakes. Brake pad radius effectiveness, r_{eff} can be determined by deducing the biggest radius of brake pad exerted to the disc with the smallest radius of brake pad exerted to the disc.

$$Slip\ ratio, s = \frac{u - r\omega}{u} \times 100\% \quad 3.20$$

The slip ratio formula as is Equation 3.20 is used for the ABS mechanism. The braking torque applied to the tires will be zero when the slip value is greater than 0.3. When the slip value is lower than 0.3, the braking torque will be calculated.

$$u = \int \frac{\sum F_x}{m} \quad 3.21$$

From the block diagram, the integration of the vehicle acceleration, a will yield the speed of the vehicle. For the straight line, there will be only longitudinal speed, u.

$$F_x = ma_x \qquad 3.22$$

From the equation above, m is the mass of the vehicle. The longitudinal force of F_x is then divided with m, which will produce longitudinal acceleration, a_x. To obtain the speed of vehicle, the a_x will be integrated.

To simulate the weight shifting during braking, there must be known of weight distribution on the all of the four tires.

$$F_{zFnew} = F_{zF} + \delta F_z = F_{zF} + \left(\frac{h}{l} \times m \times a\right) \qquad 3.23$$

$$F_{zRnew} = F_{zR} - \delta F_z = F_{zR} - \left(\frac{h}{l} \times m \times a\right) \qquad 3.24$$

The equation 3.23 is for front tires, while Equation 3.24 is for rear tires. For the front tires, both left and right tires can use the Equation 3.23. Same goes with rear tires, both left and right rear tires can use Equation 3.24. The only that differs is the transfer of weight, deltaF$_z$ which will be added to the front tires and will be subtracted to the rear tires.

$$T_f = F_x r_{tire} \qquad 3.25$$

The traction torque can be determined by multiply the traction force with the radius of the tire.

$$\frac{T_f - T_{br}}{I} = \frac{d\omega}{dt} \qquad 3.26$$

$$\int \frac{d\omega}{dt} = \omega \qquad 3.27$$

$$v_{tire} = r_{tire}\omega \qquad 3.28$$

The braking torque is then subtracted from the traction torque, because both are in opposite direction of torque. Then, it will be divided by the inertia of the tire which will produce angular acceleration of the tire. To obtain angular velocity, the angular acceleration is then integrated. The tire speed is then can be determined by multiply the angular velocity with the radius of tire.

$$X = X_0 + V \int_0^t \cos(\beta + \theta)\, dt \qquad 3.29$$

From the Equation 3.29 above, the braking distance for the vehicle can be determined. Because there is no steering angle is applied, thus the beta and theta value will be zero. Thus, the total speed will be equal to the longitudinal speed. X_0 is the initial braking distance, and it is zero. To obtain the stopping distance, the longitudinal speed is integrated.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is the peak of the whole report to present the final findings. In this chapter, the FEA, experimental results as well as simulation results will be discussed. The performance of different method of braking is discussed with the data generated from the experiments.

4.1 Disc Brake Analysis

In order to accomplish the Experiment 4 and 5, the rear disc brakes must be used. In order to do that, the available disc brakes must be fitted into the inner motor hub at the rear wheels of the vehicle. The current inner diameters for disc brakes were too small for them to be fitted into the rear motor hub. Thus, inner diameter of disc brakes must be drilled again. The analysis have been made in order to make sure that the drilled disc brakes are still able to operate properly, even with high braking force. By using ANSYS Workbench 18.1 software, the results could be made possible.

4.1.1 Analysis Results from the Original Disc Brake

From the project schematic of ANSYS Workbench 18.1, there are two types of analysis systems used. First, the steady state-thermal analysis was conducted, and followed by static structural analysis for the second analysis system. The boundary was set as in Table 4.1 below. The data boundary was determined from the maximum normal force that would be exerted to the motorcycle disc brakes.

Table 4-1 Maximum boundary set for original disc brakes

Force (N)	Torque (N.m)	Vehicle speed	Heat Flux (kW/m2)
500 N	190 N.m	70 km/h @ 19.4 m/s	97.09 kW/m2

The analysis was conducted by using the concept of single-stop braking. As the disc brakes that will be tested will not undergo multiple speeding-braking at the long period, single-stop braking is considered as the proper method in doing the analysis.

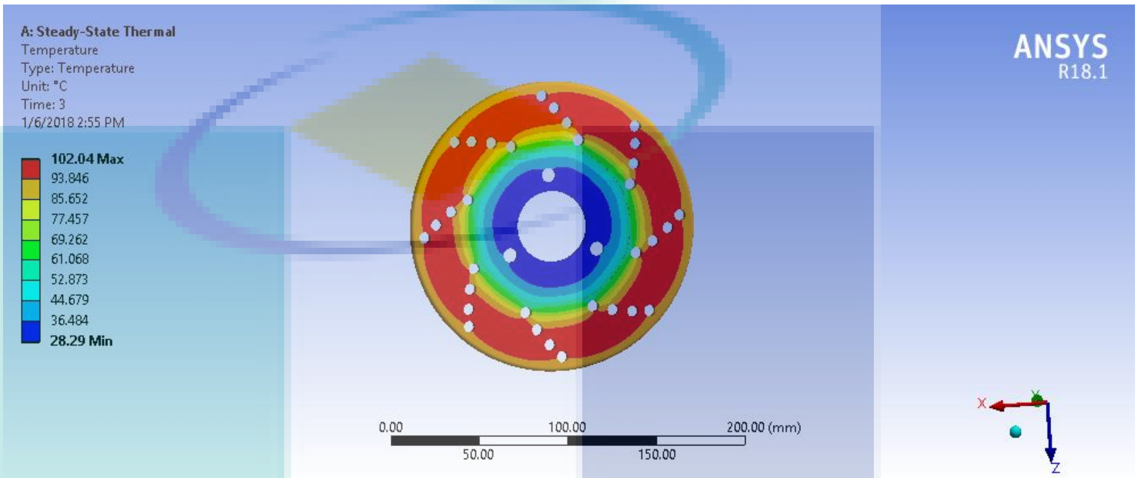


Figure 4:1 Temperature increase of original disc brake.

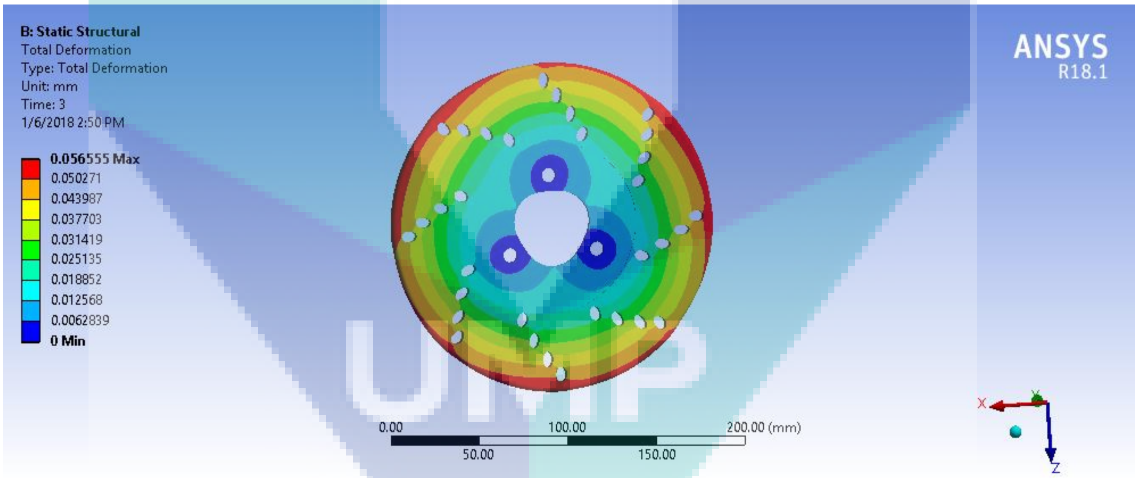


Figure 4:2 Total deformation of original disc brake.

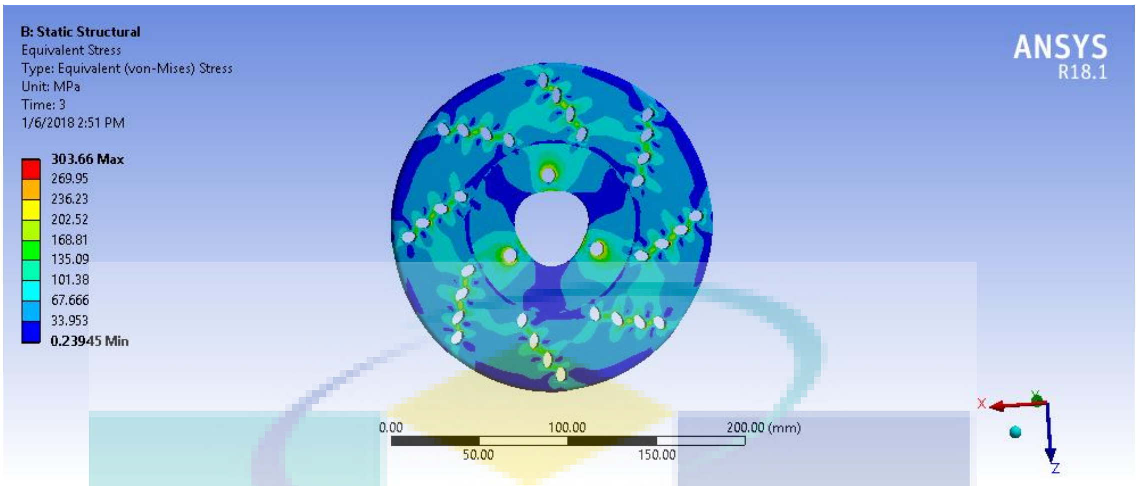


Figure 4:3 Equivalent (von-Mises) stress of original disc brake.

As can be seen from the Figure 4:1, 4:2 and 4:3 above, the highest temperature increase for the original disc brake is 102.04°C. Plus, the deformation of disc brake is only 0.056555 mm at the highest, and the maximum stress exerted to the disc brake is 303.66 MPa, lower than the ultimate tensile strength for the stainless steel which is 655 MPa. Thus, the structure is considered safe.

4.1.2 Analysis Results for the Custom-Drilled Disc Brake

For this analysis, the boundaries are set same as in Table 4.1. This is to know whether the drilled disc brake could still able to work in high braking force for a normal motorcycle. Plus, from the experiments that are conducted later on, the expected brake forces exerted to rear disc brakes will be lower compared to the current maximum boundaries set for them. If the custom-drilled disc brake could still work under high brake force, thus it would be able to work in lower braking forces too.

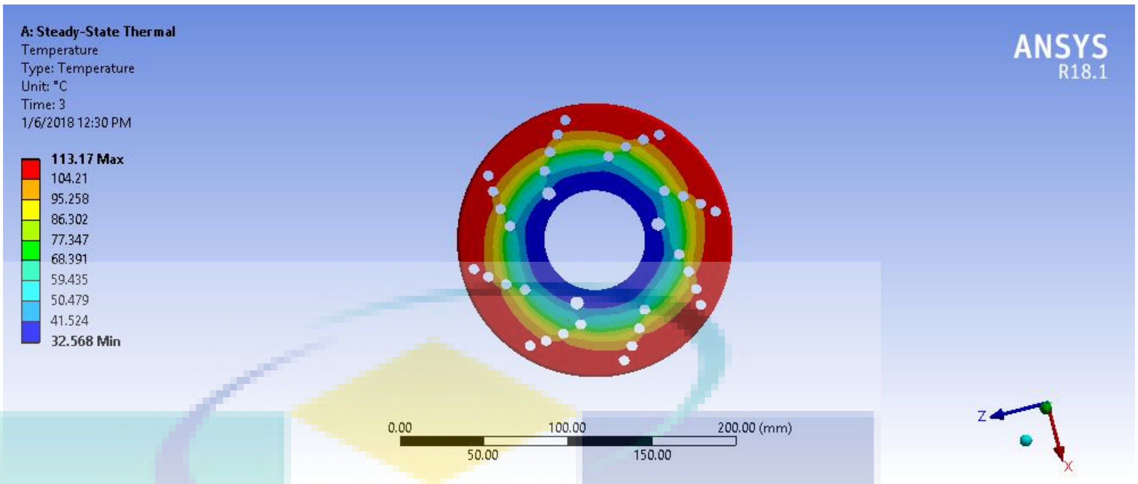


Figure 4:4 Temperature increase of custom disc brake.

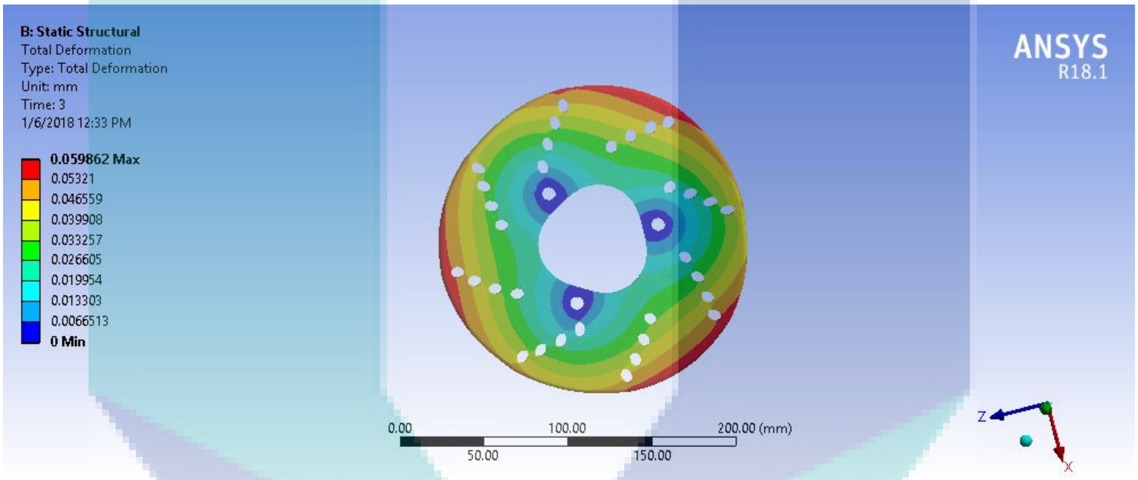


Figure 4:5 Total deformation of custom disc brake.

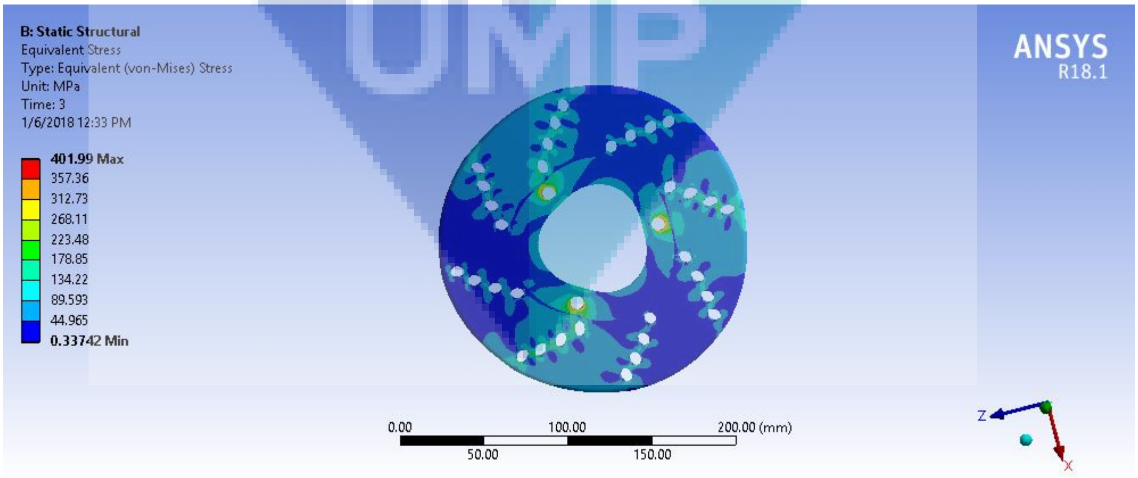


Figure 4:6 Equivalent (von-Mises) stress of custom disc brake.

From the Figure 4.4, 4.5 and 4.6 above, the maximum temperature for the custom disc brake is 113.17°C, while the total deformation for the disc brake is 0.059862 mm. The equivalent (von-Mises) stress has increased to 401.99 MPa, but still lower than the ultimate tensile strength which is 655 MPa. Table 4.2 below shows the summary for the comparison of the both designs.

Table 4-2 Comparison of disc brakes analysis for maximum expected force.

Types of disc brake	Max. Temperature (°C)	Deformation (mm)	Equivalent (von-Mises) stress
Original	102.04°C	0.056555 mm	303.66 MPa
Custom-drilled	113.17°C	0.059862 mm	401.99 MPa

4.1.3 Analysis of Custom Disc Brake using the Calculated Force from the Experiment

From the Equation 3.8 in Chapter 3, the braking force was determined for the Experiment 4: Speed 60%. The analysis for the actual braking force as well as braking torque was crucial in determining whether the structure is safe or not. Even though the analysis for the maximum braking force was already determined, the analysis must be calculated too.

Table 4-3 Boundary set for custom disc brakes

Force (N)	Torque (N.m)	Vehicle speed	Heat Flux (kW/m2)
421.54 N	25.7982 N.m	28 km/h @ 7.778 m/s	38.84 kW/m2

From the boundary that was set during the analysis, it was found that the stress produced to the custom disc brakes are still in allowed level. The results are in Table 4.4 below. From the result below, the von-Mises stress is only 353.56 MPa, lower than ultimate tensile stress. Thus, the custom-drilled disc brake is considered as safe to be used.

Table 4-4 Disc brakes analysis for calculated force.

Braking Force (N)	Max. Temperature (°C)	Deformation (mm)	Equivalent (von-Mises) stress
421.54 N	102.88°C	0.061523 mm	353.56 MPa

4.2 Experimental Results

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. As the experiments are conducted in straight line, the equation 3.4 and 3.5 are used to calculate the stopping distance of every experiment.

4.2.1 Speed 30% 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.

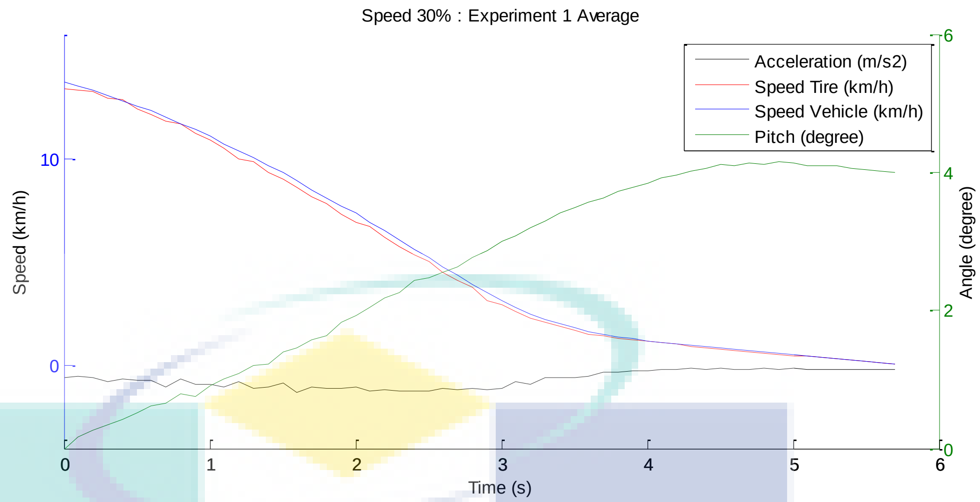


Figure 4:7 Experiment results for the average of Speed 30% : Experiment 1.

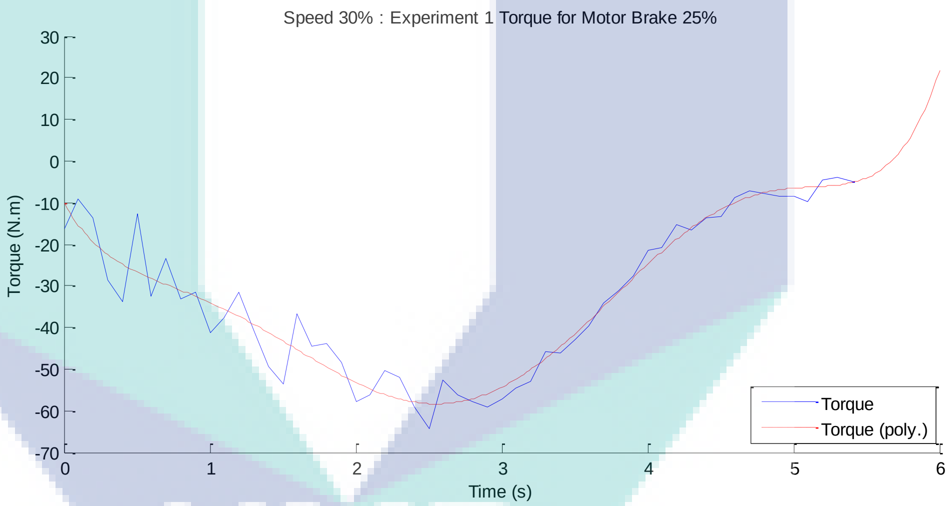


Figure 4:8 Torque for Speed 30% : Experiment 1 Motor Brake 25%.

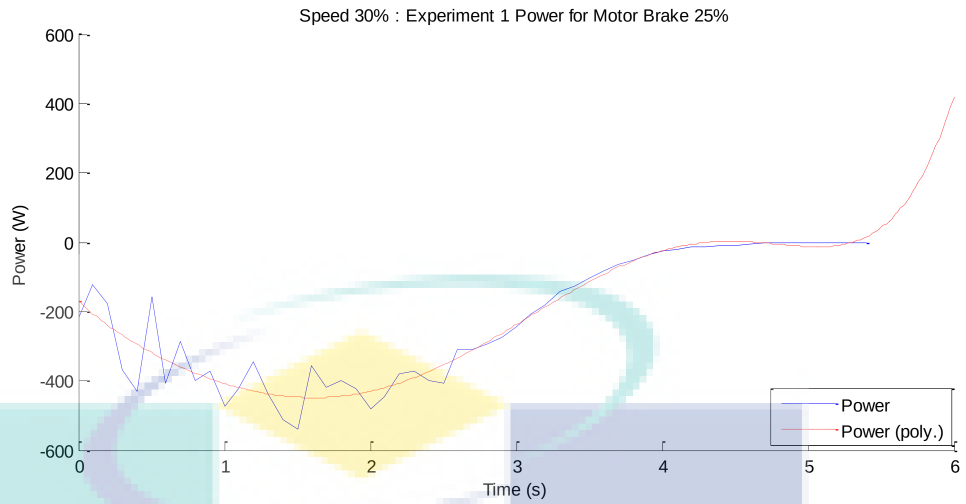


Figure 4:9 Power for Speed 30% : Experiment 1 Motor Brake 25%.

As can be seen from the Figure 4.7 above, 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 the Figure 4.8 and 4.9, the torque and power produced during braking is 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.

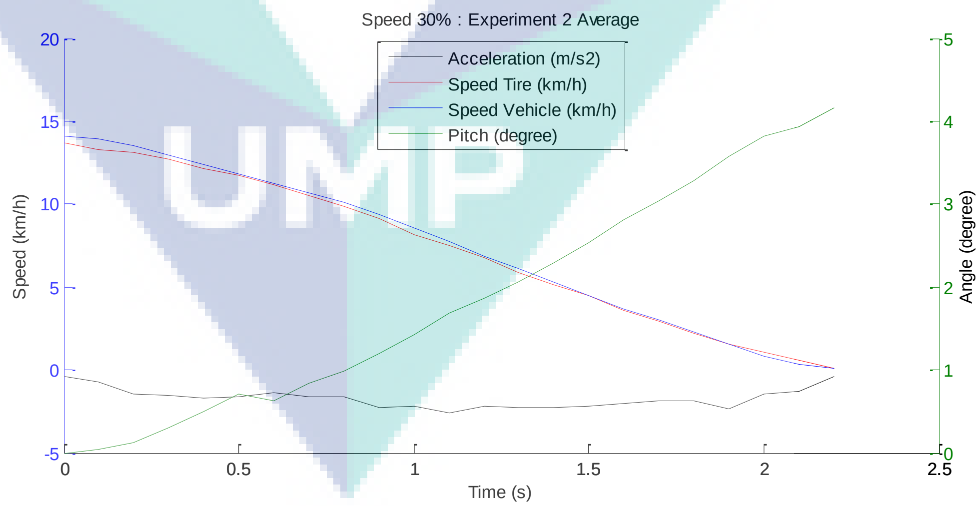


Figure 4:10 Experiment results for the average of Speed 30%: Experiment 2.

From the Figure 4.10 above, the stopping time and distance is shorter compared to experiment 1 in Figure 4.7. 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 the experiment 2 due to the usage of only front brakes to conduct the experiments.

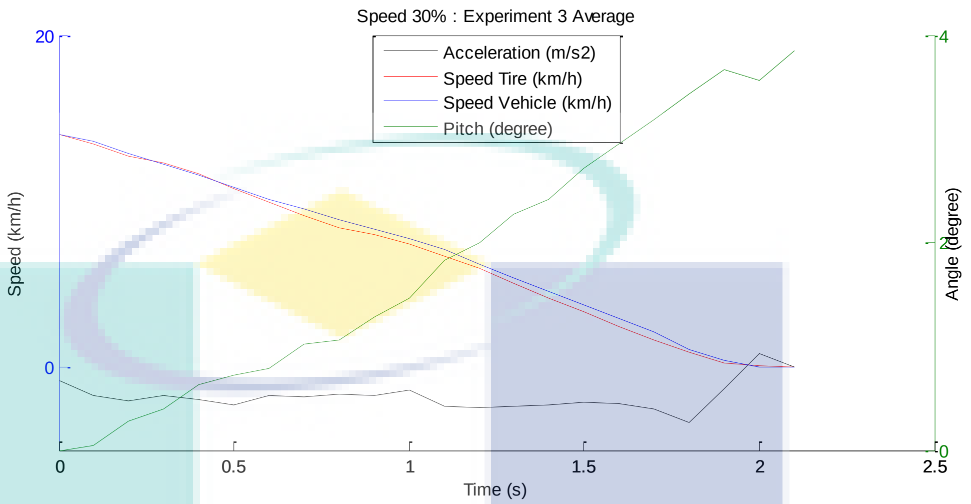


Figure 4:11 Experiment results for the average of Speed 30%: Experiment 3.

From the Figure 4.11 above, the braking method used are the combinations of motor brakes with the front disc brakes. There are improvements recorded for the 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 previous experiment, which could accumulate until only 3.564°. The average pitch recorded is expected to be lower than Experiment 2.

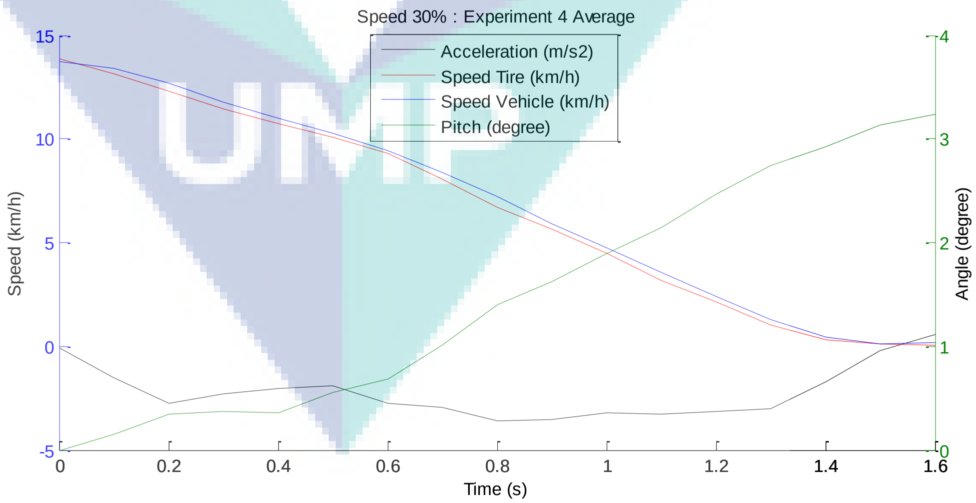


Figure 4:12 Experiment results for the average of Speed 30%: Experiment 4.

From the Figure 4.12, the method of experiment is combination of only front and rear disc brakes. In order to conduct the experiment, the hydraulic lines of front and rear disc brakes must be connected to the same master cylinder pump, and due to that the bleeding processes must be occurred. 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°.

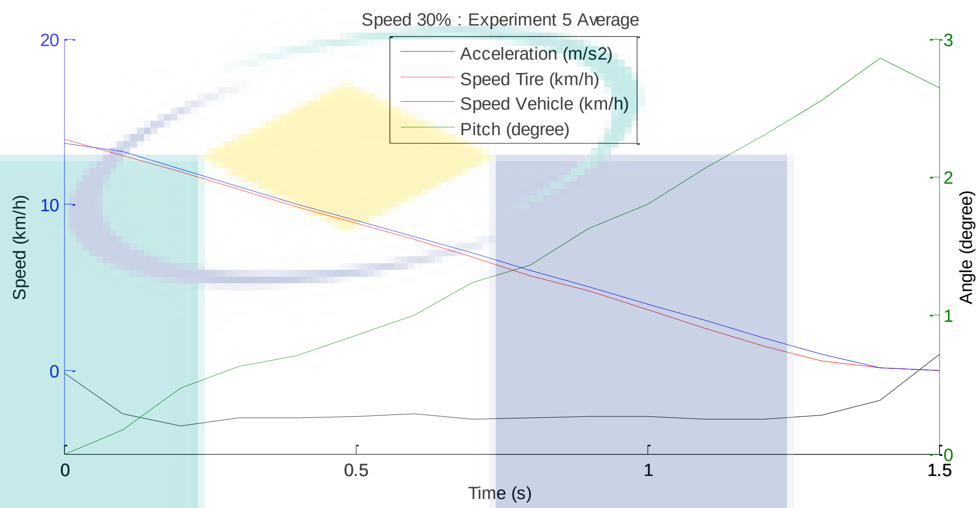


Figure 4:13 Experiment results for the average of Speed 30%: Experiment 5.

From the Figure 4.13 above, there are combinations of front and rear disc brakes as well as motor brakes are implemented. The stopping time and stopping distance is 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°.

Table 4-5 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

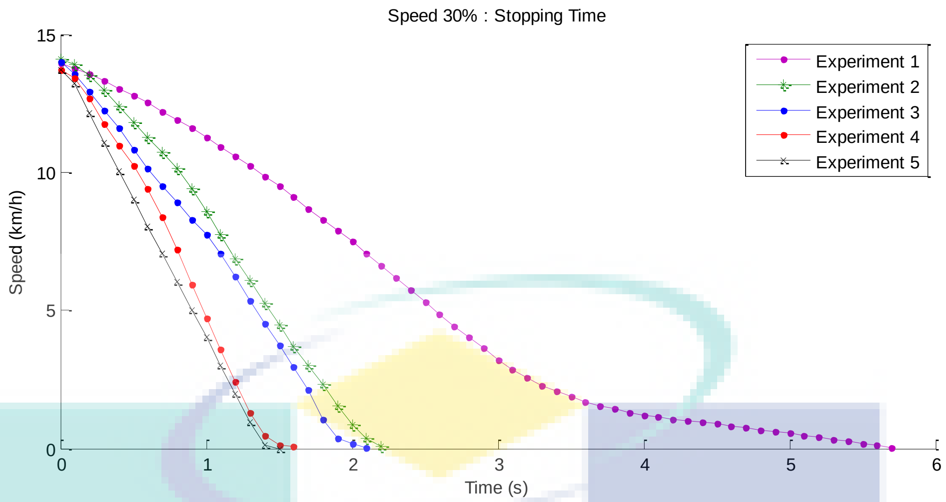


Figure 4:14 Results for the average stopping time in Experiment: Speed 30%.

As can be seen from the Figure 4.1, it took more than 5 sec for the vehicle to come to 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.

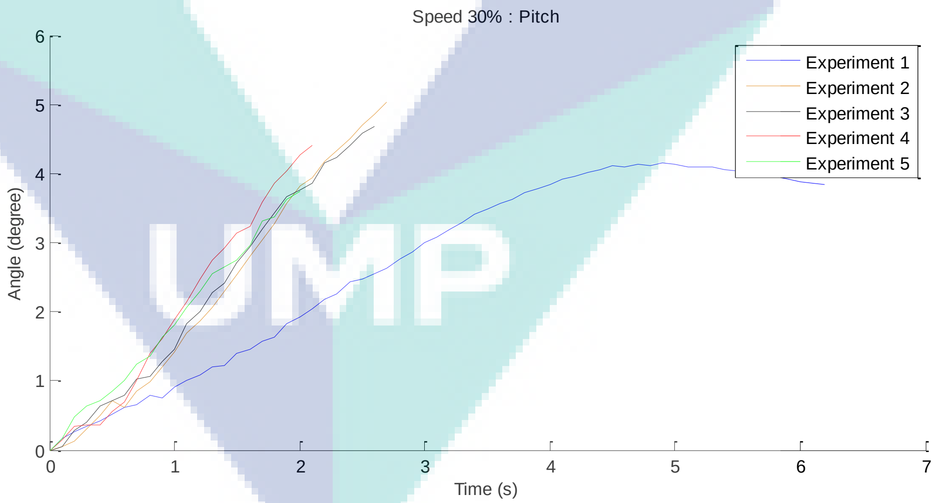


Figure 4:15 Results for the average pitch in Experiment: Speed 30%.

In Figure 4.15, 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 the Table 4.5, 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%, the Experiment 5 has the highest braking performance compared to the other four braking methods.

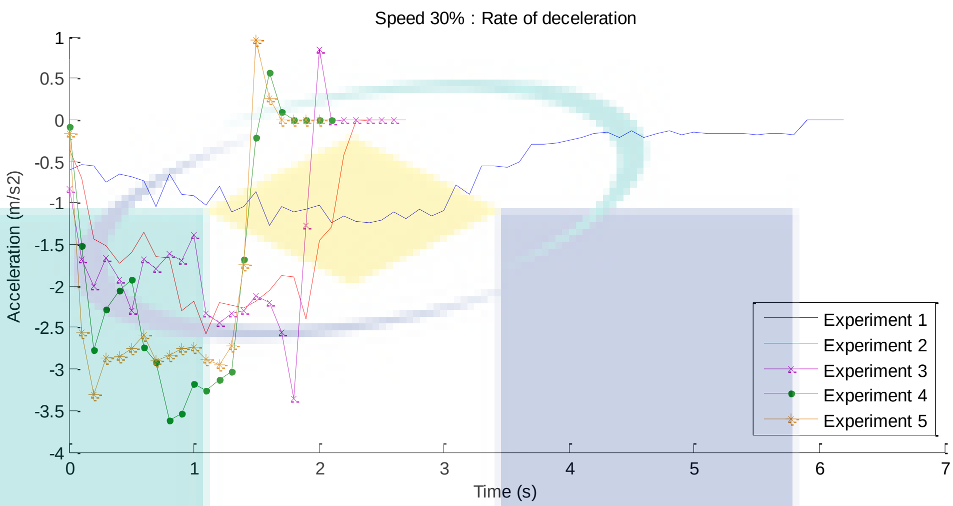


Figure 4:16 Rate of deceleration in Experiment: Speed 30%.

In the Figure 4.16, the lowest deceleration rate is recorded for Experiment 1. From the Table 4.5, 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.

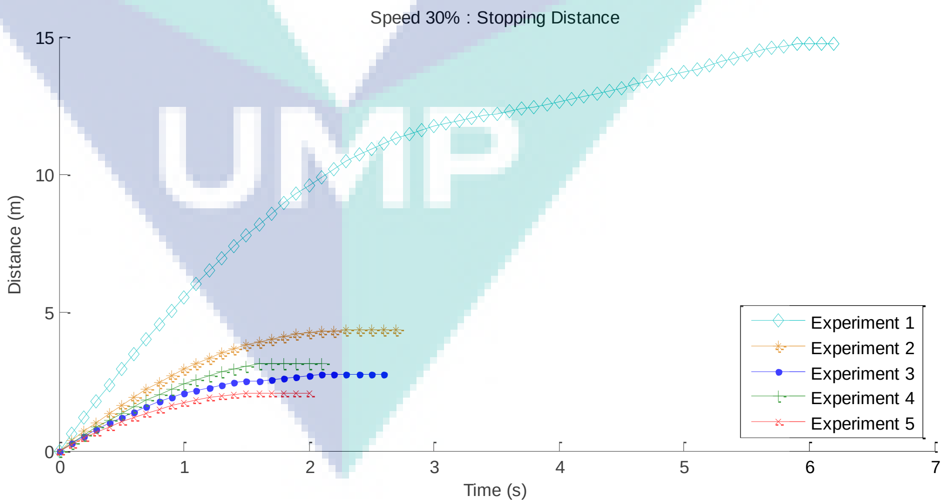


Figure 4:17 Stopping distance in Experiment: Speed 30%.

For the Figure 4.17, the highest stopping distance is recorded for the Experiment 1, which at 14.6 m. For the 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. The results are analysed from the Gyroscope sensor.

4.2.2 Speed 30% 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 brakes.

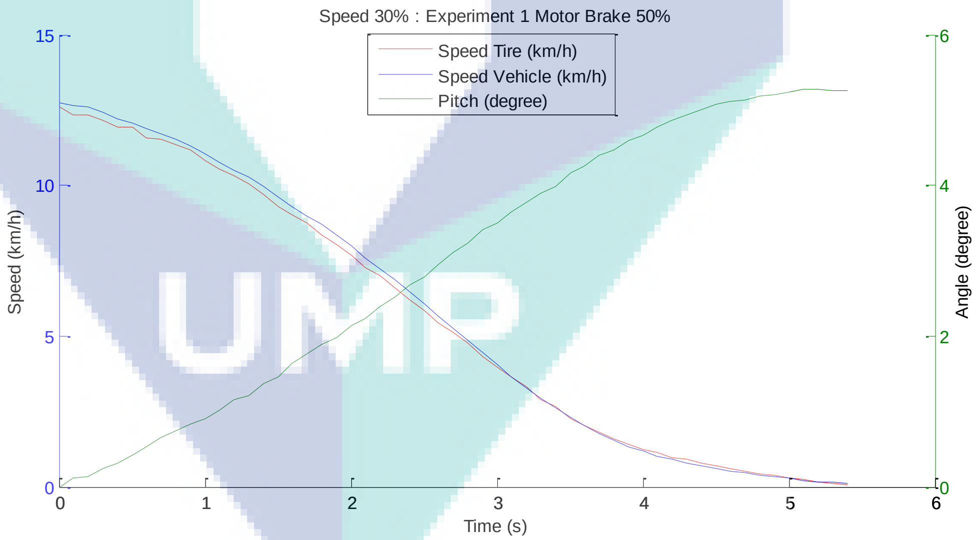


Figure 4:18 Average Experiment 1: Speed 30% Motor Brake 50%

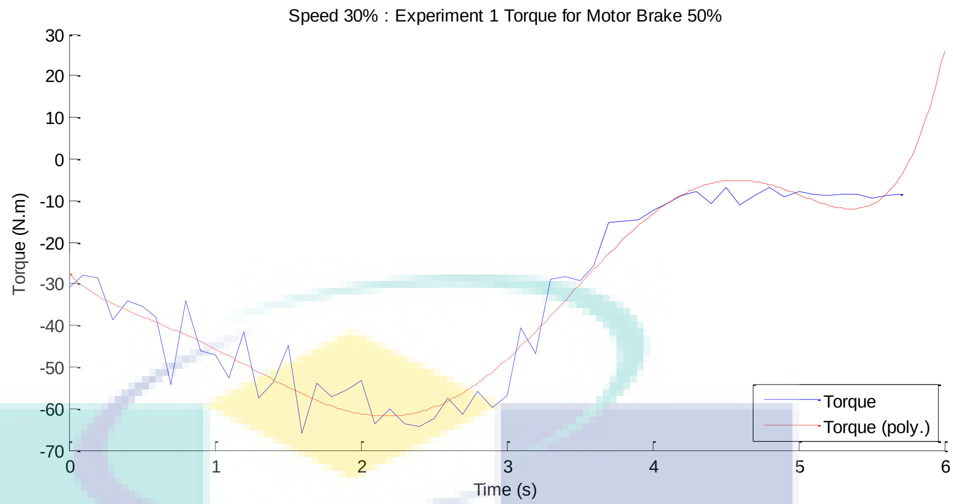


Figure 4:19 Torque for Experiment 1: Speed 30% Motor Brake 50%

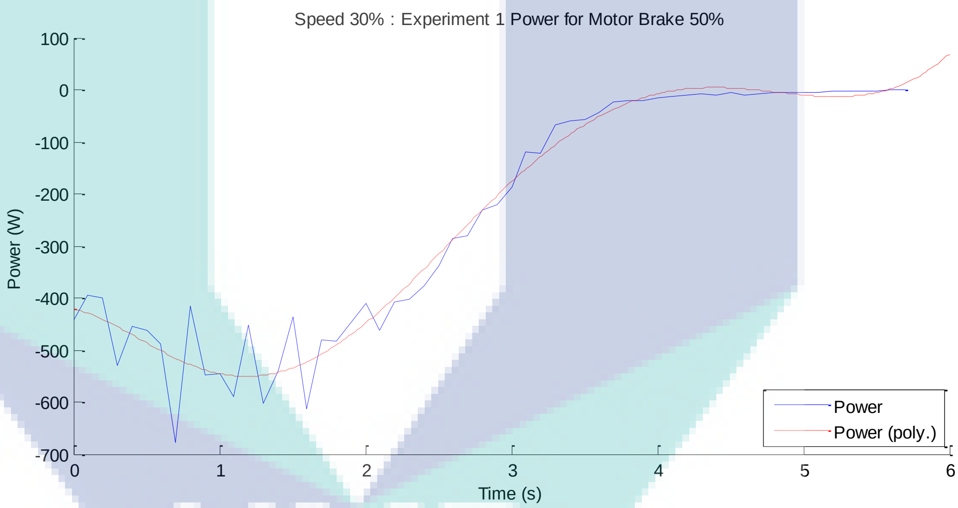


Figure 4:20 Power for Experiment 1: Speed 30% Motor Brake 50%

From the Figure 4.18, 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 4.19 and Figure 4.20, the highest torque is recorded at -61.82 Nm and highest power produced is at 550.8 W. Table 4.6 shows the comparison of the Experiment 1 Motor Brake 25% and 50% as well as the improvements in percentage.

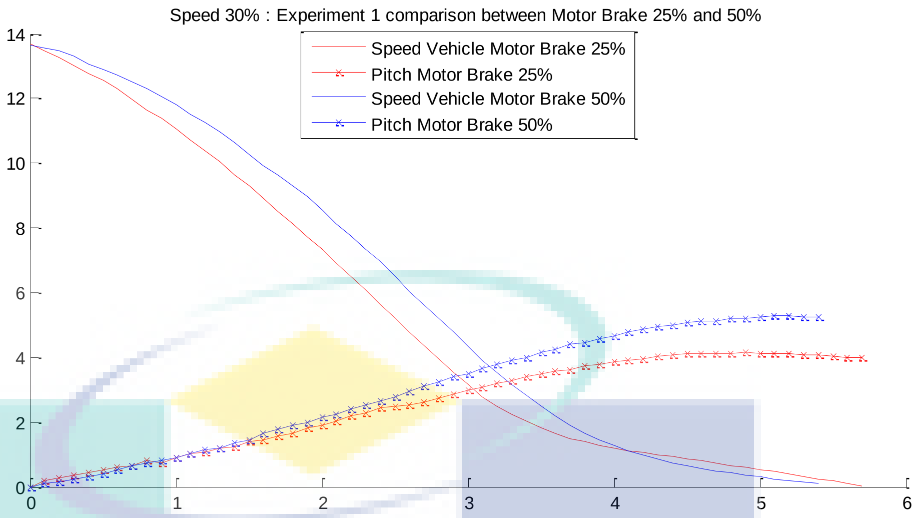


Figure 4:21 Experiment 1: Speed 30% comparison between Motor Brake 25% and 50%.

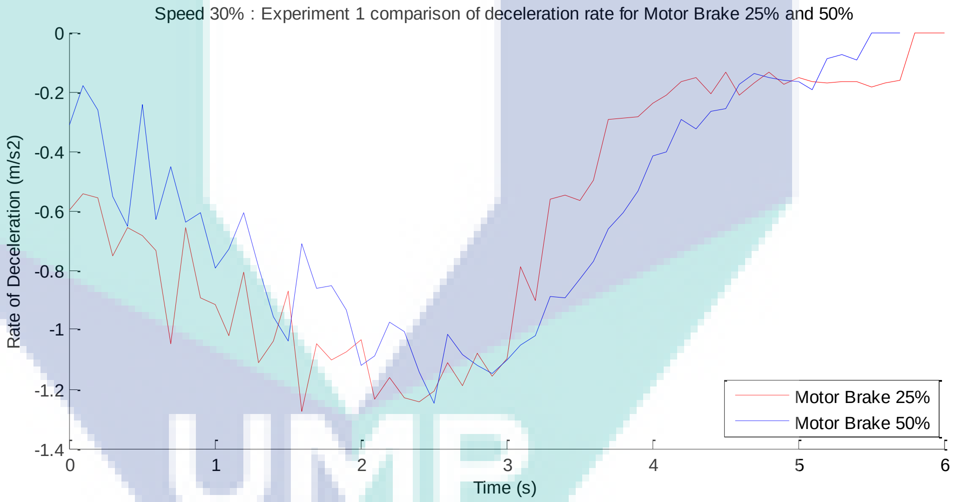


Figure 4:22 Experiment 1: Speed 30% deceleration rate comparison between Motor Brake 25% and 50%.

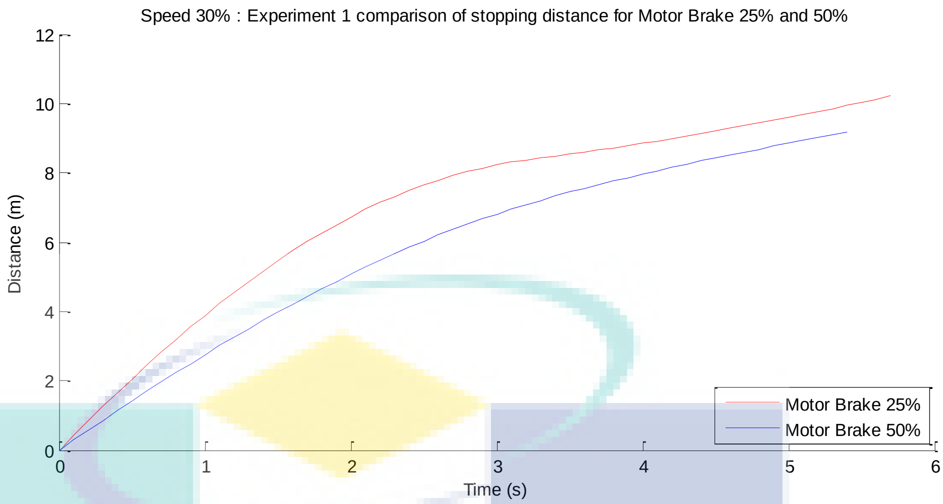


Figure 4:23 Experiment 1: Speed 30% stopping distance comparison between Motor Brake 25% and 50%.

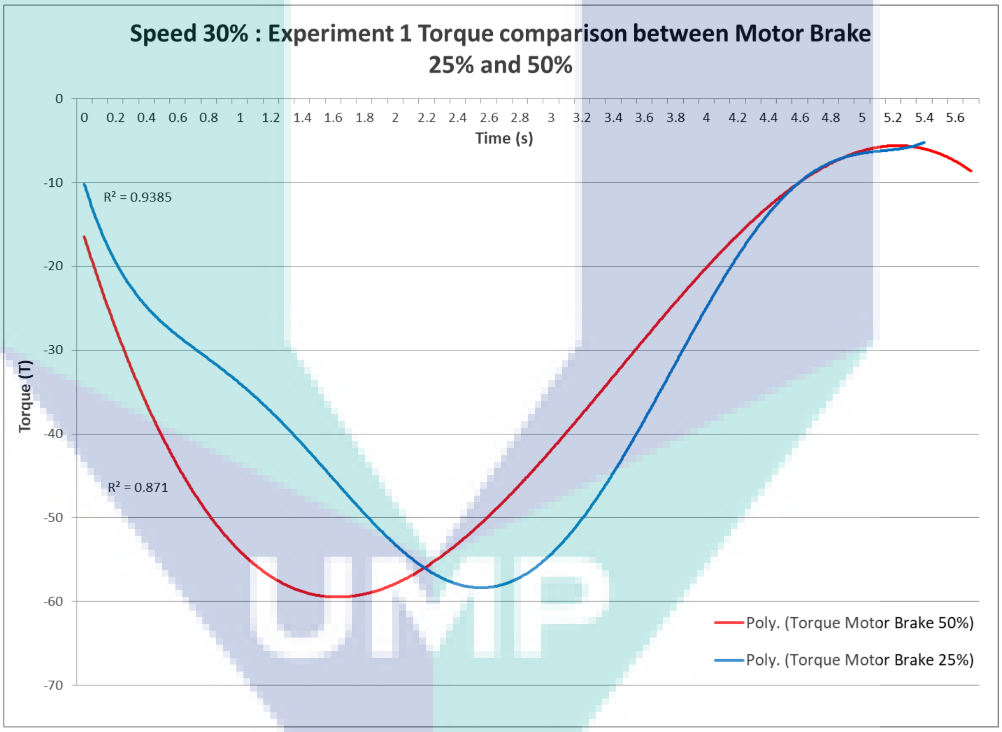


Figure 4:24 Torque comparison for Experiment 1: Speed 30% Motor Brake 25% and 50%.

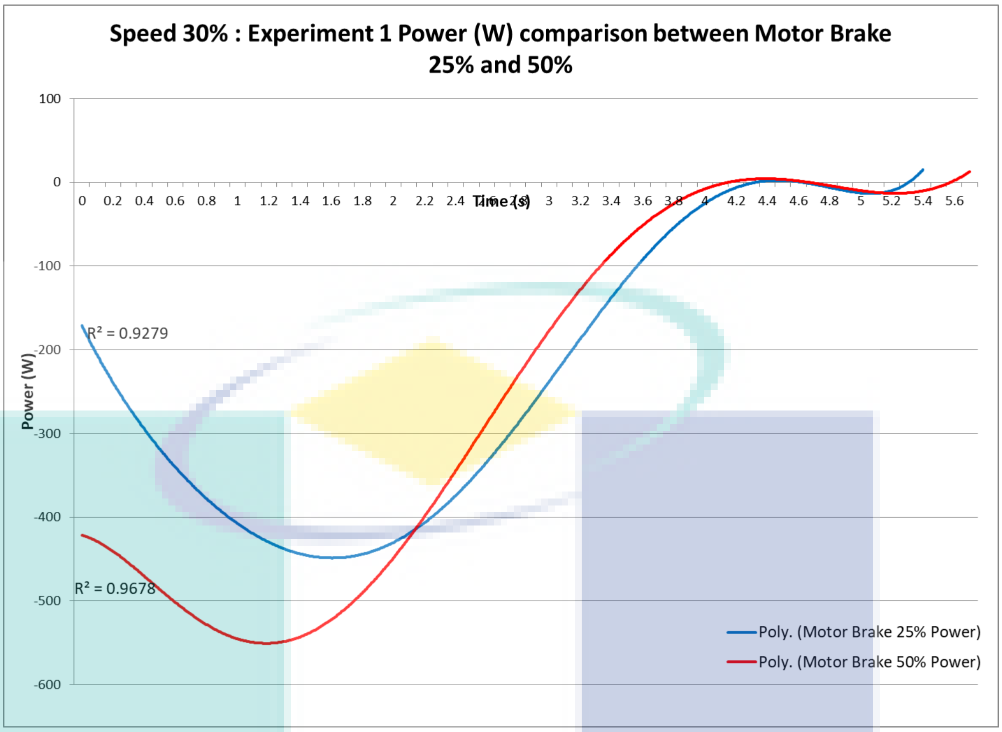


Figure 4:25 Torque comparison for Experiment 1: Speed 30% Motor Brake 25% and 50%.

From the Figure 4.24 and 4.25, there are comparisons for the torque and power produced of Motor Brake 25% and 50%. The patterns for the torques produced in Figure 4.24 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 4.25, 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 4-6 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%

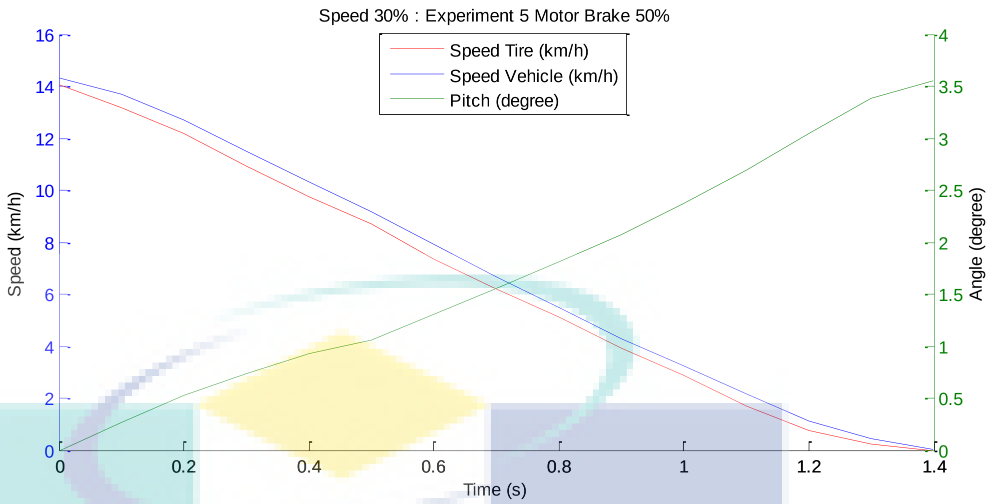


Figure 4:26 Result for Speed 30% Experiment 5 Motor Brake 50%.

Figure 4.26 shows that the result for the Experiment 5 Motor Brake 50%. The stopping time is recorded at 1.3 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 4.27, 4.28 and 4.29 shows the other comparison. In the Table 4.7 below shows the detailed results as well as improvements.

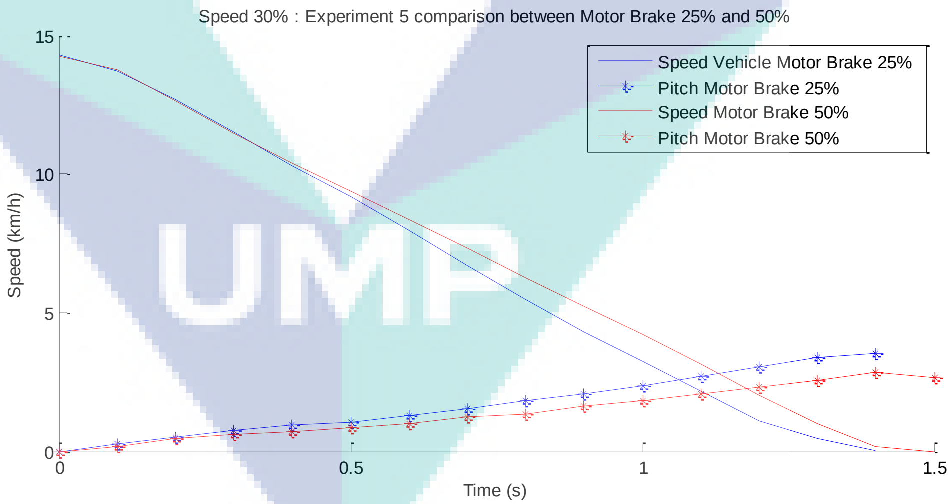


Figure 4:27 Speed comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

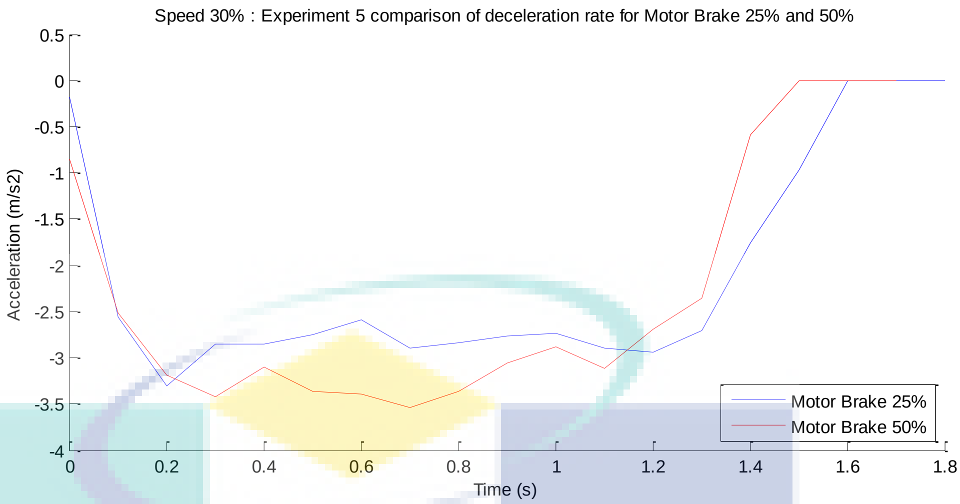


Figure 4:28 Deceleration rate comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

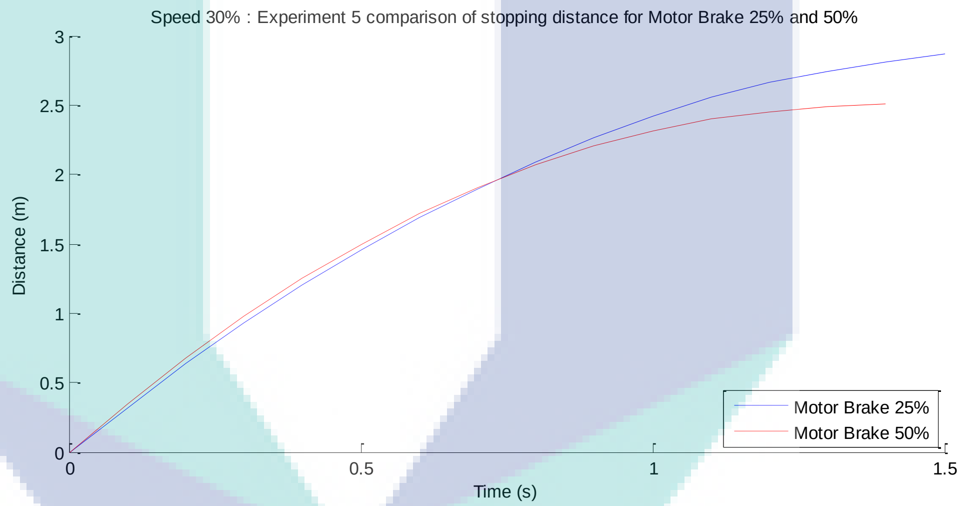


Figure 4:29 Distance comparison for Speed 30% Experiment 5 Motor Brake 25% and 50%.

Table 4-7 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 m/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 increase of motor brake efforts as well as human behaviour also affect the pitch recorded.

4.2.3 Speed 60% 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 again, it will not show the highest braking performance though the performances improved. The Experiment 2 and 4 are not repeated again due to no usage of motor brakes.

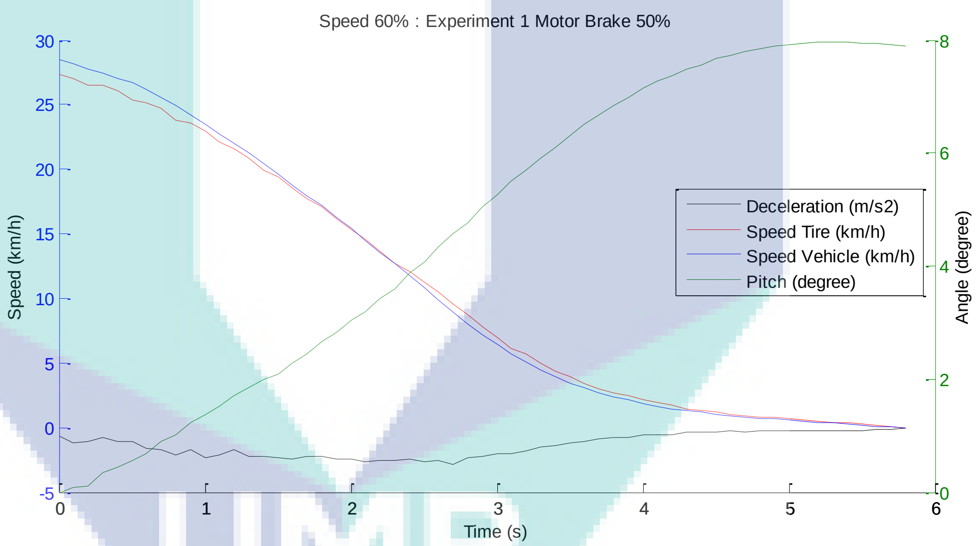


Figure 4:30 Average in Experiment: Speed 60% with Motor Brake 50%.

From the Figure 4.41, the stopping time is recorded at 5.8 s, and the stopping distance is recorded at 22.03 m. It show 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 the braking performance. Thus, the braking method for motor brake can be considered as dynamic braking as the braking effort can be changed.

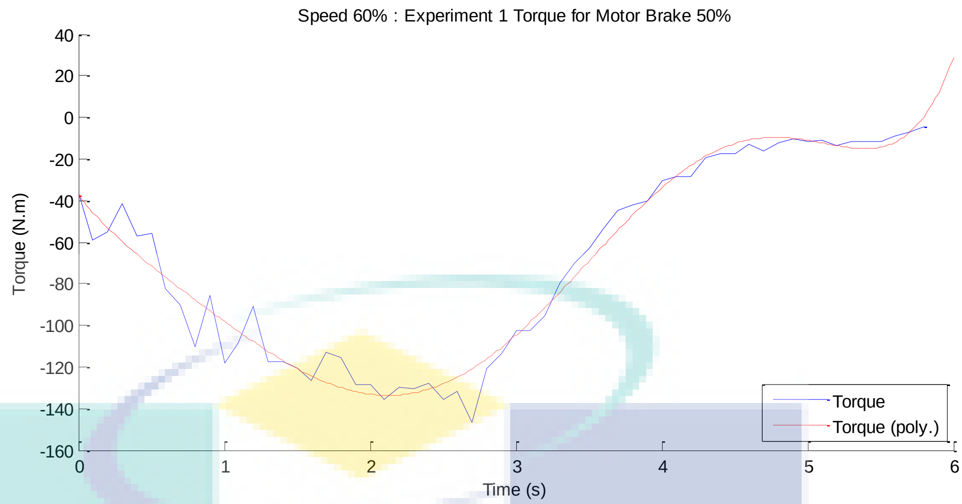


Figure 4:31 Torque for Speed 60%: Experiment 1 Motor Brake 50%.

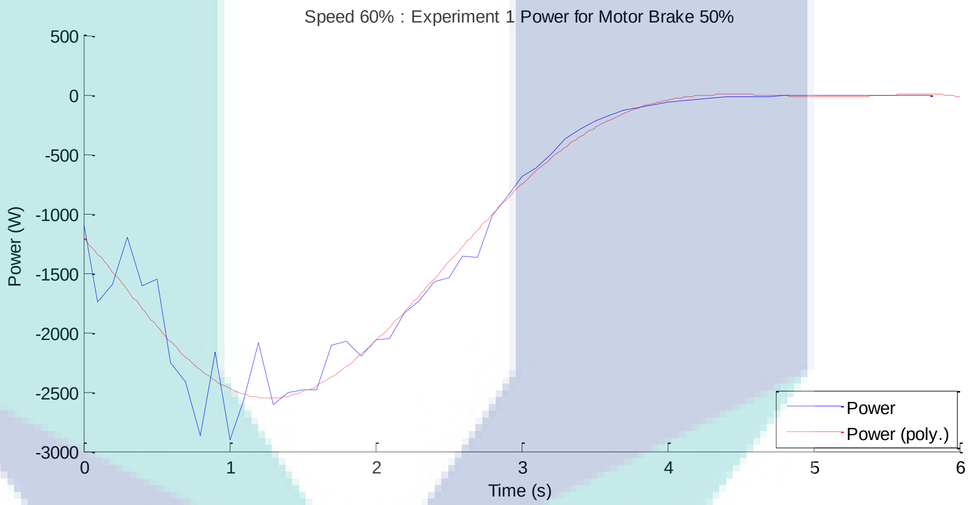


Figure 4:32 Power for Speed 60%: Experiment 1 Motor Brake 50%.

In the Figure 4.42 and 4.43 shows the graph for the torque and power over the time. The torque and power are calculated from the Equation 3.9, 3.10 and 3.11. Highest torque is recorded to be at -132.77 Nm while highest power is recorded at -2555.63 W. It shows significant increase of the torque and power when compared to the Motor Brake 25% in Figure 4.31 and 4.32. The graph shows the actual results as well as the polynomial lines for the easier understanding. R^2 value for the torque is 0.9609 and 0.9718 for the power.

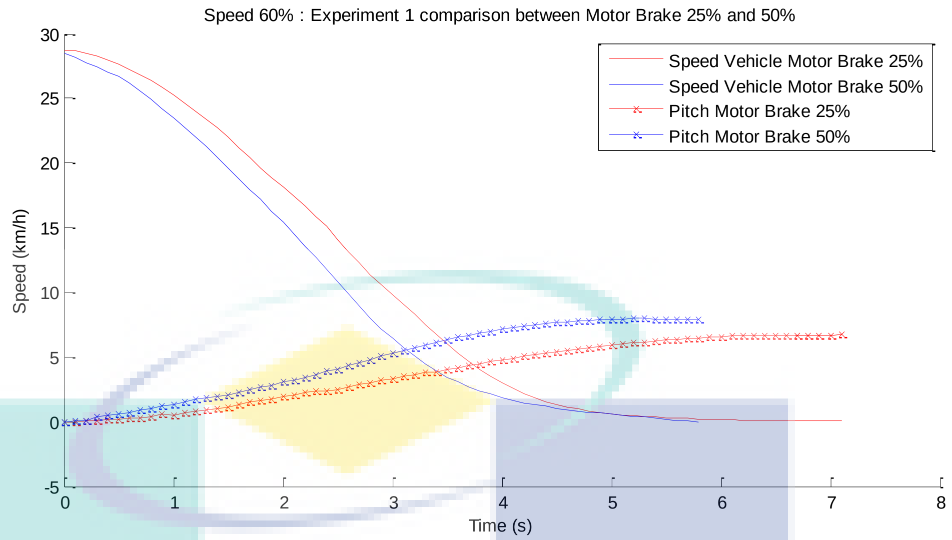


Figure 4:33 Comparison of stopping time for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

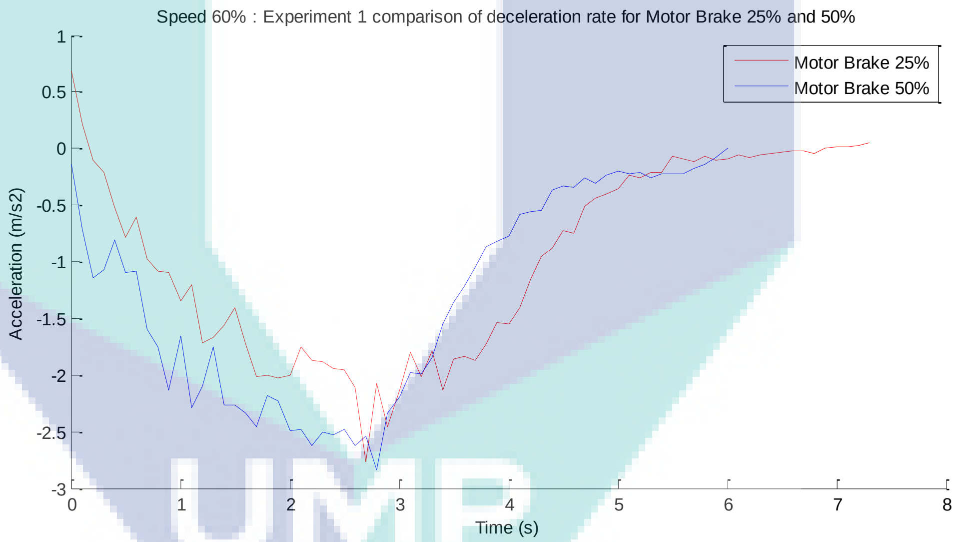


Figure 4:34 Comparison of deceleration rate for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

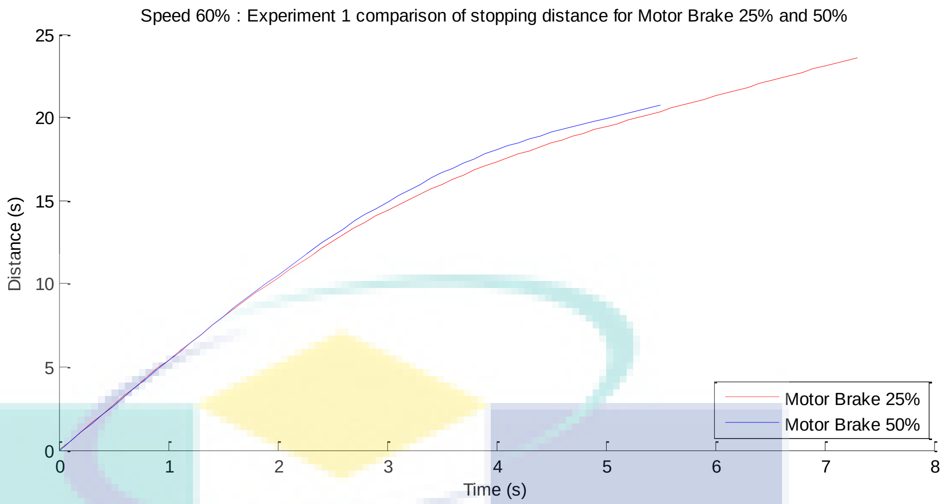


Figure 4:35 Comparison of stopping time for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

From the Figure 4.44, 4.45 and 4.46, shows the comparison for the Motor Brake of 25% and 50%. For the deceleration rate in Figure 4.45, Motor Brake 50% shows 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 higher value of torque and power.

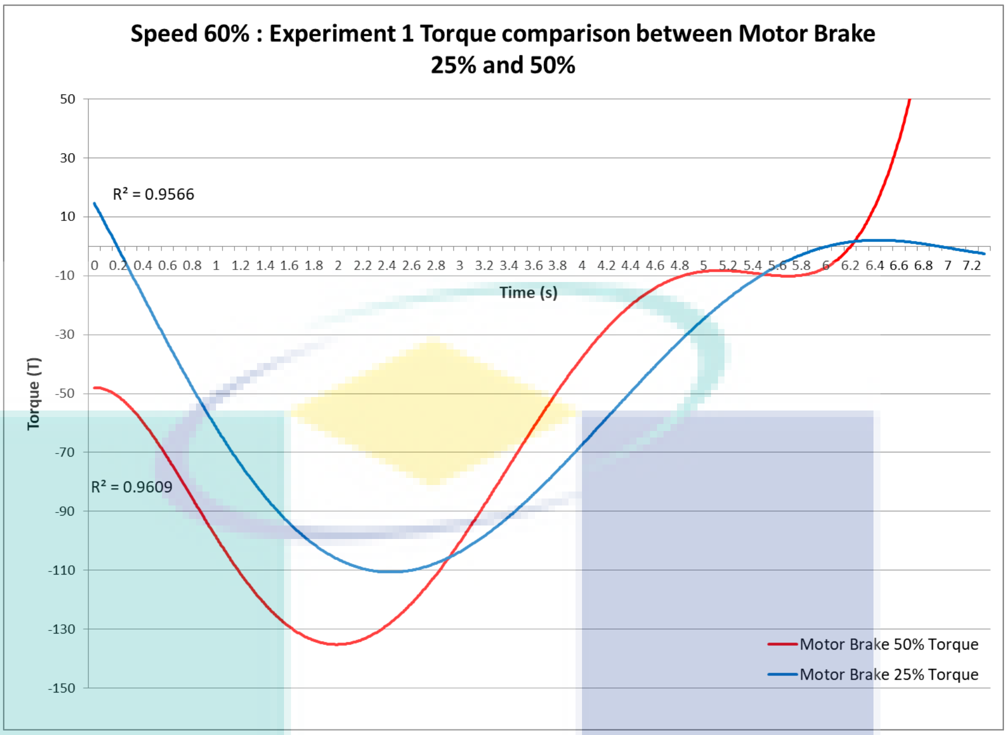


Figure 4:36 Comparison of torque for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

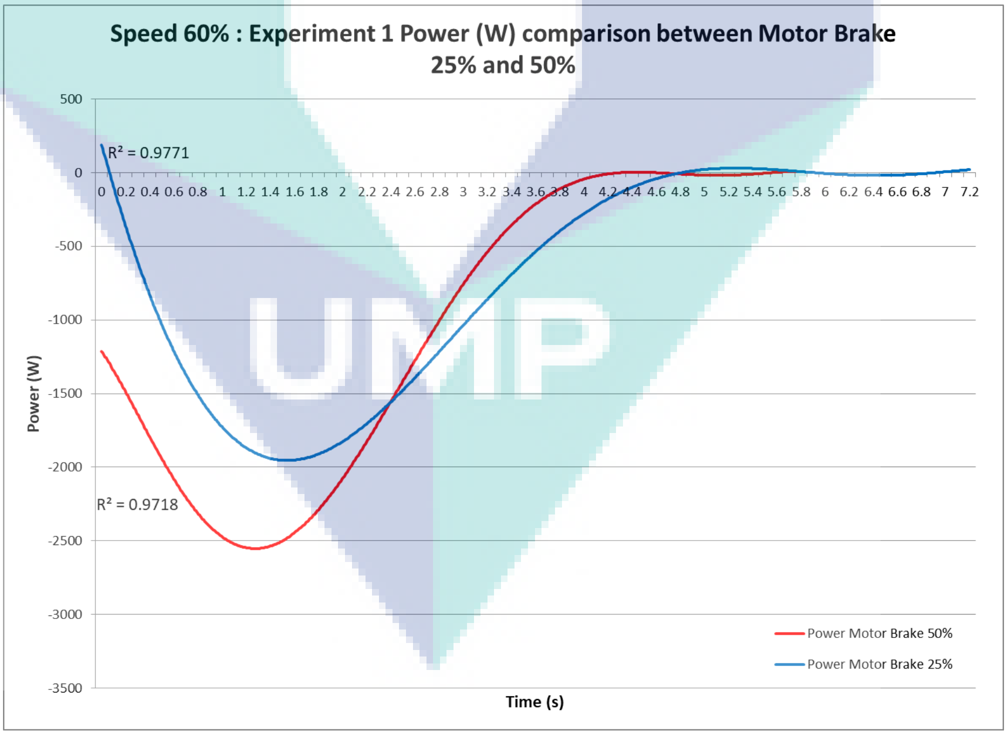


Figure 4:37 Comparison of power for Speed 60%: Experiment 1 Motor Brake 25% and 50%.

Table 4-8 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%

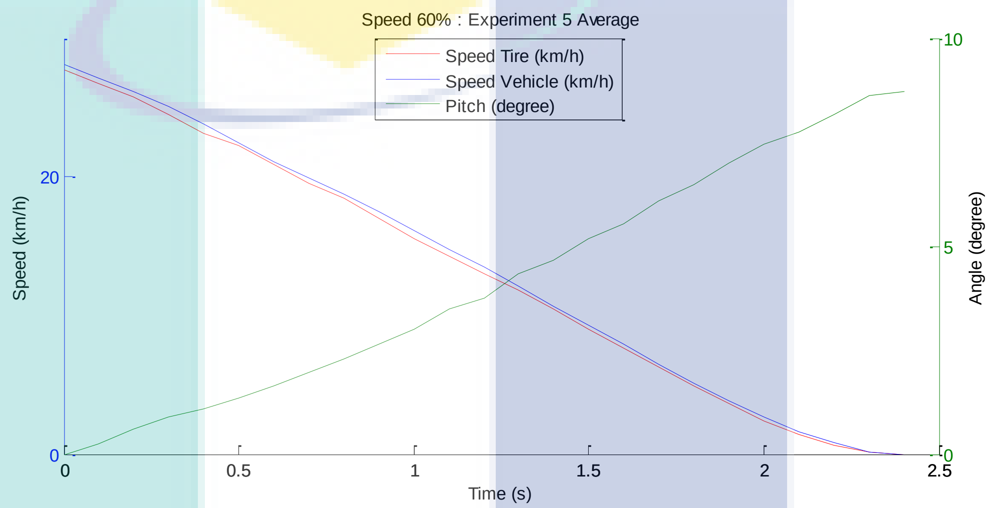


Figure 4:38 Average result for Experiment 5: Speed 60% Motor Brake 50%.

In Figure 4.49, 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 4.36. 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 the Figure 4.49, 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 the better stopping performance.

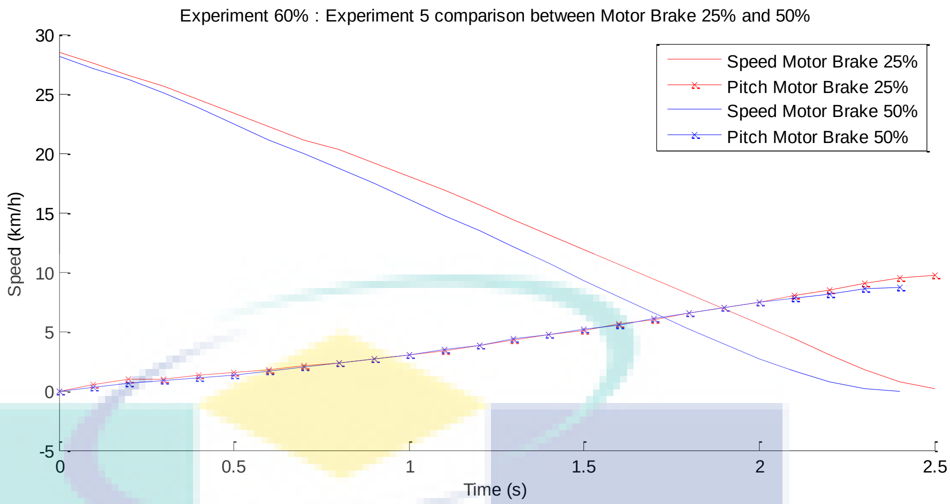


Figure 4:39 Results comparison for Experiment 5: Speed 60% Motor Brake 25% and 50%.

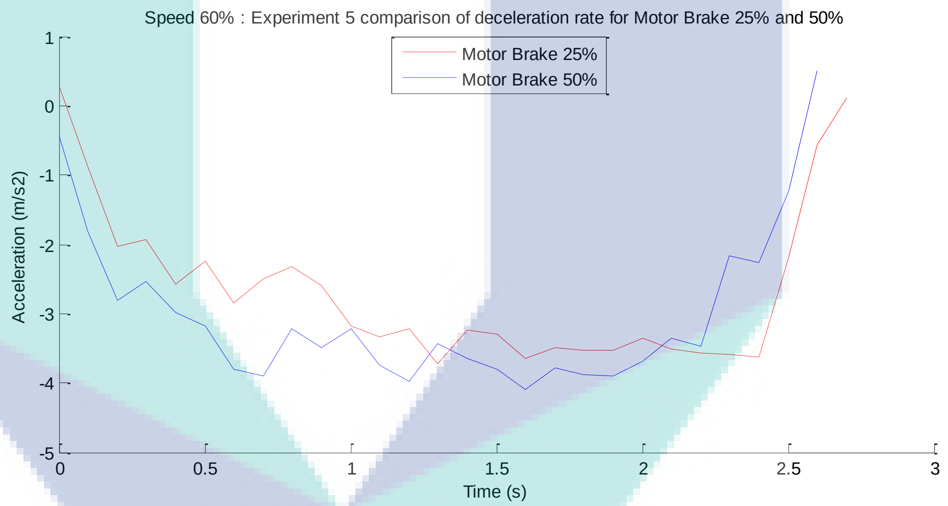


Figure 4:40 Comparison of deceleration rate for Experiment 5: Speed 60% Motor Brake 25% and 50%.

From the Figure 4.50 and 4.51, there shows 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 4.52 below, there are slight improvements for the stopping distance. From 9.5 m to 8.8 m, it shows that there is improvement of 0.7 m in stopping distance.

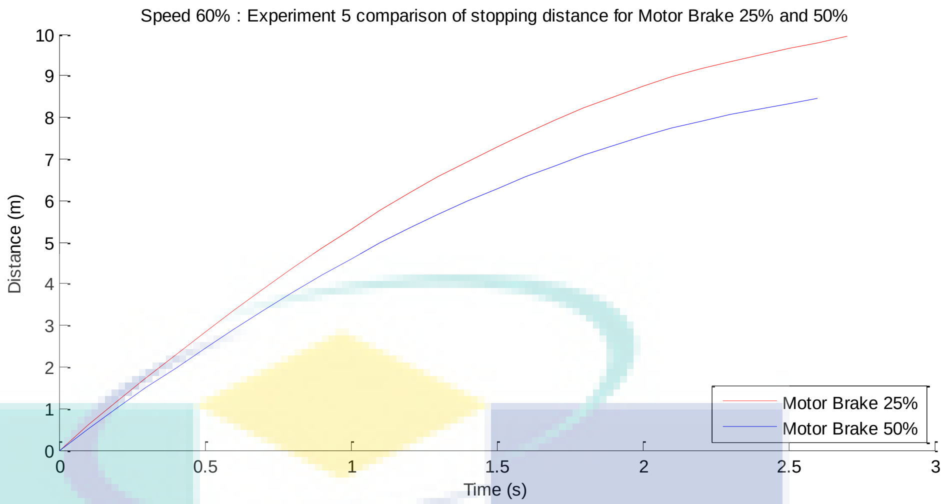


Figure 4:41 Comparison of stopping distance for Experiment 5: Speed 60% Motor Brake 25% and 50%.

Table 4-9 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%

From the Table 4.10 above shows the summary results for the 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 the 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 [30, 31].

4.3 Simulation Results

4.3.1 Validation

In order 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 4-10 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, the Equation 4.1 is used. The normal percentage error between the experiments and simulation data will be within 10%.

$$Percentage\ Error, |\%| = \frac{Experiment - Simulation}{Experiment} \tag{4.1}$$

From the Table 4.7, the validation data of the experiments and simulations are identical to each other. The parameters of the simulation should be the same with the experiments (vehicle specs, friction, etc) so that identical data could be generated.

4.3.2 Simulation during Panic Braking without ABS

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 panic situation. There were around 599 correspondents involved during the experiments. Most of the drivers are able to exert at least 90 lbs of pedal force or 400 N in SI scale [32].

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 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.

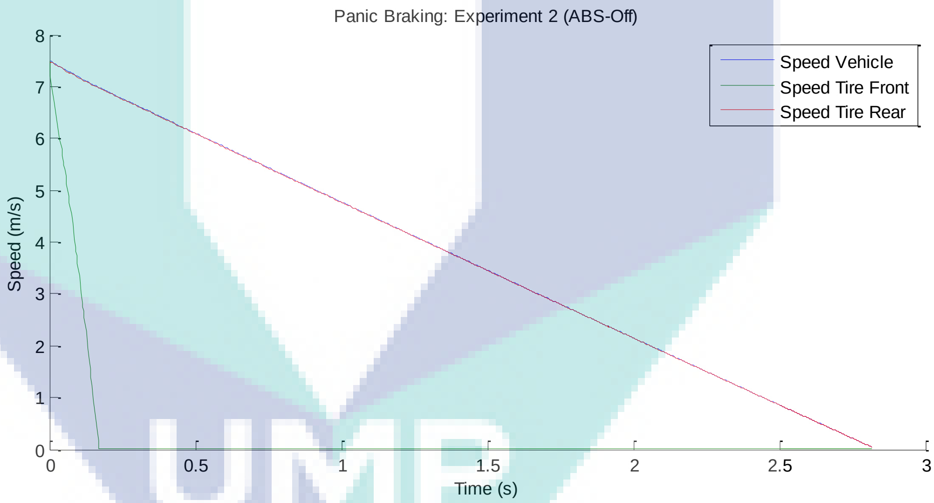


Figure 4:42 Simulation of panic braking for the Experiment 2.

From the Figure 4.53 above, 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 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.

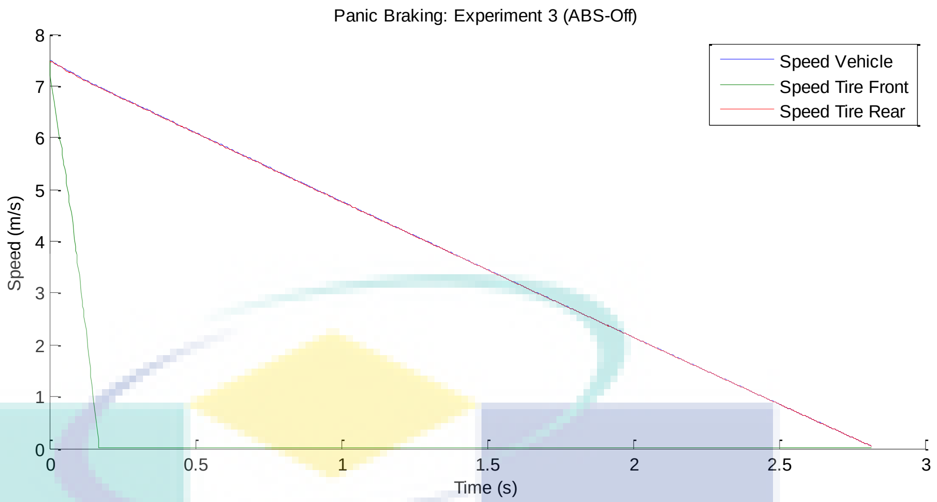


Figure 4:43 Simulation of panic braking for the Experiment 3.

From the Figure 4.54 above, 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 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.

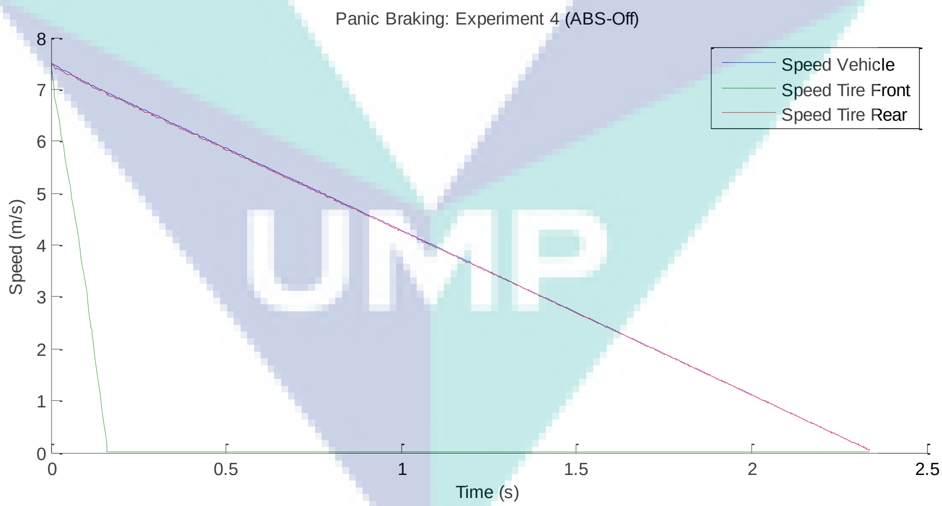


Figure 4:44 Simulation of panic braking for the Experiment 4.

As in Figure 4.55, the front and rear tires are applied with the brake force, while no motor brakes force are applied to the rear tires. The front tires are completely in 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.

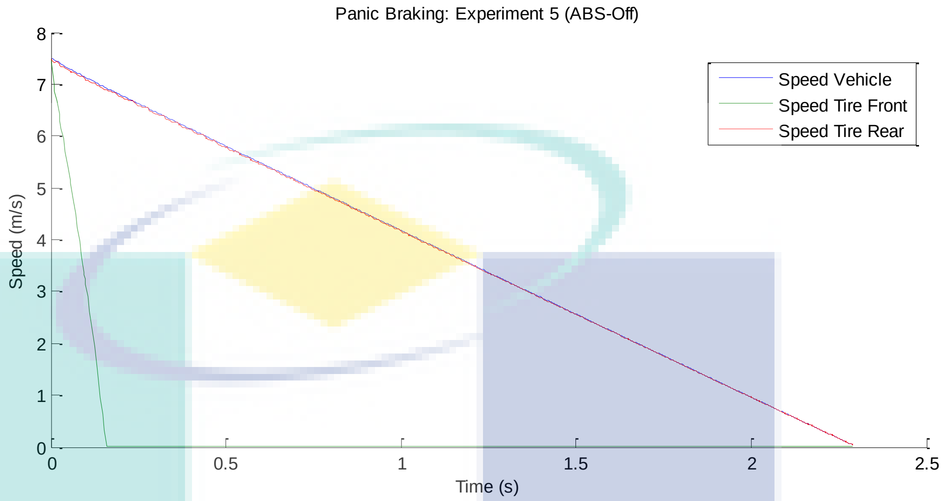


Figure 4:45 Simulation of panic braking for the Experiment 5.

As in Figure 4.56, the front and rear tires are applied with the brake force, while motor brakes force are 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 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.

Table 4-11 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 m

4.3.3 Simulation during Panic Braking with ABS

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 the braking performance, especially in terms of stopping time and stopping distance.

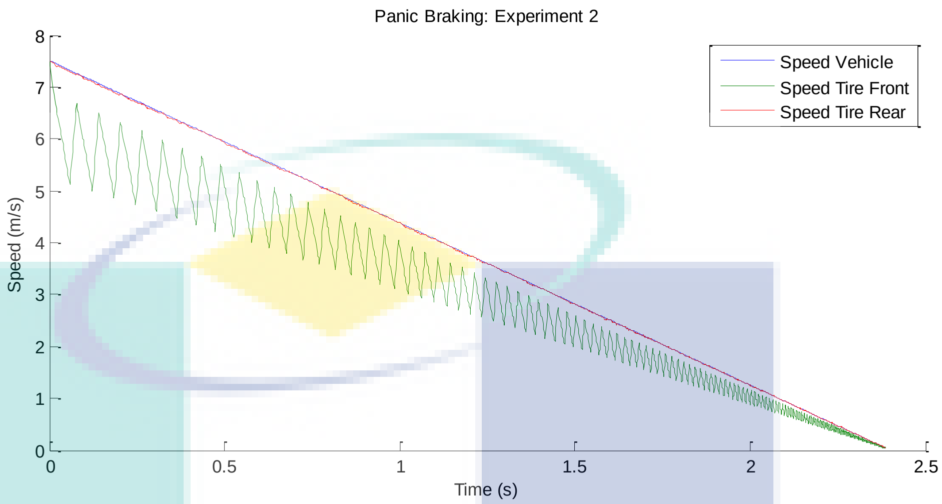


Figure 4:46 Simulation of panic braking for the Experiment 2 (ABS-On).

From the Figure 4.57, only front disc brake forces are 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 above, the speed of 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 braking method of Experiment 1, there are no possibilities of conducting the simulations because there is only motor brake forces applied to the EV. Thus, there will be no relation of pedal force to the motor brake forces.

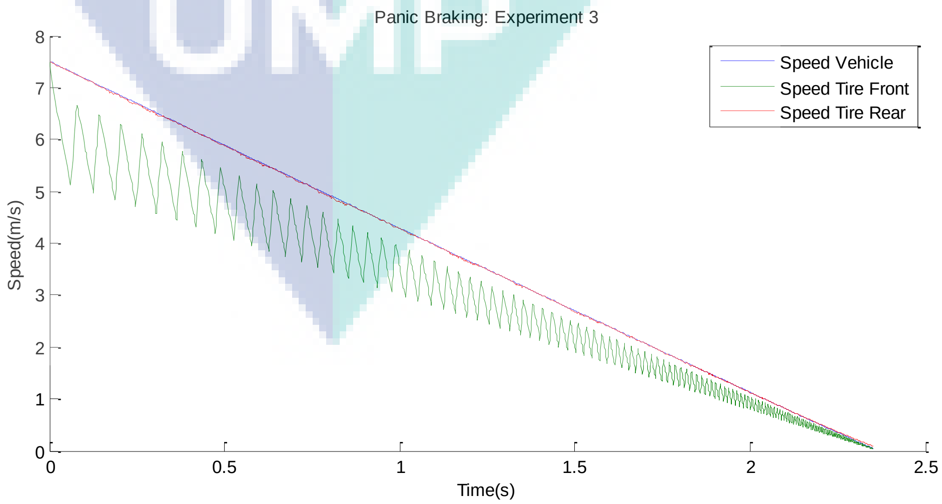


Figure 4:47 Simulation of panic braking for the Experiment 3 (ABS-On).

From the Figure 4.58, 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.

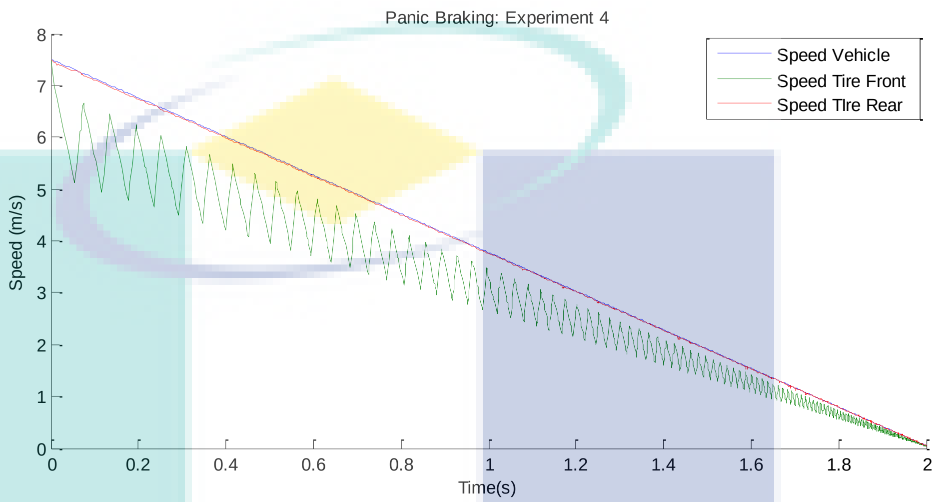


Figure 4:48 Simulation of panic braking for the Experiment 4 (ABS-On).

For the simulation of Experiment 4 as in Figure 4.59, 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 the both of front and rear disc brakes. Only motor brakes are not applied during the simulation.

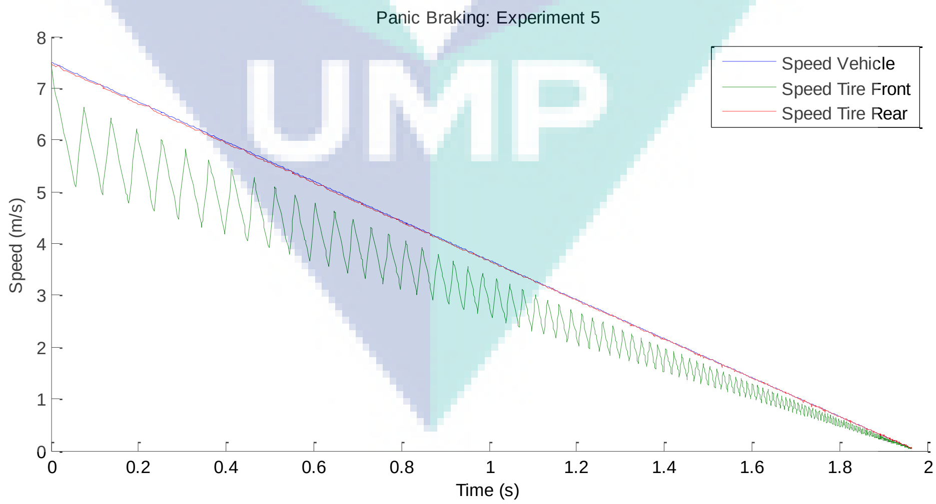


Figure 4:49 Simulation of panic braking for the Experiment 5 (ABS-On).

From the Figure 4.60 above, 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.

Table 4-12 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

CHAPTER 5

CONCLUSION

5.1 Introduction

The last chapter of the whole thesis is to summarize the whole result chapter and to recommend any further improvement for the project. The conclusion was concluded base on the result obtained from the experiments as well as simulations for this project. The recommendation is based on the potential of this study to be improved in the future.

5.2 Conclusion

The objectives of the project have been achieved, which is to study the braking performance with the combination of different braking methods. Based on the results obtained, there are areas which produce some rigid findings.

In order to conduct the Experiment 4 and 5, which is combination of front and rear disc brakes, the disc brakes must be fabricated. Before the fabrication process conducted, the disc brake was analysed. Next, the proposed design of fabricated disc brake was analysed too, and then compared with the data analysis of original disc brake. It was shown that the stress applied to the fabricated disc brake is below than the ultimate tensile stress, and most of all, the temperature increase is lower than 120°C.

During the experiments, it was expected that the combination of front and rear mechanical disc brakes with the rear motor brakes will produce the best braking performance. And the results from the experiments conducted have shown that the stopping time and distance of the Experiment 5 is the lowest compared to the other methods of braking. With the increase of motor brake to 50%, the braking performance has improved. From the deceleration rate of only 3.241 m/s^2 for Experiment 5 Motor Brake 25%, it has improved to 3.456 m/s^2 for Experiment 5 Motor Brake 50%. It is concluded that Speed 60%: Motor Brake 50% has achieved the highest braking performance for the whole experiments.

In order to go through the simulation in Panic Braking, the validation process must be conducted first. By following the same parameters as in experiments, the results of the experiments are verified with the results from the validation process. The simulation parameters data are only accepted when the difference of percentage for the data below than 10%.

After the validation, the next step was conducting the simulation in Panic Braking criteria. From the research conducted by Mortimer et al, the average pedal forces exerted by the driver would be 400 N. From this, the calculation has been done, and brake forces for the front and rear wheels have been determined. Then, simulations have been done by utilizing the ABS function of the front and rear wheels of the vehicle. Second simulations were done by adding the ABS function to the wheels, to see whether there will be braking performance improvements or not. From this simulation, it could be concluded that the fifth method of braking would produce the best stopping time and stopping distance.

5.3 Recommendations

In this project, it is approved by experiment that the motor brake can improve the braking performance of the vehicle. The simulation results have shown that the motor brake also can be an actuator of ABS to prevent the tire from lock-up during emergency braking. For future works, it is recommended to control the regenerative brake on the wet surcafe.

CHAPTER 6

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