SPEED CONTROL OF 4-WHEEL ELECTRIC VEHICLE USING PI BASED CONTROLLER

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in fulfilled of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "Speed Control Of 4-Wheel Electric Vehicle Using PI Based Controller" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

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Date :

APPROVAL

I have checked this report and the report can now be submitted to JK-PSM to be delivered back to supervisor and to the second examiner.

Signature :...................................

Name of Supervisor :...................................

Date :...................................

DEDICATION

I will dedicate this thesis to my beloved family, lecturer and friends that always support me during my hard time.

ABSTRACT

This thesis presents the modelling, simulate and control of an electric vehicle to investigate their performance after running for a 1500 second. This electric vehicle was built using individual components and each component selection based on the previous research and discussion with supervisor. The basic component for the electric vehicle drivetrain were electric motor, battery, power electronics, driver controller, vehicle body and a drive cycle. This drivetrain was validated with a real vehicle first before modelling it through a Matlab-Simulink software and it just viewed as a Vehicle Longitudinal Model. The regenerative braking system also included in this simulation cause by the ability of the dc motor to act as a generator during braking. Several simulation tests were performed by employing the same reference speed as the vehicle validation which were 40 km/h, 60 km/h, and another reference speed proposed by Society of Automotive Engineer (SAE), namely the Federal Test Procedure 75 (FTP75). The result of this study shows the simulation about the velocity, torque, power, current, voltage of the motor and the battery state of charge (SOC).

ABSTRAK

Tesis ini berkaitan pemodelan, simulasi dan kawalan kenderaan elektrik untuk menyiasat prestasi kenderaan setelah berjalan selama 1500 saat. Kenderaan elektrik ini dibina menggunakan individu komponen dan setiap pemilihan komponen adalah berdasarkan kajian dan perbincangan sebelumnya dengan penyelia. Komponen asas untuk "drivetrain" kenderaan elektrik adalah motor elektrik, bateri, elektronik kuasa, pengawal pemandu, badan kenderaan dan kitaran pemacu. "Drivetrain" ini disahkan dengan kenderaan sebenar terlebih dahulu sebelum memodelkannya melalui perisian Matlab-Simulink dan ia hanya dilihat sebagai Model Longitudinal Kenderaan. Sistem brek regeneratif juga dimasukkan dalam simulasi ini disebabkan oleh kemampuan dc motor untuk bertindak sebagai penjana elektrik semasa menekan brek. Beberapa ujian simulasi dilakukan dengan menggunakan kelajuan rujukan yang sama dengan pengesahan kenderaan iaitu pada 40 km/jam, 60 km/jam dan kelajuan rujukan lain yang dicadangkan oleh "Society of Automotive Engineer" (SAE), iaitu "Federal Test Procedure 75" (FTP75). Hasil kajian ini menunjukkan simulasi mengenai halaju, daya kilas, kuasa, arus, voltan motor dan bateri "State of Charge" (SOC).

ACKNOWLEDGEMENT

First and foremost, I want to thank my advisor Dr. Fauzi bin Ahmad. It has been an honour to be his Degree Project student. I appreciate all her contributions of time, and ideas to make my Degree Project experience productive and stimulating. The joy and enthusiasm he has for his research was contagious and motivational for me, even during tough times in the Degree pursuit. I am also thankful for the inspiration and encouragement during conducting this thesis.

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LIST OF ABBREVIATIONS

PI	Proportional Integral
N-PI	Nonlinear proportional integral
EV	Electric Vehicle
BEV	Battery electric vehicle
ICE	Internal Combustion Engine
ICEs	Internal Combustion Engines
SOC	State of Charge
DOF	Degree of Freedom
HEV	Hybrid Electric Vehicle
PID	Proportional integral derivative
AC	Alternate Current
DC	Direct Current
FTP75	Federal Test Procedure 75
WLTP	Worldwide harmonised light vehicle test Procedure
NEDC	New European driving cycle
KM/H	Kilometres Per Hour
KG	Kilogram
M	Metres

V	Voltage
AH	Ampere-Hour
SAE	Society of automotive engineer
CG	Centre of gravity
CC	Cubic centimetres
PMSM	Permanent magnet synchronous motor

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CHAPTER 1

INTRODUCTION

1.1 Overview

The electric vehicles (EVs) are innovations in automobile industry that is powered by an electric motor rather than the petrol or diesel engine. The EVs are future transport for community, and this technology already available in the market but with a little value. This small value is a due to the shortcomings found in this technology that needs to be improved regarding infrastructure and modern technology accepted by the community. The EVs are safe to use to the environment and need to expand its use. Common issues that still bother many consumers as well as the limited driving range, battery charging issues, high costs and scarce charging infrastructure in markets. This problem needs to be researched to find the solution, but the actual studies will cause the high cost and take a long time. This research is conducting to develop an updated of EV be more advance and subsequently able to gain wider adoption in the market. Focus of this study are to model and validate an EV, simulation, control of EV model and to assess the ability of the design EV in the variable speed limit. The findings indicate the performance parameters for the speed, state of charge and current with a drive cycle through the simulation results. This may be a decent prediction to explore and improve this technology for the future.

1.2 Research Background

Petroleum derived from the fossil fuels is a major source of energy used in ICE. These fossil fuels take a long time to produce because it is formed from natural processes such as embedded anaerobic decay of dead life. However, the rate of utilization of the fuel advances higher than the rate of creations. It will be totally depleted without any petroleum products to satire the high demand. Electric vehicles are seen as one of the best solutions to this problem because of its advantages such as more efficient, environmentally friendly, quiet, and more powerful than ICE regarding speed. To drive the EV system, one or two electric motor each can be used for each wheel, in this study, the case of two-wheel drive electric motor is to be considered.

In addition, an EV generally uses a battery as its main power source (Bambang Sri Kaloko *et al*, 2011) (Dhameja “S”, 2003) (Husain, I. 2003). Meanwhile, vehicle energy resource is a major challenge affecting driving distance, long charging time and a high cost. The power source or battery pack of an EV should have enough power for a certain driving range and sufficient power capability for the accelerations and decelerations. To estimate the energy consumption of an EV, it is very important to have a proper model of the vehicle (Gao *et al*., 2007; Mapelli *et al*., 2010; Schaltz, 2010). The model of an EV is very complex which it contains many components such as electric machines, battery, power electronics and transmission while each of the component need to be modelled properly to prevent wrong result. The design or rating each component's parameters is a difficult task because it will affect the power level of another one. If one of the components is rated inappropriately, it might make the vehicle unnecessary expensive or inefficient.

Next, the limitation of regenerative braking system because not all braking energy can be recycled. It is influenced by many factors such as braking intensity and battery state of charge (SOC). For a conventional car, only 20 percent of the energy efficiency will be recycled and remaining 80 percent of its energy being converted to heat through a friction. The focus of this study will be on modelling, control and simulate an EV. The less consideration will be put on determination of each component for power system as this is a tremendous task in itself.

1.3 Problem Statement

The problem statement of this study are as follows:

i. Misunderstanding concept of the electric vehicle's operation. Electric vehicle is powered by an electric motor or traction motor to generate torque instead of an internal combustion engine. The main component for the EV are electric motor, the battery pack, and the power controller. Rapid development of this technology makes it is difficult to learn and understand.

ii. High cost for prototyping construction. Any new technology that will use in EV need to be tested and must be validated its durability.

iii. Limitation of driving range for the EV comparing with the petrol or diesel engine. This cause by the limitation of the charging station in the market and then make it is difficult to improve the capability of EV.

1.4 Objectives

The objectives of this project are as follows:

i. To model and validate a longitudinal model using Proton Iswara to be used in the simulation.

ii. To simulate and control of electric vehicle by using PI based controller.

iii. To evaluate the speed control of the designed EV and regenerative braking system in variable speed driving conditions.

1.5 Scope Of Project

The scopes of this project are:

i. The Electric Vehicle model utilized in this investigation is viewed as Vehicle Longitudinal Model.

ii. Only considered 5 degrees of freedom (DOF) on handling and ride model in this investigation.

iii. The braking characteristic like tire longitudinal slip, stopping time and stopping distance would not been focused since this study just to grasp the ability of the braking system to generate current during braking.

iv. Only use the constant speed at 40 km/h, 60 km/h and Federal Test Procedure 75 (FTP75) as a simulation reference.

v. Note that, all the simulations are made in programme MATLAB Simulink software.

1.6 Thesis Outline

The thesis.is organised as follows, with each section containing a substantial amount of knowledge on the topic:

Chapter 1: This section includes a general summary, the context of the research, a statement of issues, the study's objective, scope, and relevance.

Chapter 2: This part presents a literature review with respect to the EV system. This chapter also included the modelling and simulation studies of an EVs that have been made before.

Chapter 3: This section presents about the methodology that used in this thesis. Two (2) phases to be discuss in this section that are Phase.1: Modelling and validation the Electric Vehicle Model and Phase 2: Simulation and Control of Electric Vehicle. The Vehicle Longitudinal Model is considered to modelling the EV model. When the Electric Vehicle Model has been approved, simulations of Electric Vehicle can be conduct with a various configuration and parameters through the drive cycle.

Chapter 4: This part examines the discoveries and discussions that emerge from simulation and testing. It explained about the result of the simulation of an EV. The discoveries of the connection among the simulation result and experimental are discussed.

Chapter 5: Next, this stage consists of the summary about the study's completion. This section also provides a last comment on the new idea as a commitment in the EV research zone. Finally, recommendations and directions for future research are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As an alternative toward the green transportation in this world, the electric vehicle (EV) technology began to get attention from the public. This technology appeared a few centuries ago, but it still could not match the capabilities of the internal combustion engine and caused it failed to be a competitor in the market. Through much advancement has been made in the past decade, the wide adoption of this technology still in question. In this chapter, the history respect to the EVs technology and previous research about it such as for modelling, control and simulate are also discussed.

2.2 History of Electric Vehicle

An EVs started to appear after the invention of the power source that is a battery. In 1821, electric motor has been created by the English chemist Michael Faraday. In 1822, the Faraday's motor was applied to turn a wheel by Peter Barlow, English Mathematician and Physicist. In 1831, the world's first dynamo was created by Faraday than can create an electrical energy by the use of mechanical. Then, the electric locomotive was made in 1838. In 1841, Galvani that the name of larger loco was created by Davidson, but it did not last long in the market due to high price which caused their invention went to the end. After that, a Dutch chemistry professor, and Sibrandus Stratingh were invented a more practical battery-powered carriage which caused a good performance, but it was very noisy, smoky, and uncomfortable while being tested. Then, the way to recharge battery was found by Gaston

Plante, a Belgian scientist and the first EV was invented by Gustave Trouve from France in 1881 powered by the rechargeable batteries. In that year, a three-wheeled EV powered by rechargeable batteries was introduced. Up to this year, many electric vehicles have been successfully produced by developers including Nissan Leaf, BMW i3 and Tesla Model S.

2.3 Previous Research of Modelling, Control and Simulate the EV.

An Electric Vehicle (EV) technology is evolving very fast at all times and all over the world. It causes from the development of automated technology that previously used non-renewable energy such as petroleum or diesel fuel to more environmentally friendly energy consumption that is electric energy and the most importantly it is renewable energy. Tali Trigg and Paul Telleen (2013) stated in the city areas, internal combustion engine (ICE) becomes an issue for the second highest factor of the global warming approximately 21% of greenhouse gasses emissions. Due to current concerns about environmental pollution, such as noise and exhaust emissions, electric vehicles (EVs) are gaining popularity around the world. EVs are classified into three types which are battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). BEVs and FCEVs are electric vehicles that powered entirely by the electricity, as opposed to HEVs, which it combines a conventional powertrain with an electric motor. BEVs are one of the most promising indicators for the automotive industry among these three categories of electric vehicles. In comparison to FCEV, and unlike HEV, BEV does not release any polluted gases into the air due and it is a mature technology.

Most EVs have five major components a vehicle body, an electric motor, a battery, a power converter and a controller. To achieve the best performance and solve previous problems, it is important to identify each of the EV components in modern technology. Chau (2014) explained how modern and advanced electrical drives are used in electric propulsion, as well as their energy storage and control systems. The authors summarised their current situation and future growth prospects at the conclusion of their study.

Research and testing of an EVs takes a long time and require a very high cost to produce prototypes, so testing through computer simulations began to be the focus by researchers. Researchers created virtual vehicles based on road-based data from vehicles using simulation and modelling tools to improve the performance of EV technology. There are many simulations and modelling software have been produced by the developers such as ADAMS/Car from MSC Software Corporation, CarSim from AeroVironment Inc., ADVISOR (DOE’s National Renewable Energy Laboratory, US), V-Elph (Texas A&M University), MARVEL (Argonne National Laboratory) and Nouh *et al.* (2006) stated that the latest software ELEctric VEhicle Simulator (ELEVES), is currently being developed in the University of Technology of Belfort-Montbéliard (UTBM) as a research project as assisting in the development of EV technologies. Each simulation of vehicle software has its own set of pros and cons.

Howroyd, S. and Thring, R. (2018) in his study present the modelling and simulation of the Nissan Leaf based on object-oriented approach to a vehicle model using Python 3 and S. Massey (2016) from Michigan Technol. Univ. also present about the modelling and simulation based on the Matlab-Simulink software for the Toyota Prius HEV system as a baseline using a brushless AC motor. The goal was to optimise the power drive mechanism of a modern passenger car for propulsion in an urban driving environment. K. L. Butler, *et al*. (1999) used a four-vehicle drive train in their investigation to model, simulate and analyze using Matlab-Simulink software including the full EV, HEV, parallel Hybrid EV (HEV) and ICE series. The objective is to look at contamination, fuel economy, and fuel efficiency. Using visual programming, the user can change all parameters, structures, and graphical analysis of the results easily.

CarMaker software differs from other software in that it not only tests passenger cars and light vehicles, but it can also simulate real-world test scenarios in the virtual world, including the entire environment. According to Varga *et al.* (2016), this software can solve hardware-in-the-loop (HIL) and complex-in-the-loop system hardware functional authentication control problems by integrating with other software such as MATLAB and dSPACE.

Modelling of an EVs need a lot of effort because of their complex system. Farhan A. Salem (2013) derived and represented the detailed and accurate mathematical models for both subsystem that are electric motor and the vehicle platform system in Simulink. S. A. H. M. Ali, *et al*. (2014) presents point by point about the Hybrid Electric Vehicle (HEV) modelling method using the multi-physics approach. A complete model of drive train system for HEVs from series to parallel has been implemented to give an opportunity for design engineer to analyse the component selection effects, develop control systems and automated optimization processes. In the same perspective, Shukla Amit (2012) has found that the modelling on an EVs able to be the basis of the advanced control system with additional features such as high fuel efficiency and make the car and its powertrain to be optimised.

Then, Qi Huang *et al*. (2010) discussed about the control of EV driven by a different motors and implementations of the controller with DSP and the results are presented. Similarly, Husain & Islam (1999) focuses on electric propulsion unit and drive evaluation to get the desire performance using a switched reluctance motor (SRM). On the contrary of the performance, Bambang Sri Kaloko *et al*. (2011) provided a model that can be used to estimate the battery life in EV and to determine the performance of it during starting process or running in constant speed.

Chang *et al.* (2015) stated that producing electric energy is one of the challenges in EV technology, citing his study as the first step towards systematic design and optimization of EVs using computer-aided design. On the contrary to the perspective model by Bai *et al.*, (2019) this focuses on the electric vehicle battery charger model, which should be reliable and efficient.

2.4 Components of electric powertrain

The configuration or architecture of EVs refers to the layout of EV components. There are three main subsystems of EV as shown in Figure 2.1 such as energy storage, electric propulsion and auxiliaries.

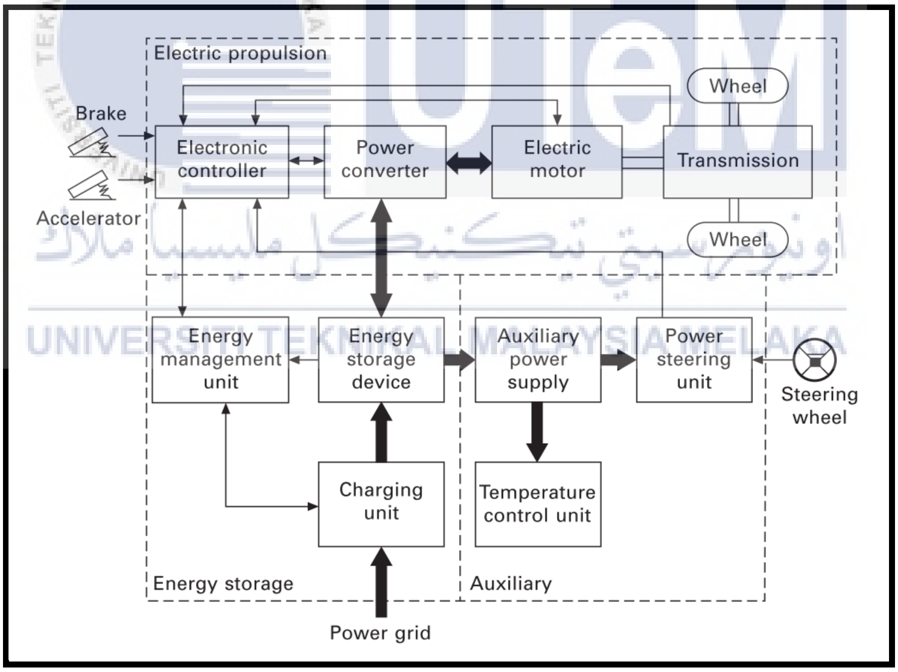


Figure 2.1: General EV system configuration (Chau, 2014)

The electric propulsion subsystem comprises of electronic controllers, power converters, electric motors, mechanical transmissions and driving wheels. A power steering unit, a temperature control unit and an additional power supply are the components of auxiliary system. The energy storage subsystem consists of energy storage devices, energy management units and charging units. This literature review from Chau (2014) focuses on certain EV components, which are motors, controllers, power sources, transmission, battery, and the drive cycle.

2.4.1 Electric motors

Electric motor is the most important element of the EV. The motor in an electric vehicle replaces the internal combustion engine. To move the wheel, the motor converts electrical energy into the kinetic energy in the form of torque. There are many different types of motors, but they all work on the same concept of creating torque by using the opposite electro-magnetic field. When a rectangular coil is placed in a magnetic field and current flows through it, the friction between the magnetic field of the motor and the electrical current in the wire produces energy in the form of shaft movement. Electric motors have a high efficiency that often surpasses 90%, making them far more efficient than engines with a peak efficiency of less than 40% (Leitman and Brant, 2009). High power density, high starting torque, and high efficiency are all desirable properties for electric motors used in automotive applications.

Since the performance of EV depends on electric motor, the development and control technique has made it possible to use various types of electric motors on it. In EV applications, there are five different types of electric motors such as DC, induction, switched reluctance, brushless DC motors and permanent magnet synchronous. Chau (2014) analysed the characteristics of each electric motor for use in electric vehicles. The results revealed that the DC motor required maintenance, the switched reluctance motor produced significant acoustic noise, making it undesirable in comparison to the induction motor, and the PM brushless motor had a high-power density, high efficiency, and low cost.

Nouh.*et al.* (2006) selected a Permanent Magnet Synchronous Motor (PMSM) as an electric motor in their simulation because of its low mass and potential for a high power-to-weight ratio. This led to the reduction in unsprung mass and improved drive comfort. In contrast to McDonald (2012), a DC motor was chosen for simulation due to its widespread use in undergraduate engineering education, despite the fact that, due to its weight and efficiency, it was no longer viable for use in EV applications. In modern electric vehicle applications, DC motors are no longer used.

2.4.2 Battery

Battery is the main power sources for the EV where it is the only energy storage containers and components that have high cost, volume, and weight. As a result, the performance of electric vehicles is determined by the battery architecture. The battery should be able to deliver enough current for the motor to move the vehicle in the long run. Hundreds of battery cells are connected in series and parallel in an electric vehicle to meet this demand. As each EV application battery type is different, there are several battery types that can be used for EV applications. As a result, some criteria were taken into account when selecting a suitable battery, such as life span, cost, safety, performance, specific power, and specific energy (Larminie and Lowry, 2003). The lithium-ion (Li-Ion) battery is the most often utilised battery type in electric vehicles, according to studies by Larminie and Lowry (2003). This battery meets all of the criteria listed above, with the exception of its high operating temperatures, which may have a negative impact on energy performance and lifecycle.

2.4.3 Regenerative braking

Regenerative braking is a type of electric vehicle (EV) system that saves and conserves energy by electrically converting the motor into a generator. The kinetic energy of a moving vehicle is frequently lost after the brakes are applied. Using a regenerative braking, which converts the motor into a generator, the lost kinetic energy will be saved in the car's battery. After the car accelerates again, previously stored energy will be used.

Spring, flywheel, hydraulic, and electromagnetic energy conversion techniques are all accessible in the Regenerative Braking System. An electromagnetic system connects the drive shaft to an electric motor, which employs magnet fields to limit drive shaft rotation, slow the vehicle, and generate electricity. The electricity generated is subsequently transmitted to the batteries, allowing electric and hybrid vehicles to be recharged. The kinetic energy of the vehicle is captured and used to spin a flywheel connected to the drive shaft by a transmission and gearbox. The drive shaft will then receive additional power from the rotating flywheel. The regenerative spring-loaded braking system is commonly found on bicycles, wheelchairs, and other human-powered vehicles.

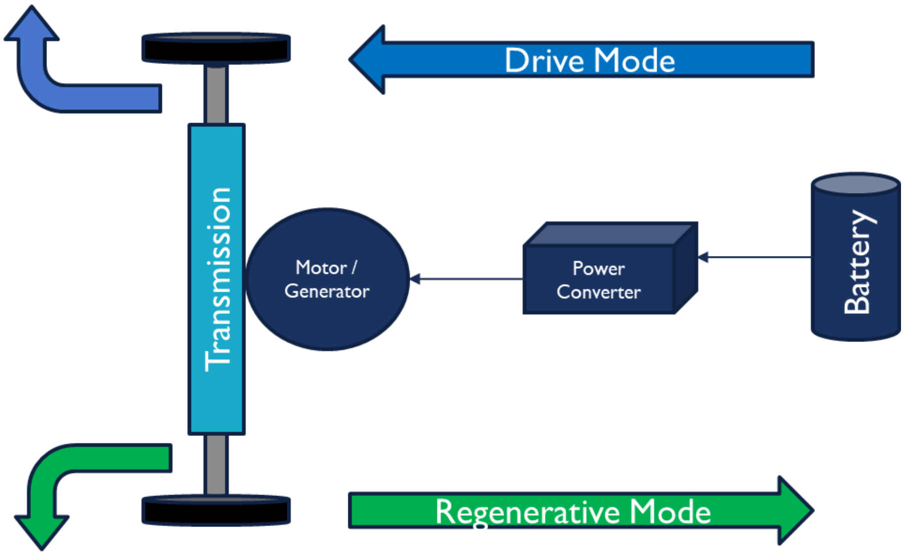


Figure.2.2: Regenerative braking diagram

2.4.4 Driver model

The driver model is a model that operates as an automatic driver by simulating a driver's actions. During the simulation process, the vehicle must detect a specific speed profile and decide whether to brake or accelerate to complete the driving cycle. This driver model is essentially a tracking controller that accepts the driver's throttle and brake commands as input and outputs them.

Each research has a separate driving model depending on the goal. Ahmad *et al*. (2014) investigated the longitudinal direction of vehicle dynamic behaviour using the entire vehicle model. Whereas, the Hegazy and Sharaf (2013) analysis to evaluate the vehicle's ride comfort, they used a quarter vehicle model. This method is known as the simplified method for developing vehicle dynamics models. Three simplified vehicle models are commonly used in vehicle dynamics analysis which are the half vehicle model, quarter vehicle model and full vehicle model.

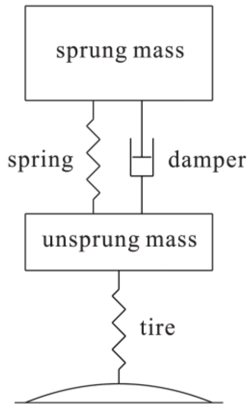


Figure 2.3: Quarter vehicle model (Soong *et al.*, 2017)

A quarter vehicle model is a mathematical model of only one-quarter of a vehicle. As shown in Figure 2.3, it came with one tyre, one absorber, and one spring connected from the frame to the axle. It consists of a one-dimensional sprung mass (roughly a quarter of the chassis) and an unsprung mass (the wheel) (Soong *et al.*, 2017). This results in a 2-DOF system with a pair of vertical differential equations for the chassis and vertical summing forces for the wheel.

Similarly, the half vehicle model is made up of two quarter vehicle models that take into account half of the car. A half car model can be divided into two types which are a half car roll plane model, which includes the front or rear halves of a car (and their associated roll dynamics), and a half car pitch plane model, which includes the left and right halves as well as their pitch and bounce dynamics. The vertical displacement of the front wheel, the vertical displacement of the rear wheel, the vertical displacement of the chassis (i.e., the "bounce"), and the rotation angle of the chassis (i.e., the "pitch") characterise this 4-DOF system. (Najam, 2018).

The suspension system in the entire vehicle model couples the sprung mass, which is the chassis of the car, to four wheels rather than one (unsprung mass). It can be separated into two models which are 7 DOF ride model and 7 DOF handling model. The whole vehicle model, according to Sandhu *et al*. (2016), is more accurate than the quarter car and half car models since in modelling, it considers the braking force and four-wheel traction. To analyse the vehicle's behaviour in longitudinal, lateral, and vertical directions, the whole vehicle model will be employed.

2.5 Electric vehicle speed control

The number of studies on the EV is still limited. Despite this, several researchers have been able to successfully demonstrate the usefulness of EV. However, their research objectives were limited to examining the usability of the vehicle's electrical system, which is solely dependent on the performance of the low-layer actuator control, rather than focusing on the development of the vehicle's longitudinal control itself. Almost all of the researchers who tested the EV used PID controllers (Nian *et al*., 2014), sliding mode control (SMC) (Vighneswaran and Nair, 2018), and fuzzy logic controllers (FLC) (Zhang *et al.*, 2018). According to Nian.*et al*. (2014), the application of PID controllers in electric vehicles has resulted in good performance in terms of tracking the required vehicle speed response and longitudinal dynamic of the vehicle. This is due to the PID controller's ability to calculate the difference between a desired and actual tyre slip and make a real-time correction based on proportional, integral, and derivative factors. Despite this, the PID controller has a significant flaw which is the controller's linearity, which determines EV effectiveness that could not be tested at various vehicle speeds.

Because of the flaws in the PID controller, other researchers have used FLC as the vehicle speed controller in their experiments Zhang *et.al*, (2018). Using the PID controller as the benchmark, ABS-based FLC performance was validated to be better than the PID controller in terms of effectiveness in tracking the target vehicle speed, rise time, and overshoot of system responses were more adaptable to changes in vehicle speed. Other researchers presented a simulation study on vehicle speed control based on an EV controlled by an SMC controller (Vighneswaran and Nair, 2018). Despite the impressive results, the simulation did not investigate the impacts of speed variation on the performance of the control system.

2.6 Summary

This chapter provides an overview of the electric vehicle and its components, as well as a discussion of the research identified in previous EV modelling and simulation studies. The explanation of various types of EV modelling has been elaborated through the use of various types of software that are commonly used by researchers to investigate the behaviour of each component model. According to the literature review, there are numerous areas where the EV's performance can be enhanced. The motor and battery components are two areas where improvements can be made. High starting torque, high power density, and high efficiency are all desirable properties for electric motors used in automotive applications. The developed EV model's capability for learning and research was evaluated using a DC motor with regenerative braking and Li-Ion batteries.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes about the methodology used in this study to obtain the performance evaluation of the EV. This project starts with modelling EV model and then validated it with a real car through an instrumented experimental vehicle namely Proton Iswara which is the Malaysian Nasional’s car. The vehicle's mathematical model is shown in the following subtopic. The experimental results are compared to simulated data in this approach of validation. Finally, the validated vehicle model's performance was evaluated by simulating it with the proposed drive cycle input. Figure 3.1 depicts the entire research process.

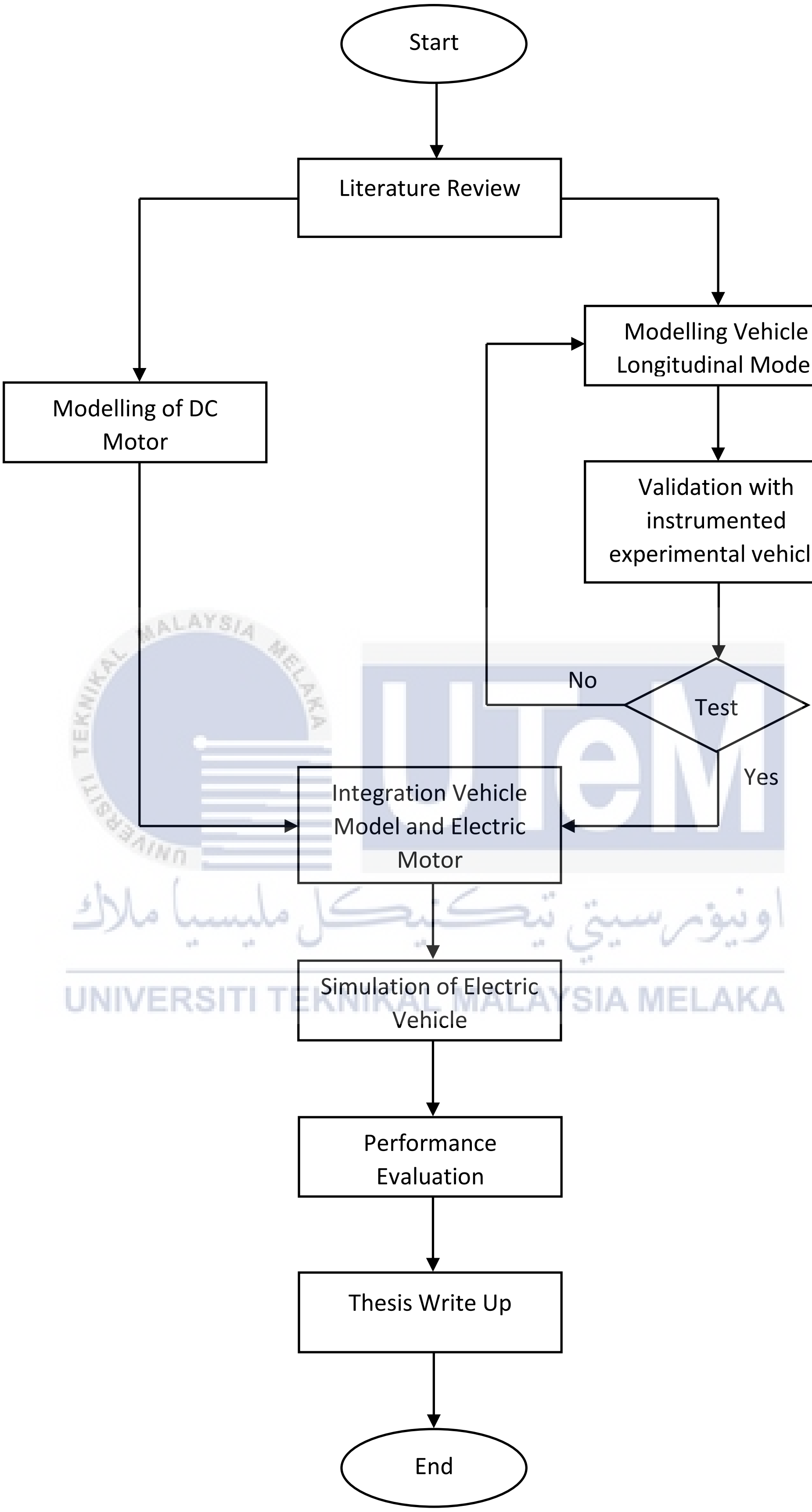


Figure 3.1: Flow Process of Research Work

3.2 Vehicle longitudinal modelling and drive train

In the first phase, the Vehicle Longitudinal Model is considered in this process to create the EV drive train and simply generates forward motion based on the dynamics of the vehicle. Figure 3.2 represents the typical longitudinal vehicle motion on an inclined route.

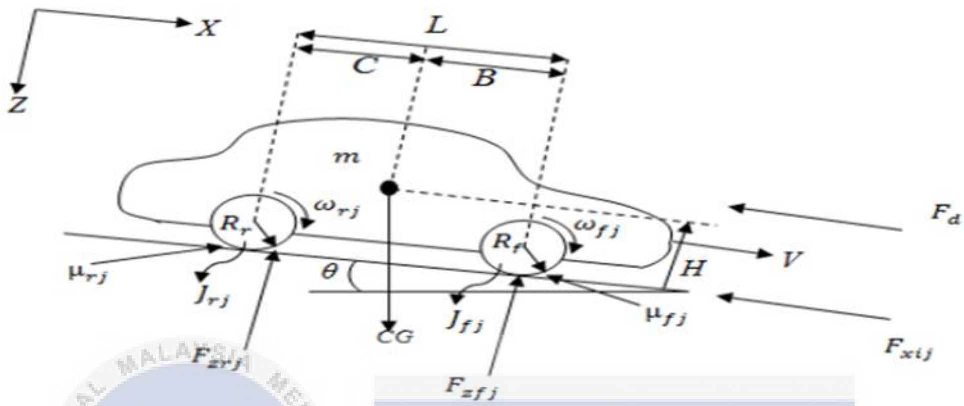


Figure 3.2: Two-dimensional schematics diagram of the four-wheel traction model (Ahmad *et al.*, 2014)

From the Figure 3.2, the vehicle's centre of gravity is denoted by CG, the vehicle's lumped mass is denoted by m, and the vehicle's wheelbase is denoted by L. The distance between the CG, front axle, and rear axle, respectively, is B and C. H is the height of the CG from the ground, and θ is the road's slope. V denotes the speed of translational in the longitudinal direction. The wheel's rotational velocity is described by ω, where R is the wheel's rolling radius and J is the wheel's moment of inertia. The friction coefficient is indicated by the μ. The subscripts f, r, l, and j refer to the vehicle's front, rear, right, and left sides, respectively.

Newton's second law states that when force (F) is applied to the mass of a body (m), acceleration (a) is produced, which can be expressed mathematically as:

$$\sum F = ma \tag{3.1}$$

Also, it can be expressed as;

$$a = \frac{\sum F}{m} \tag{3.2}$$

Equation 3.2 can be used to obtain the vehicle equation of motion. The total force operating on the vehicle is made up of the forcing force applied to the wheel in the direction of motion, F x, and the friction force acting in the opposite direction, F tr. Therefore, the equation is,

$$\frac{dv}{dt} = \frac{\sum F_x - \sum F_{tr}}{m} \tag{3.3}$$

The relationship between longitudinal tyre force and normal force in the vehicle longitudinal model can be defined as:

$$F_{x_{ri}} = \mu_f \ F_{z_{ri}} \tag{3.4}$$

$$F_{x_{fi}} = \mu_f \ F_{z_{fi}} \tag{3.5}$$

Front and rear wheel normal forces are as follows:

$$F_{z_{ij}} = \ mg\left[\frac{\frac{B}{C}}{L}\cos(\theta) - \frac{H}{L}\sin(\theta)\right] + m\left(\frac{dV}{dt}\right)\frac{H}{L} \tag{3.6}$$

The total force is calculated by adding the reactions on both sides of the wheels and becomes:

$$F_{x\,Total} = 2F_{xij} + \ 2F_{zij} \tag{3.7}$$

The overall torque performed in each wheel must be considered because the equation of motion in the longitudinal direction is influenced by the torque acting on each wheel. The following is a representation of the 3.8 equation:

$$J_{ij}\omega_{rj} = \tau_{rij} - \tau_{bij} + \tau_{aij} + \tau_{dij}\omega_{ij} \tag{3.8}$$

Where τ_{aij} is applied throttling torque and the applied braking torque is τ_{bij}. The reaction torque is denoted by τ_{rij}, while the viscous friction torque is denoted by τ_{dij} for each wheel.

By considering tyre rotational velocity and vehicle longitudinal velocity as the primary dynamics state to be simulated, the total force acting on the vehicle can be described as

$$\frac{dV}{dt} = \frac{-F_{x\,Total} + g\sin(\theta) - F_d(V)}{m} \qquad (3.9)$$

$F_d(V)$ is the drag force which is the summation of rolling resistance force, F_r and aerodynamic resistance force, F_a.

$$F_d = F_r + F_a \qquad (3.10)$$

Where,

$$F_a = \frac{1}{2}\rho A C_d (V^2) \qquad (3.11)$$

$$F_r = mgC_r(V) \qquad (3.12)$$

Where C_r is the coefficient of rolling resistance, A is the frontal area of the vehicle, C_d is the coefficient of drag force, and ρ is the density of air, which is 1.23 $\frac{kg^3}{m}$.

The recommended drive train for this investigation is shown in Figure 3.3. In this drive train, there are six components included the electric motor, battery, power electronics, driver controller, vehicle body and a drive cycle.

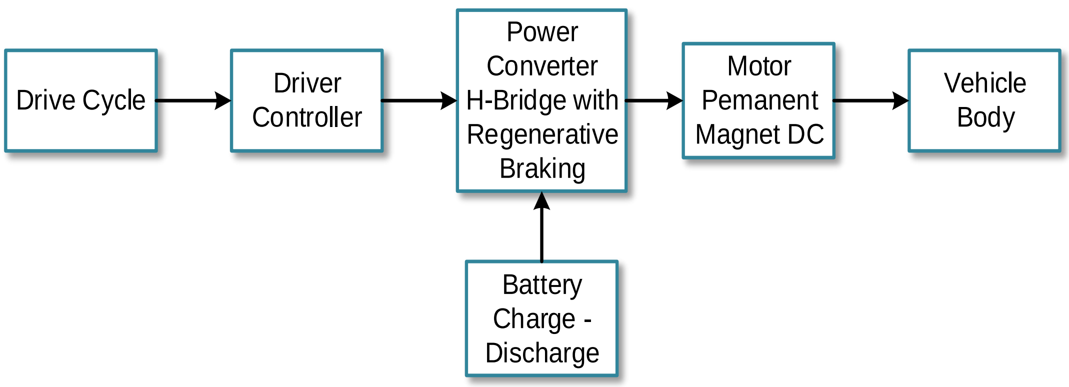


Figure 3.3: Electric Vehicle Drive Train

From the Figure 3.3, the drive cycle will be an input to the driver controller that act as the speed tracking controller for generating normalized acceleration and braking commands based on reference and feedback velocities. Next, the battery act for energy storage and provide the current to the power electronics that will be manipulated the voltage, current and frequency to the electric motor as require. Vehicle body provide space to carry loads.

3.2.1 Tyre longitudinal slip

In this study, the Pacejka Magic Formula tyre model proposed by Siegler (2002) is used to depict the tyre characteristics. The longitudinal and lateral forces exerted by the tyre are determined by the slip angle and longitudinal slip in relation to the road. The difference between the tangential speed of the tyre and the axle speed is determined by the equation 3.13, which is a tyre longitudinal slip.

$$\lambda_{ij} = \frac{V - ijR}{\max(V, \omega_{ij})} \tag{3.13}$$

where λ is the longitudinal slip, R is the radius of the wheel, ω is the angular velocity, and V is the speed of the axle. The value of the longitudinal slip is limited such that $|\lambda_{ij}| \leq 1$

3.2.2 Brake system model

Brakes work on the principle of friction. When a movement element collides with a stationary element, the rotation of the moving subject is affected. This is due to friction, which acts in opposition to action, converting kinetic energy into heat energy. According to Aparow *et al.* (2013), the brake disc pressure can be calculated using Eq. (3.14), where Pb is the applied brake pressure, Kc is the simple pressure gain, ub is the brake setting, and τbs is the brake lag. Then, the brake torque can be calculated as Eq. (3.15) by considering ϑ as a simple pressure gain,

$$P_{bij} = 1.5K_{cij}u_{bij} - \tau_{bs}\dot{P}_{bij} \tag{3.14}$$

$$T_{bij} = P_{bij} K_{bij} \min\left(1, \frac{\omega_{ij}}{\vartheta_{ij}}\right) \tag{3.15}$$

3.3 Validation of vehicle model

The Malaysian National Car, a 1300cc Proton Iswara, as illustrated in Figure 3.4, has been built as an experimental instrumented vehicle for the aim of validating provided by Ahmad *et al.* (2014).

Figure 3.4: Proton Iswara

These are the vehicle's detailed technical parameters, as listed in Table 3.1, based on experiment by Ahmad *et al.* (2014).

Table 3.1: Proton Iswara General Technical Specifications (Ahmad *et al.*, 2014)

Parameters	Value
Vehicle mass	920 kg
Wheelbase	2380 mm
Wheel track	1340 mm
Wheel rolling radius	220 mm
Front axle to centre of gravity	1340 mm
Rear axle to centre of gravity	1040 mm
Height centre of gravity from ground	600 mm
Gear ratios:	
1st	3.363
2nd	1.947
3rd	1.285
4th	0.939
5th	0.777
Final drive	4.322

3.4 DC motor modelling

There are two types of characteristics in a DC motor which are electrical and mechanical. Figure 3.5 provides an illustration of a DC motor circuit. On the electrical characteristics of a DC motor, E_B are voltage sources across the armature coil. An inductance, L_H is in series with resistance, R_a and in series with an induced voltage, V_d that opposes the source of voltage which can be used to represent the electrical equivalent of the armature coil. The induced voltage V_d is produced by the electrical coil's rotation through the permanent magnets' fixed flux lines. The back emf is a term used to describe this voltage (electromotive force).

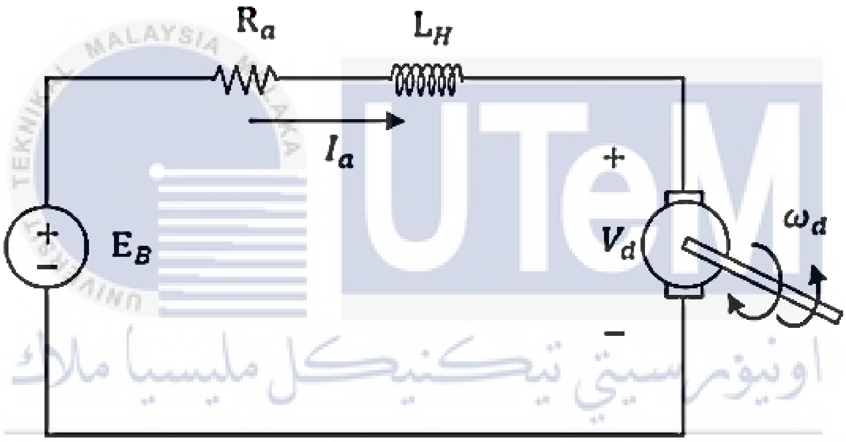


Figure 3.5: DC motor circuit

For mechanical properties, the electric armature current is converted into a mechanical torque on the shaft. The torque produced is known as electromagnetic torque, T_d and it is proportional with the current, I_a that passes through the armature winding. A motor constant is defined as K_m. It can be mathematically written as:

$$T_d = K_m \cdot I_a \tag{3.16}$$

Voltage that developed in the motor, V_d is proportional to the armature speed, ω_d ;

$$V_d = K_m \cdot \omega_d \tag{3.17}$$

The terminal voltage is calculated by adding the developed voltage, resistance, and inductance voltage drop. Because the motor's high side voltage and current are directly connected to it, it is assumed to be the same as high side voltage. As a result, the motor high side voltage (terminal voltage), V_H is given by:

$$V_H = I_H \cdot R_a + L_H \cdot \frac{di\,(t)}{dt} + V_d \quad (3.18)$$

where, I_H is the current at the high side (terminal current), R_a is the armature resistance value, and the L_H is inductor value at the high side. The vehicle's detailed DC motor parameters are shown in Table 3.2.

Table 3.2: Electric motor parameters

Parameters	Value
Armature inductance	$12x10^{-6}$ H
No load speed	16000 rpm
Rated speed	15900 rpm
Rated load (mechanical power)	5000 W
Rated DC supply voltage	400 V

3.4.1 Motor controller

The motor controller is assumed to be the best controller possible, with no power loss and no time lag. To meet the greater voltage requirements of the motor, the controller effectively raises the battery voltage. To meet the motor's requirements, the K ratio of the input and output voltages must be computed. The same K ratio is used to regulate the current to ensure that the input power is equal to the basic motor controller's output power. The electric torque that has developed, T_d is equal to the mechanical torque output, T_{mech}, provided. There are no friction or inertia losses. As a result, the electrical power generated equals the mechanical power generated.

High side voltage (input),

$$V_H = K \cdot V_L \tag{3.19}$$

High side current (input),

$$\mathrm{I}_H = \left(\frac{1}{K}\right) \cdot \mathrm{I}_L \tag{3.20}$$

where K is the controller gain value, V_L is voltage at the low side (output), and I_L is the current at the low side (output).

3.4.2 Battery

The battery is represented as a voltage source, E_B and the internal power loss in the battery resistance is represented as R_a.

$$V_L = \mathrm{I}_L \cdot \mathrm{R}_a + \mathrm{E}_B \tag{3.21}$$

Using the current and voltage from the motor controller, the required battery's internal voltage is computed. PI controller used the difference between the calculated E_B ($\mathrm{E}_{B(\text{calculated})}$) and the actual E_B ($\mathrm{E}_{B(\text{actual})}$) represents the battery voltage error, B_{Err} for gain adjustment. The battery's parameters are listed in Table 3.3 below.

$$\mathrm{B}_{Err} = \mathrm{E}_{B(\text{actual})} - \mathrm{E}_{B(\text{calculated})} \tag{3.22}$$

Table 3.3: Battery parameters

Parameters	Value
Nominal voltage	400 V
Rated capacity	320 Ah
Initial state of charge	100%

3.5 Proportional integral speed control structure of electric vehicle

Figure 3.6 depicts the basic structure of a PI control system for EV speed control. The PI controller's control action was triggered by the error signal $e(t)$ derived from the differences between actual (v_{act}) and desired (v_{des}) speed values. By multiplying the error by the controller weighted signals, it generates a controller signal, $u(t)$ which corresponds to the ideal torque that the electric actuator must track. The following is the PI controller action for the EV and the generation of the control signal $u(t)$.

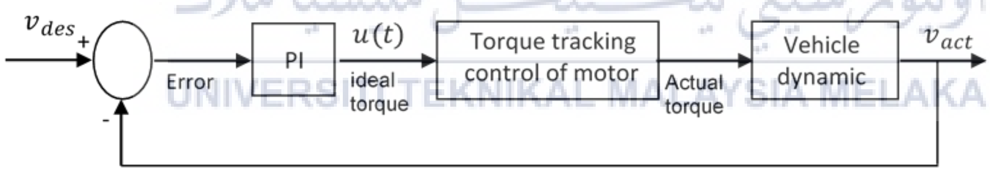


Figure 3.6: Control structure-based PI controller

$$u(t) = k_p(t)e(t) + k_i(t) \int e(t)dt \tag{3.23}$$

Here, $\int e(t)$ represents the integral of the error, k_p is proportional gain, and k_i is the integral time constant.

PI controllers are frequently sufficient for controlling a linear system process, according to the literature (Kaya, 2003). However, as operating conditions or environmental parameters change, the requirements for a high-performance control system frequently exceed the capabilities of simple PI controllers (Munoz-Hernandez *et al.*, 2020). To overcome this problem, Munoz-Hernandez *et al.*, (2020) proposed combining the PI controller with other control methods and/or modifying the PI parameters to improve performance, such as the self-tuning method, fuzzy logic controller, and the other methods such as fractional order PI and nonlinear PI method. Fractional powers $(1-\alpha)$and $(1-\beta)$ are added to the traditional constant gains k_p and k_i, respectively, transforming the linear PI controller into a nonlinear fractional gain PI controller (FPI), which can be mathematically described as equation (3.24).

$$u(t) = k_p{}^{1-\alpha}(t)e(t) + k_i{}^{1-\beta}(t)\int e(t)dt \tag{3.24}$$

3.6 Drive cycles

Standardized driving cycle tests and constant speed testing are commonly used to assess vehicle performance. Both tests were used in this study (Larminie and Lowry, 2003). First is the constant speed test, even if the test is impractical, the evaluation rules are simple and clear. Therefore, for the purposes of this study, the drive cycle is designed in such a way that the power flow can be observed during both motoring and regeneration. Various driving cycles were used to test the vehicle's performance parameters such as speed, state of charge, and the value of current that battery consumed. The test was performed at speeds of 40 and 60 kilometres per hour.

Then, the vehicle operated by a constantly changing speed profile is the second type of experiment, which is more effective and sophisticated. The drive cycles are designed to meet normal driving behaviours in a variety of situations. Because the cars are constantly changing speed during the experiment, the computation, as well as the output of all the other components of the systems vector, becomes increasingly difficult. WLTP (Worldwide harmonized Light Vehicle Test Procedure), NEDC (New European Drive Cycle), FTP

(Federal Test Procedure) and Japanese modes are the drive cycles developed by Europe, United States, Japan, China and India which are very significant in the automotive industry. However, though the FTP was designed to be a reference point for fossil-fuelled vehicles, the UDDS and thus the FTP are also used to estimate the range of an electric vehicle on a single charge (Chuck Squatriglia, 2014). Therefore, FTP is used for the purpose of vehicle test performance.

3.7 Regenerative Braking

Through the regenerative braking system, two motor's direction operation that are clockwise and anticlockwise will be considered. Motor's operation can be described through four quadrants in Figure 3.7.

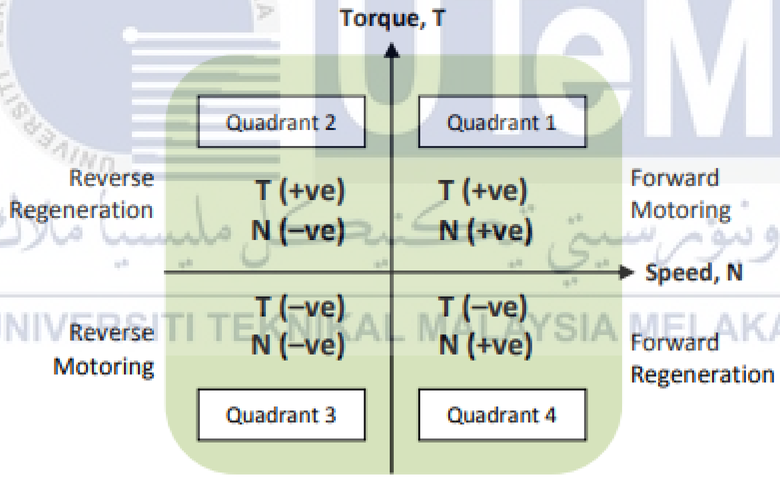


Figure 3.7: Four Quadrant of Motor's Operation

From the Figure 3.7, the motor is in the motoring mode when the torque and speed values of it in the same polarity (1^{st}Quadrant and 3^{rd} Quadrant), and it is in regenerating mode when the polarity values of torque and speed are different (2^{nd} Quadrant and 4^{th} Quadrant). For the first quadrant, the motor moves forward with both positive polarities, but the motor moves backward in third quadrant with both negative polarities. In the second quadrant, when the torque is positive and speed in negative, the motor will be decelerating and recharge the battery in reverse braking while the torque is negative and speed is in positive, the battery will be recharge in forward braking. Energy in battery will be decrease during motoring mode but it will be increase in regenerating mode during regenerative braking because the motor is function as generator at that time.

3.8 Simulation and control of electric vehicle

On the second phase, once the model has been validated, we can conduct the simulation with a various configuration and parameters. For this simulation, we will run it with the design configuration and simulated cases as shown in Table 3.4. Then, the vehicles parameter that will be consider in this project is shown in Table 3.5.

Description	Options
Speed Limit	Malaysian expressways (90 & 110 km/h) Federal roads (60, 80, & 90 km/h) State roads (60, 80, & 90 km/h)
Steep Ascent/Descent	A slope of 10 percent and above is considered steep gradient.

Table 3.4: Design configuration

Vehicle parameter	Quantity	Units
Mass	1000	kg
Wheel radius	0.3	m
Frontal area	3.0	m^2
Rolling resistance coefficient	0.015	-
Battery (Lithium-Ion)	400(320)	V(Ah)

Table 3.5: Vehicle parameters

3.9 Integration vehicle longitudinal model and components of electric vehicle powertrain

The models for each electric vehicle part of the power system are explained above. By integrating all the sub model, the electric vehicle can be modelling as Figure 3.8. The drive cycles act as an input to the controller and battery provide the electricity to the electrical component. DC motor will receive the input from electrical component and generate torque for the vehicle. Finally, the vehicle body act as a carry load.

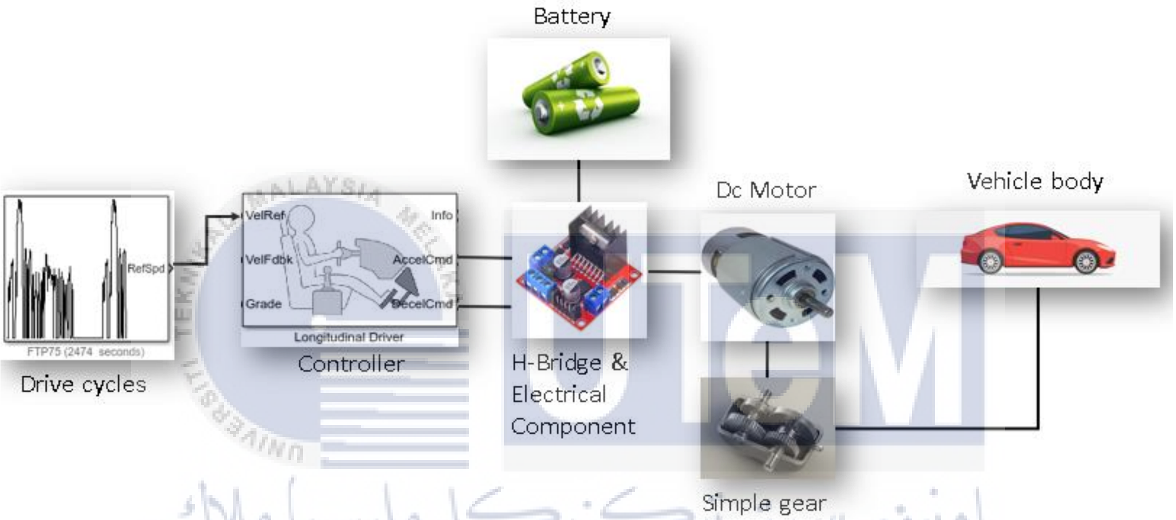


Figure 3.8: Modelling of Electric vehicle using MATLAB-Simulink software

3.10 Summary

This chapter discusses a number of methodologies. The first step is to model the vehicle longitudinal model, which is then validated using experimental data obtained from previous researchers. Using the validated model, an EV simulation was created by combining a DC motor with an electric power train system and the PI controller as a speed tracking controller. Several tests were carried out, and the results can be found in the following chapter which is Chapter 4: Results and Discussion.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Through this chapter, it includes the vehicle model validation results, which compare the simulation and experimental vehicle behaviours, as well as explanations for any errors that occur during the validation procedure. Then, this chapter also discusses the simulation results of EV model performance. The simulation was done with three different drive cycles as the EV model's reference speeds. Finally, this chapter discusses the DC Motor's capability as an electric motor for an EV and the regenerative braking effect.

4.2 Vehicle model validation results

The results of a simulation and an experiment for the longitudinal orientation of a vehicle are presented. In the acceleration and sudden braking mode, the experiments used two speeds of 40 km/h and 60 km/h. This section also covered the comparison of simulation and test results in order to show the various potential failures that could occur during the test. During the experiment, the errors were also thoroughly interpreted.

4.2.1 Validation of vehicle model in 40 km/h

The results of the model validation acceleration and braking test at 40 km/h are shown in Figures 4.1 through 4.10. Figure 4.1 illustrates the simulation results for a vehicle model, while the dotted line represents the experimental results from Ahmad *et al.* (2014).

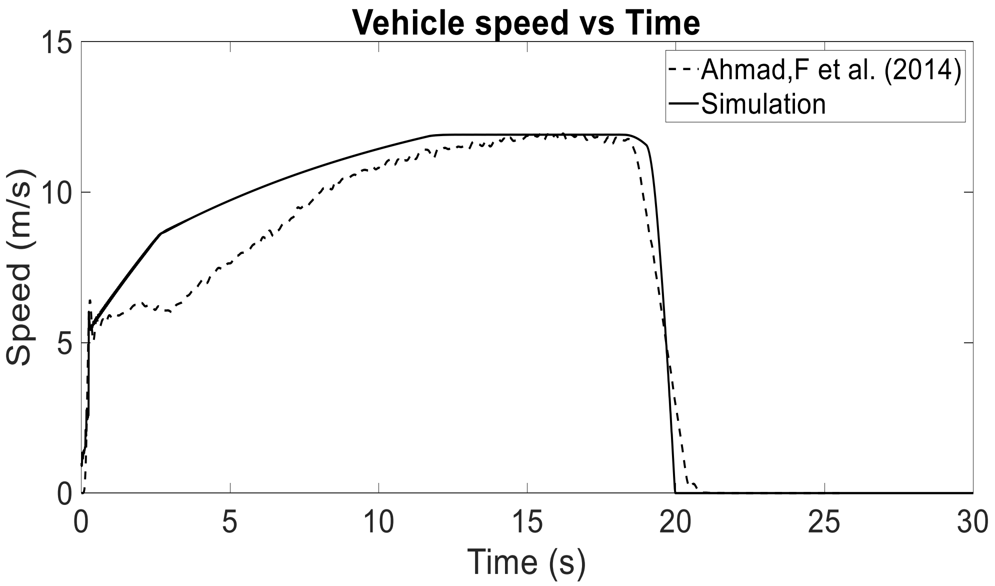


Figure 4.1: Validation results of sudden braking test at a constant speed of 40 km/h; Vehicle speed

Figure 4.1 illustrates that the response to a simulation is slightly faster than the test response seen in t=1 seconds until to t=10 seconds. It takes 10 seconds for the vehicle to reach a speed of 40 km/h. The speed is then constant for around 5 seconds before the full braking is applied at t=16 seconds. The disparity in response is caused by a time delay in changing gears, a drop in rpm, and a contradictory crash when the driver changes the gears and manually disconnects the clutch while changing gears in the experimental vehicle. This causes the engine torque to be diverted away from the wheel. In contrast to the experimental vehicle, automatic transmission is used in the vehicle model simulation. Without frequent interruption, automatic transmission performs autonomously, resulting in relaxation and constant gear change.

The rotation of all wheels propels the vehicle's movement. Figure 4.1 represents the actions of the car being driven through all four wheels of the vehicle, as seen in Figures 4.3 through 4.6. Figure 4.2 represents a comparison of the body and wheel speeds. Figure 4.2 shows that the vehicle slows down at t=20 seconds after receiving brake feedback at t=16 seconds. The wheel appears to lock at t = 19 seconds and pull the car to a complete standstill, as shown in Figures 4.2 to 4.6. This results in slip conditions for the four wheels on regular ground surfaces.

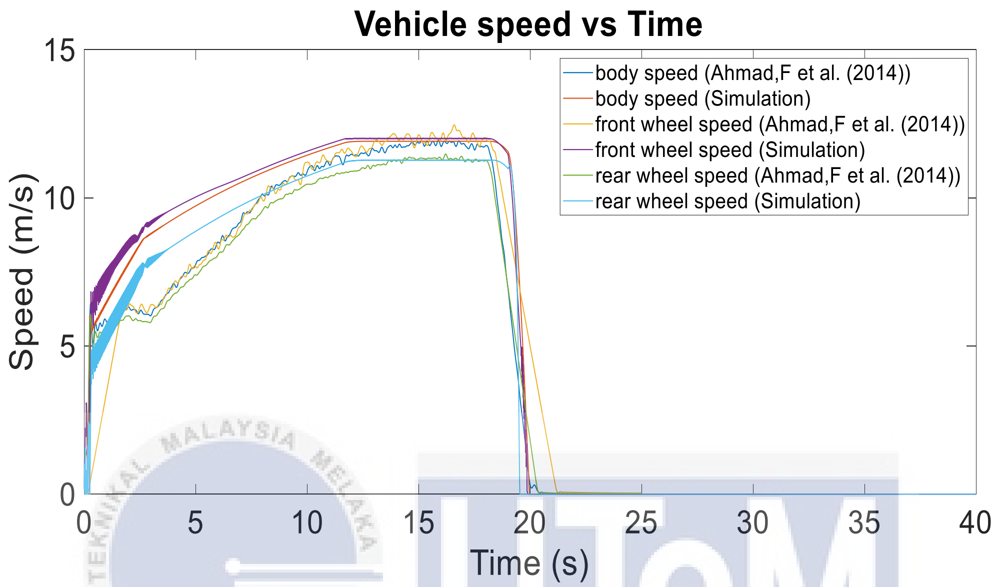


Figure 4.2: Validation results of sudden braking test at a constant speed of 40 km/h; Comparison speed of body and wheels

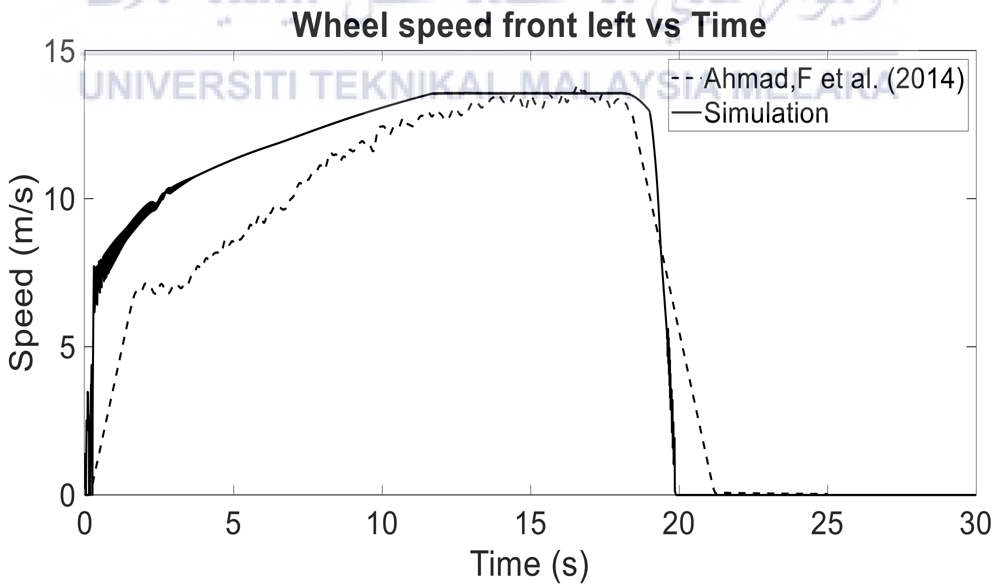


Figure 4.3: Validation results of sudden braking test at a constant speed of 40 km/h; Wheel speed front left

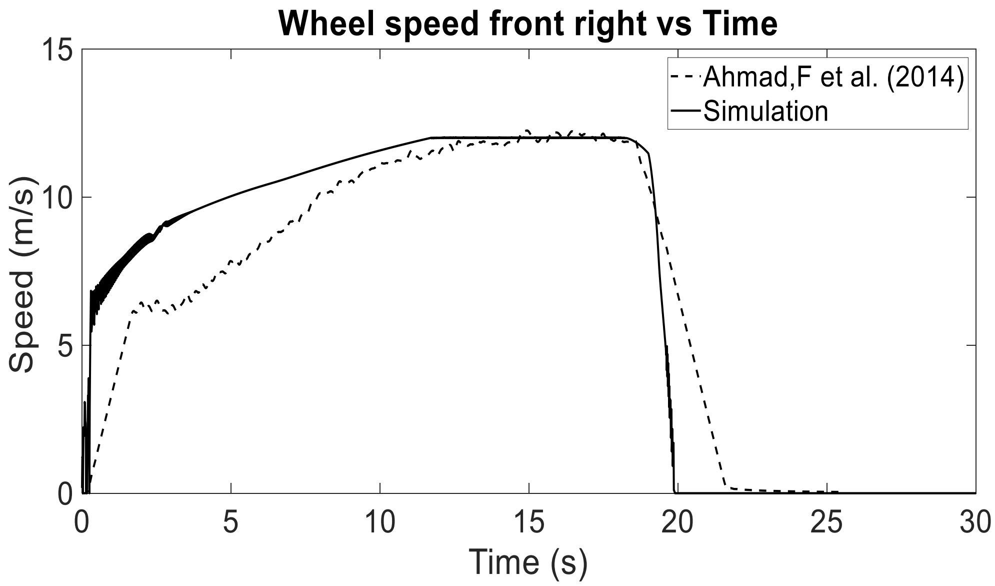


Figure 4.4: Validation results of sudden braking test at a constant speed of 40 km/h; Wheel speed front right

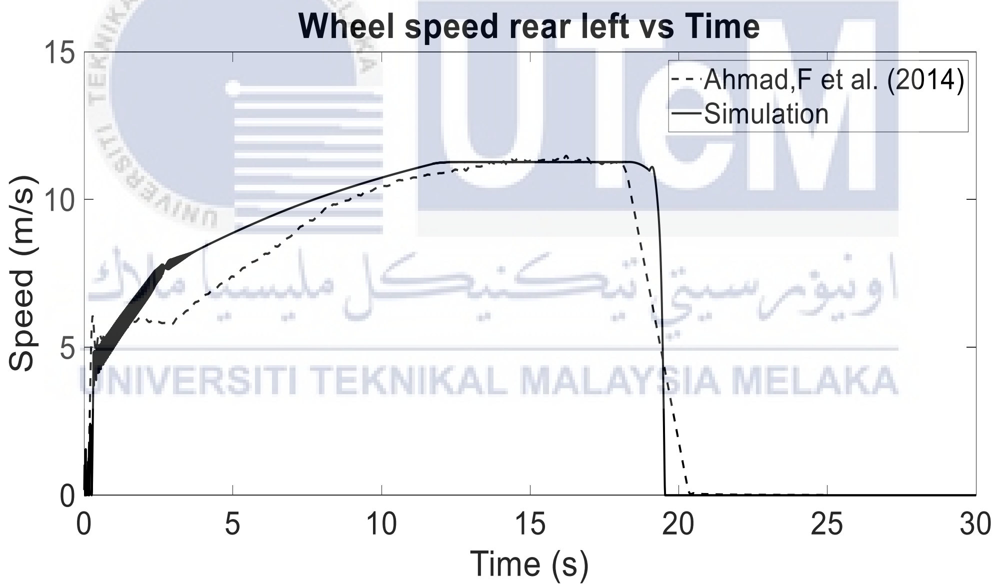


Figure 4.5: Validation results of sudden braking test at a constant speed of 40 km/h; Wheel speed rear left

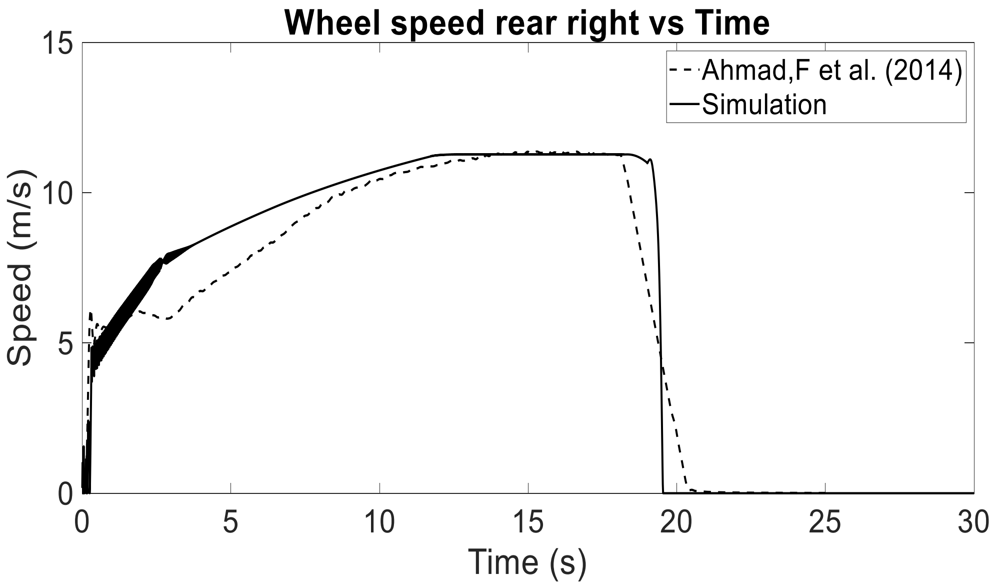


Figure 4.6: Validation results of sudden braking test at a constant speed of 40 km/h; Wheel speed rear right

Figures 4.7 through 4.10 show that after applying brake input at t=20 seconds, a validation of longitudinal slip reaches positive 1. It occurs because the wheel tends to lock when the brake is applied suddenly, then causes the wheels to slip and there is no rotation movement due to wheel locking. With a minor variation in the transition region between transient and stable periods, the longitudinal slip responses of all wheels are adequate. The longitudinal slip reactions of all wheels in the experimental data slightly differ from the longitudinal slip reactions in the simulation data, particularly for the rear wheels. This causes due to the driver's inability to maintain a steady pace while driving. The simulation assumes the vehicle is driving on a flat lane, as opposed to the test field's road profile, which has an uneven surface. This could be another source of variation in the response to the longitudinal slip of the wheels.

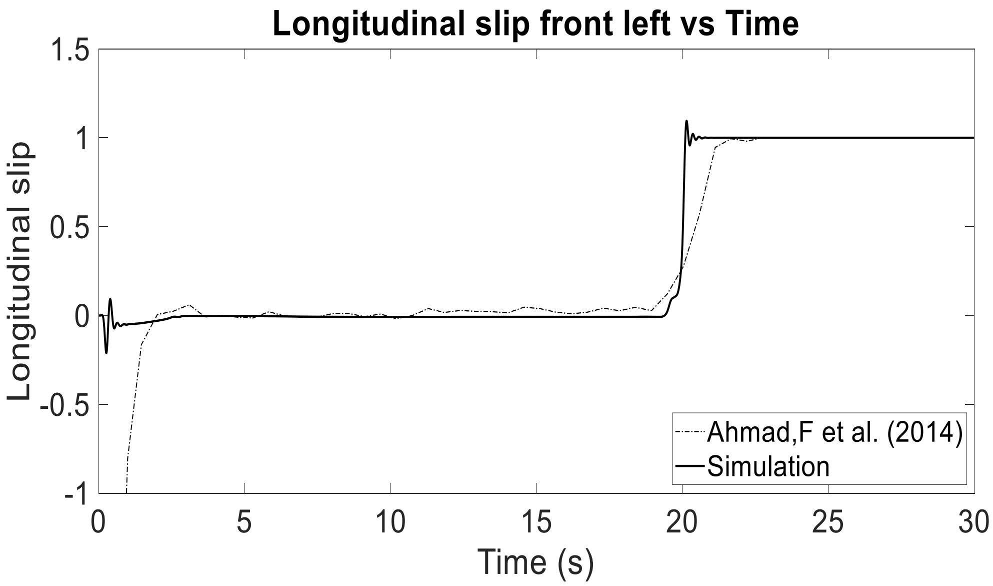


Figure 4.7: Validation results of sudden braking test at a constant speed of 40 km/h; Longitudinal slip front left

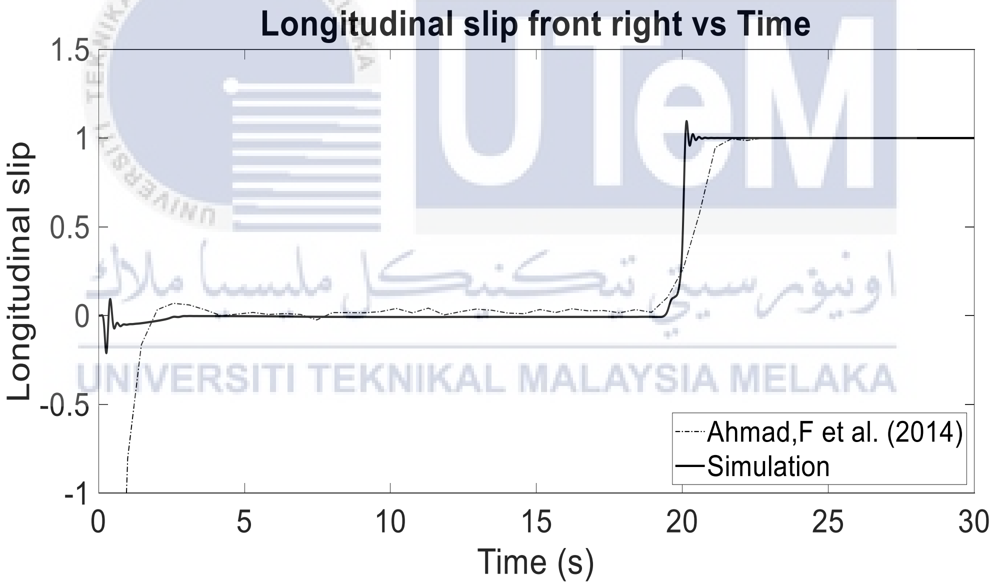


Figure 4.8: Validation results of sudden braking test at a constant speed of 40 km/h; Longitudinal slip front right

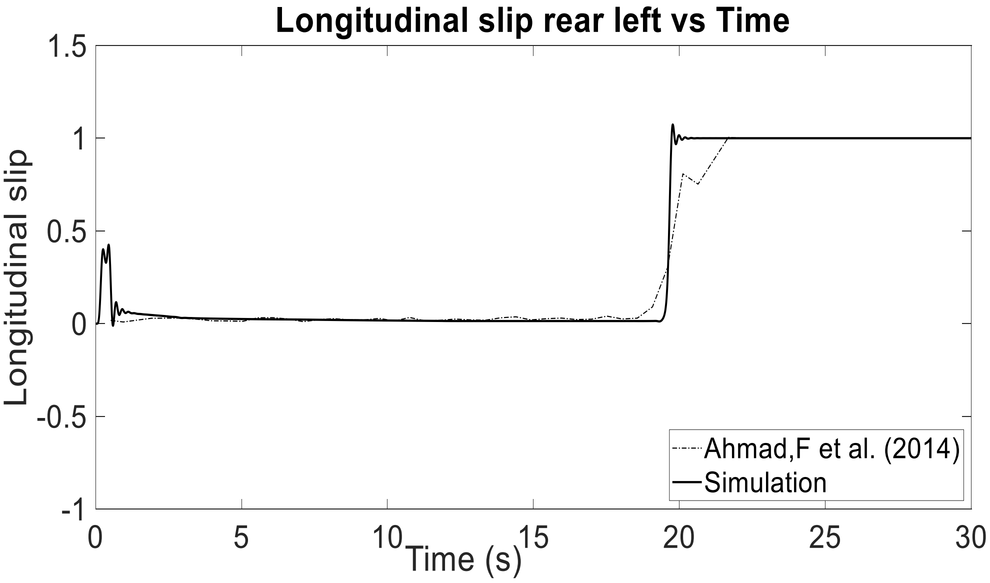


Figure 4.9: Validation results of sudden braking test at a constant speed of 40 km/h; Longitudinal slip rear left

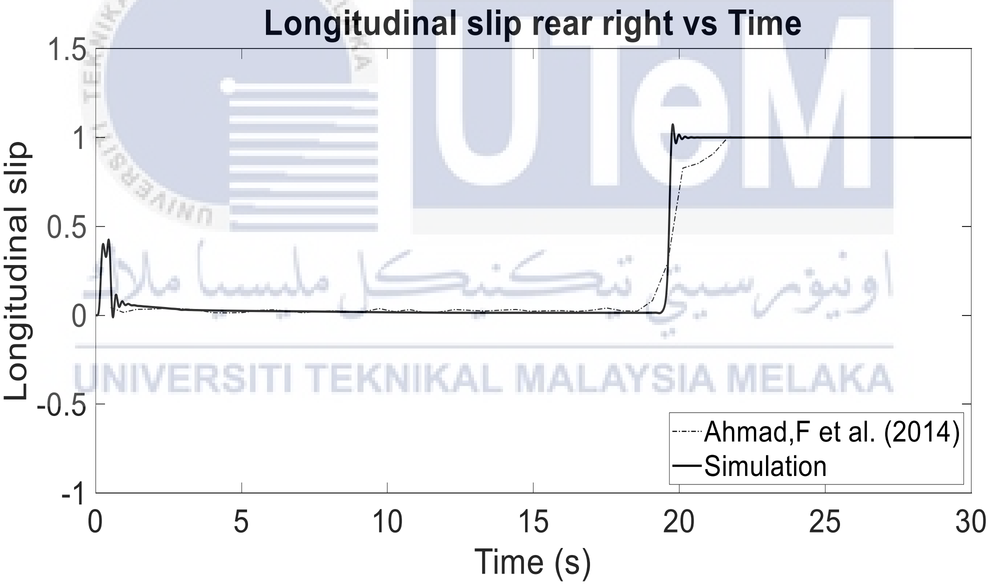


Figure 4.10: Validation results of sudden braking test at a constant speed of 40 km/h; Longitudinal slip rear right

According to the Table 4.1, the relative absolute error (RAE) value for body vehicle is 5.19%, wheel speed front left is 6.41%, wheel speed front right is 4.04%, wheel speed rear left is 3.35% and wheel speed rear right is 2.67%. It should be noted that the vehicle is equipped with an automatic transmission, whereas the experimental vehicle is equipped with a manual transmission. Therefore, it is very impossible to mimic the simulation of manual transmission. That is why there is a deviation in the first 10 seconds, which is called the transient response. As a result, the relative absolute error for a 40 km/h speed is taken at 10 m/s.

Table 4.1: Relative Absolute Error for 40km/h speed

Parameter	RAE %
Body vehicle	5.19
Wheel speed front left	6.41
Wheel speed front right	4.04
Wheel speed rear left	3.35
Wheel speed rear right	2.67

4.2.2 Validation of vehicle model in 60 km/h

Another evaluation was carried out under the same test conditions to better determine the validity of the vehicle model. Figures 4.11–4.20 show the outcomes for the same performance variables. In terms of the car's longitudinal speed, the measurements indicate that the simulation results and experimental data are reasonably reliable, as shown in Figure 4.11, but there is a range of 0 until 5 seconds between the first transient reaction. The statistics from the simulation reactions show that the vehicle takes approximately 5 seconds to reach a steady velocity of 60 km/h from rest. The experimental response appears to indicate that the vehicle can accelerate from a rest to a steady speed of 60 km/h in less than a second.

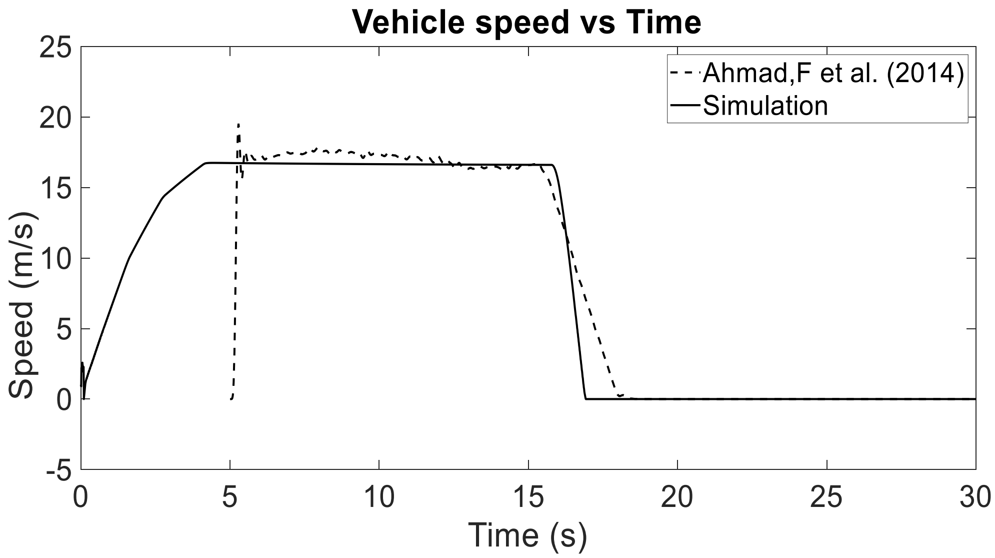


Figure 4.11: Validation results of sudden braking test at a constant speed of 60 km/h; Vehicle speed

To look more deeply into this issue, because this experiment was conducted by humans, an error occurred when the driver was late to trigger the sensor system. The sensors were triggered when the vehicle's speed increased to a constant speed of 60 km/h, indicating that the sensor is activated by the phase reaction in 5 seconds to 6 seconds. Comparisons between linear wheel speed and longitudinal body length are frequently used to analyse the vehicle's actions during an immediate braking manoeuvre. Figure 4.12 represents a comparison of simulation and experimental response. The figure shows that the front wheel's speed is significantly greater than the vehicle's speed, while the rear wheel's speed is less. This case cannot be challenged because the vehicle is front wheel drive. The vehicle's acceleration is caused by the front wheels because there is no push torque feedback on the rear wheels. During extreme acceleration, weight is transferred from front to back, and the rear wheels are dragged with greater resistance, benefiting the front wheels. As a result, the front wheel spinning increases the front wheels' longitudinal speed.

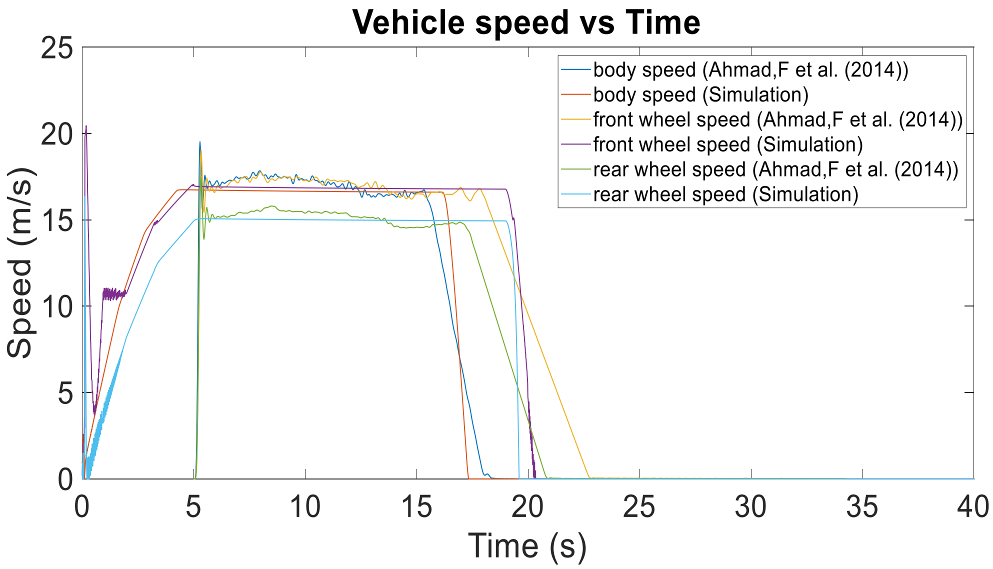


Figure 4.12: Validation results of sudden braking test at a constant speed of 60 km/h; Comparison speed of body and wheels

In terms of the wheel's linear speed, the results in Figures 4.13 through 41.6 show that, with the exception of the first 5 seconds, the experimental data and simulation results agree fairly well. The experimental speed responses are nearly identical to those obtained in previous validation results, particularly for all wheels, where the difference is slightly greater than the data obtained from simulation.

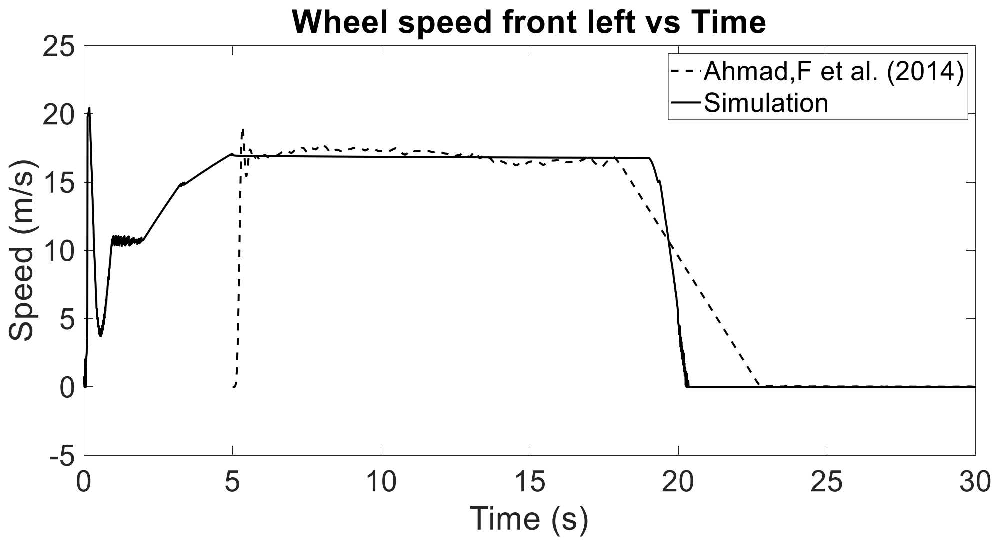


Figure 4.13: Validation results of sudden braking test at a constant speed of 60 km/h; Wheel speed front left

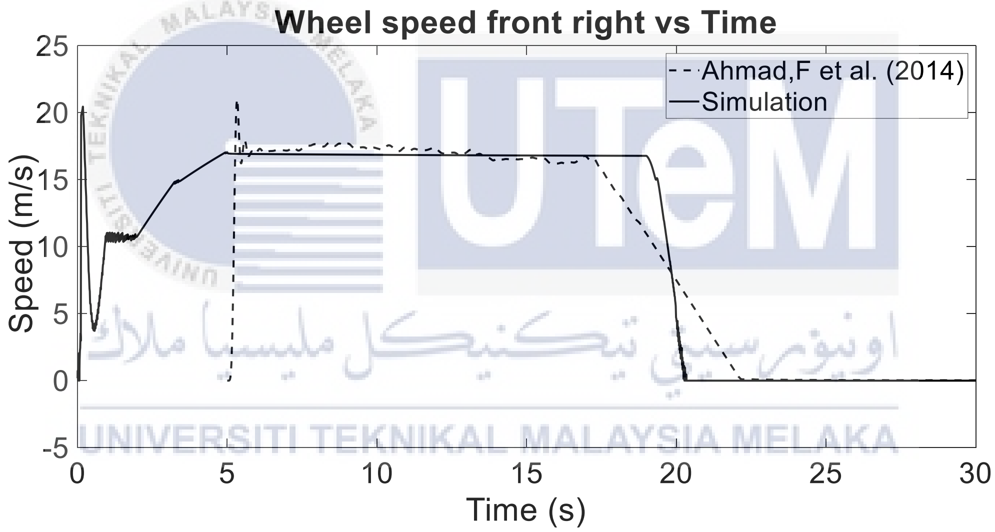


Figure 4.14: Validation results of sudden braking test at a constant speed of 60 km/h; Wheel speed front right

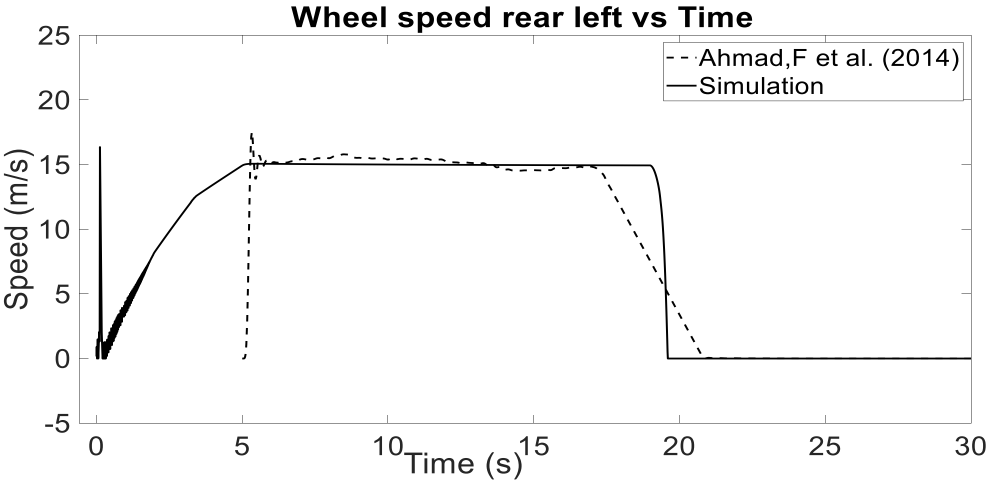


Figure 4.15: Validation results of sudden braking test at a constant speed of 60 km/h; Wheel speed rear left

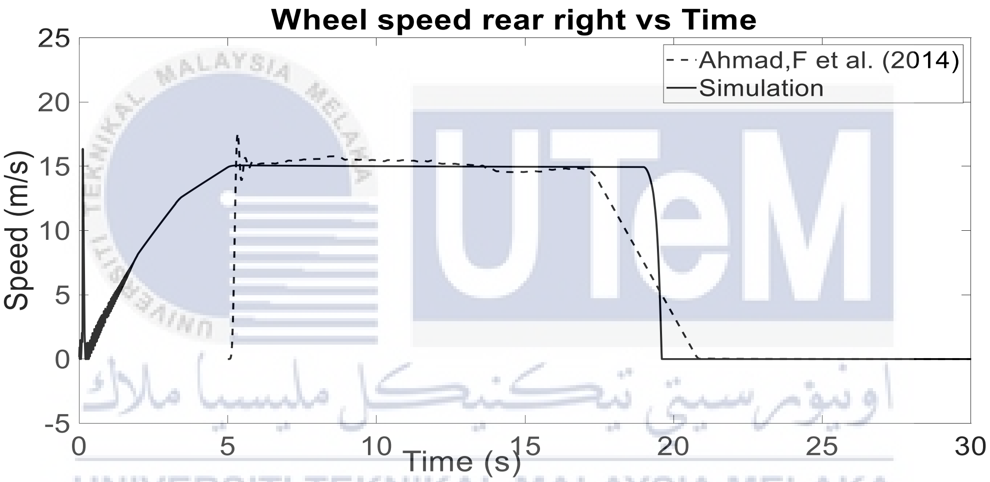


Figure 4.16: Validation results of sudden braking test at a constant speed of 60 km/h; Wheel speed rear right

Again, this causes due to the driver's inability to maintain a steady pace. As a result, the simulation model's assumption that the vehicle is driving down a flat road is extremely difficult to comprehend in reality. Wheel characteristics can change during vehicle testing due to road abnormalities in the testing field. The magnitude of the linear wheel's speed may be reduced as a result of simulation compared to experimental data if the steering inertia is ignored. During the first 5 seconds of the simulation model, the vehicle attempted to accelerate as quickly as possible to reach the target speed by applying strong throttle torsion to the wheel. As a result, the wheel's angular velocity is high, causing the wheel to spin as shown in Figures 4.17 to 4.20.

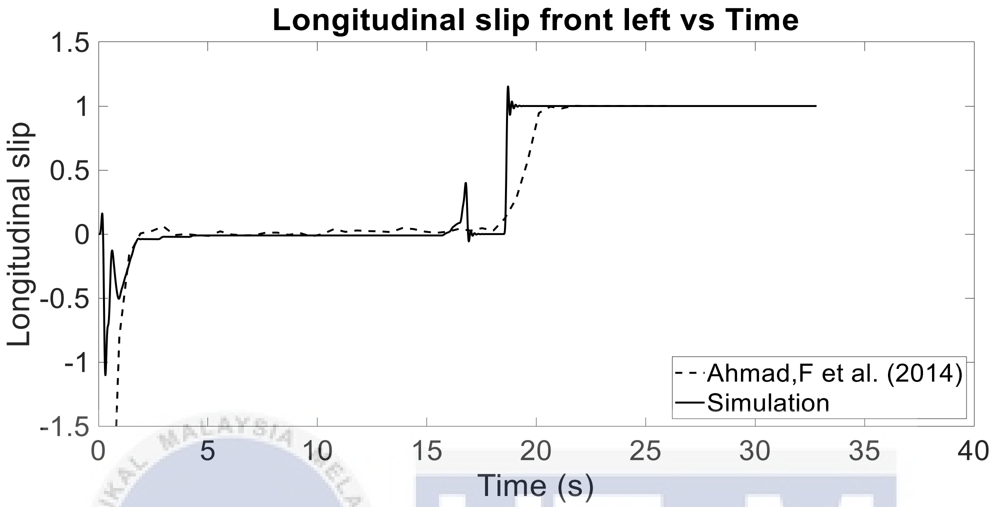


Figure 4.17: Validation results of sudden braking test at a constant speed of 60 km/h; Longitudinal slip front left

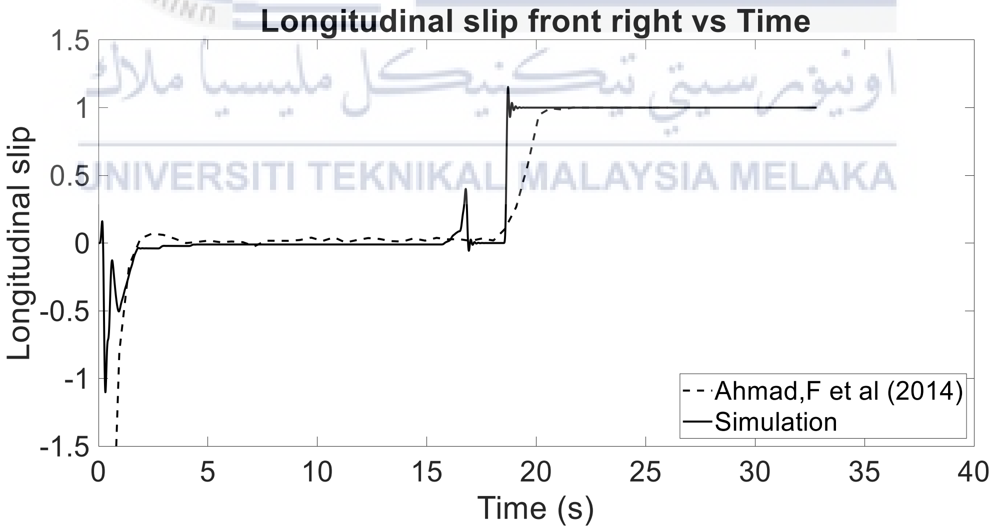


Figure 4.18: Validation results of sudden braking test at a constant speed of 60 km/h; Longitudinal slip front right

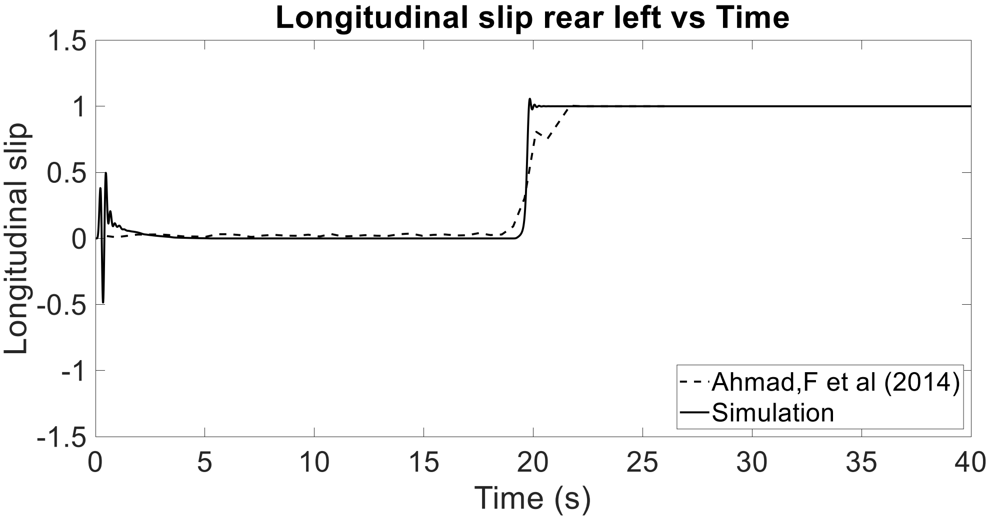


Figure 4.19: Validation results of sudden braking test at a constant speed of 60 km/h; Longitudinal slip rear left

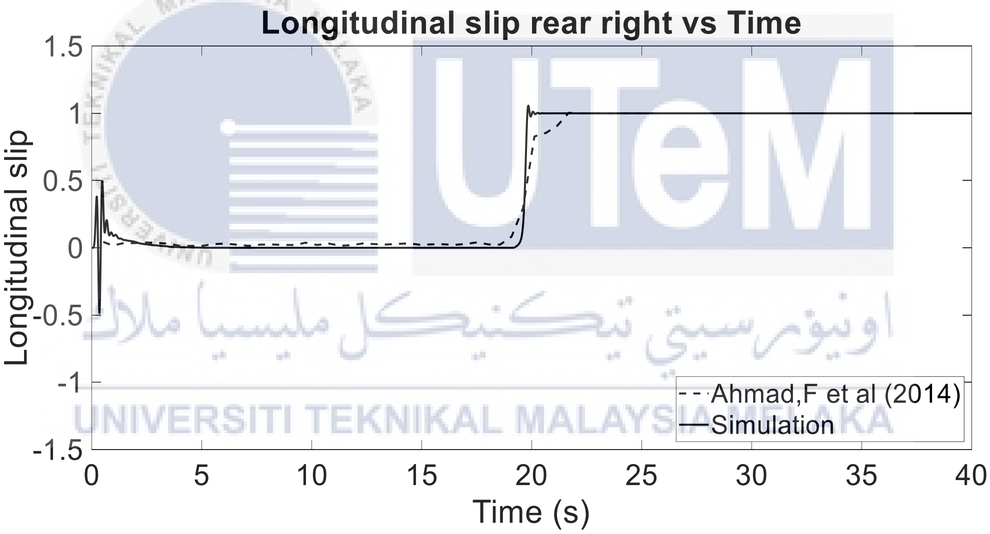


Figure 4.20: Validation results of sudden braking test at a constant speed of 60 km/h; Longitudinal slip rear right

Table 4.2 displays the relative absolute error (RAE) value for the body vehicle, wheel speed front left, wheel speed front right, wheel speed rear left, and wheel speed rear right Similarly, the relative absolute error for a speed of 60 km/h is taken at 10 m/s due to transient response.

Table 4.2: Relative Absolute Error for 60km/h speed

Parameter	RAE %
Body vehicle	4.03
Wheel speed front left	2.38
Wheel speed front right	2.32
Wheel speed rear left	2.65
Wheel speed rear right	3.04

4.3 Performance evaluation of the speed control of electric vehicle

To determine the effectiveness of the PI controller and the electric vehicle system, a simulation test was performed by applying the same method as the vehicle validation and standard energy consumption test for urban driving recommended by the Society of Automotive Engineers (SAE), which is the Federal Test Procedure 75 (FTP-75).

4.3.1 Performance evaluation of the speed control of electric vehicle in 40 km/h

Figures 4.21 until 4.23 show the drive simulation model of EV that was created using mathematical equations from Chapter 3 and represented by each subsystem block. Three simulations were run from the model, and output scopes were added to determine and illustrate the energy flow, efficiency and their performance.

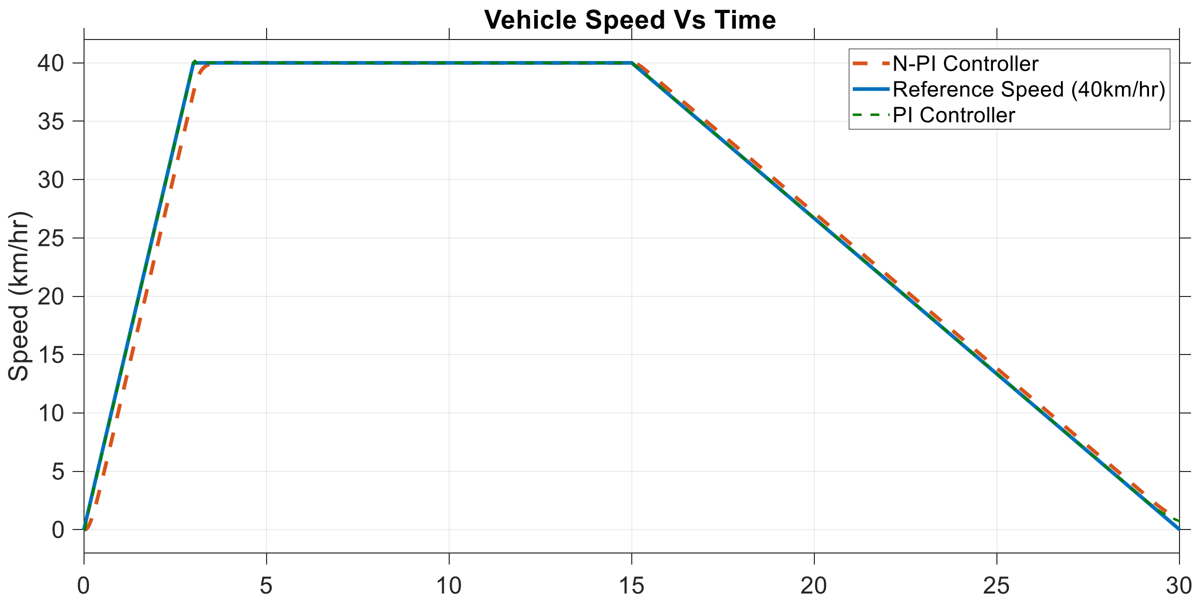
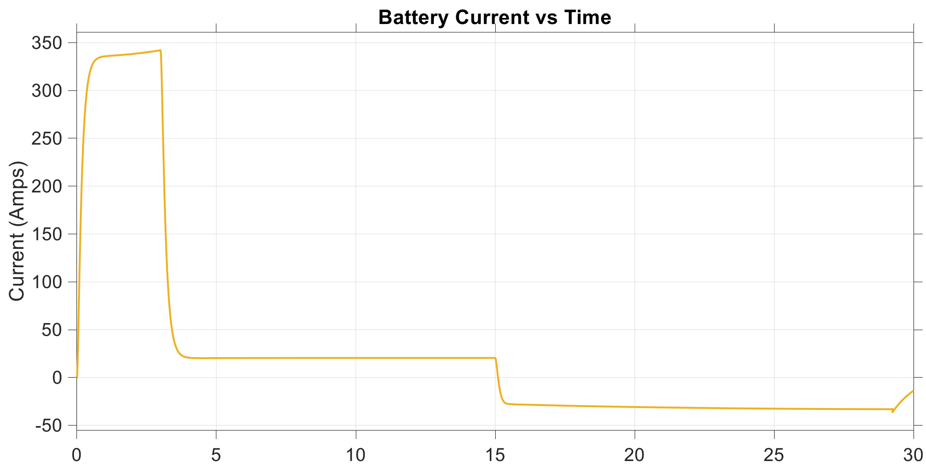
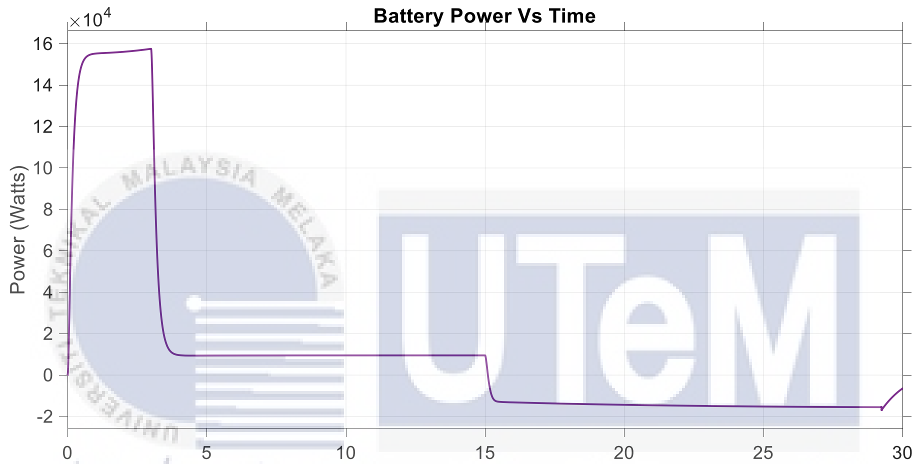


Figure 4.21: Simulation results of reference speed of 40 km/h; Vehicle Speed

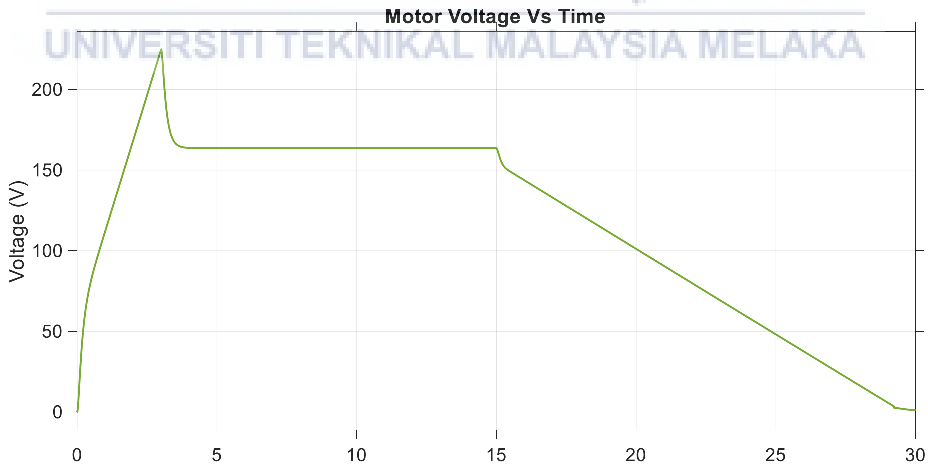
Figure 4.21 represents the simulation results of a vehicle speed in comparison to the reference speed. Figure 4.21 shows that the reference speed had reached 40 km/h at 3.3 seconds, while the vehicle speed had reached the target speed at 3.7 seconds. Because of the vehicle's inertia, it took 0.4 seconds longer to reach 40 km/h than the reference speed. While the vehicle begins to maintain a speed of 40 km/h, figure 4.22 shows that the battery current and power remain constant at 20.3 amps and 9400 watts, respectively. The voltage pattern exhibits an overshoot, peaking at t=3.7 seconds and remaining at 162.7V.



(a)



(b)



(c)

Figure 4.22: Simulation results of reference speed of 40 km/h; (a) Battery Current; (b) Battery Power; (c) Motor Voltage

The brake is applied at t=15 seconds to simulate the vehicle model's regenerative braking effect. Power is drawn from the battery to the load during motoring mode and returned to the battery during regeneration mode, as shown in figure 4.22 (b). When the current and voltage flow in the opposite direction, the motor enters regenerative braking mode (generator). Battery pattern trend of the state of charge decreases along the simulation and sometimes increases due to regenerative braking, as illustrated in figure 4.23. The distance travelled at the end of the simulation is 233.3m. The vehicle speed is slightly lower than the reference speed input, indicating that it is reasonably accurate.

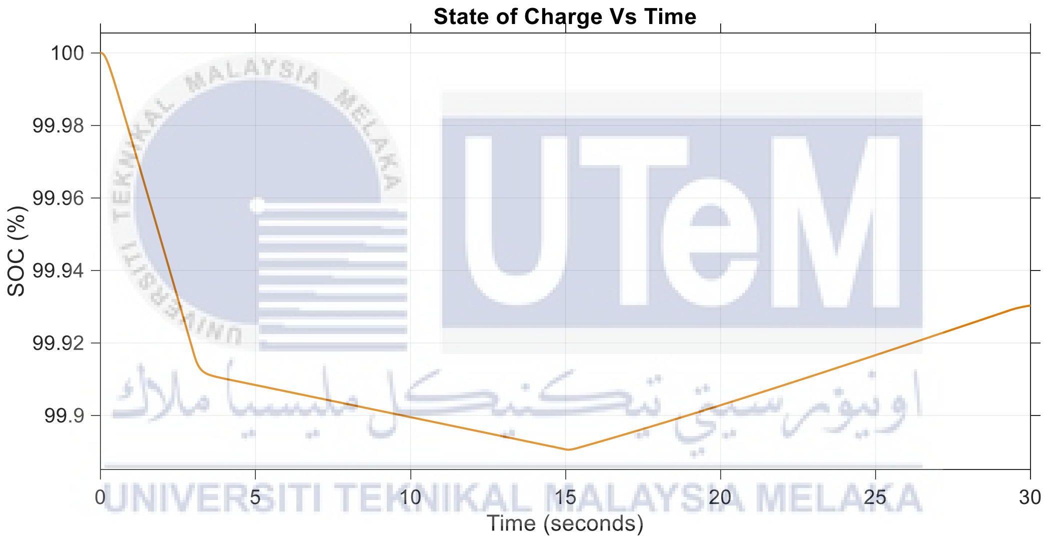


Figure 4.23: Simulation results of reference speed of 40 km/h; State of charge

4.3.2 Performance evaluation of the speed control of electric vehicle in 60 km/h

The simulation continued with a reference speed of 60 km/h because the vehicle model can reach 40 km/h. The distance covered in 30 seconds of simulation is approximately 349.2m. As illustrated in Figure 4.24, this vehicle model has no trouble reaching the reference speed.

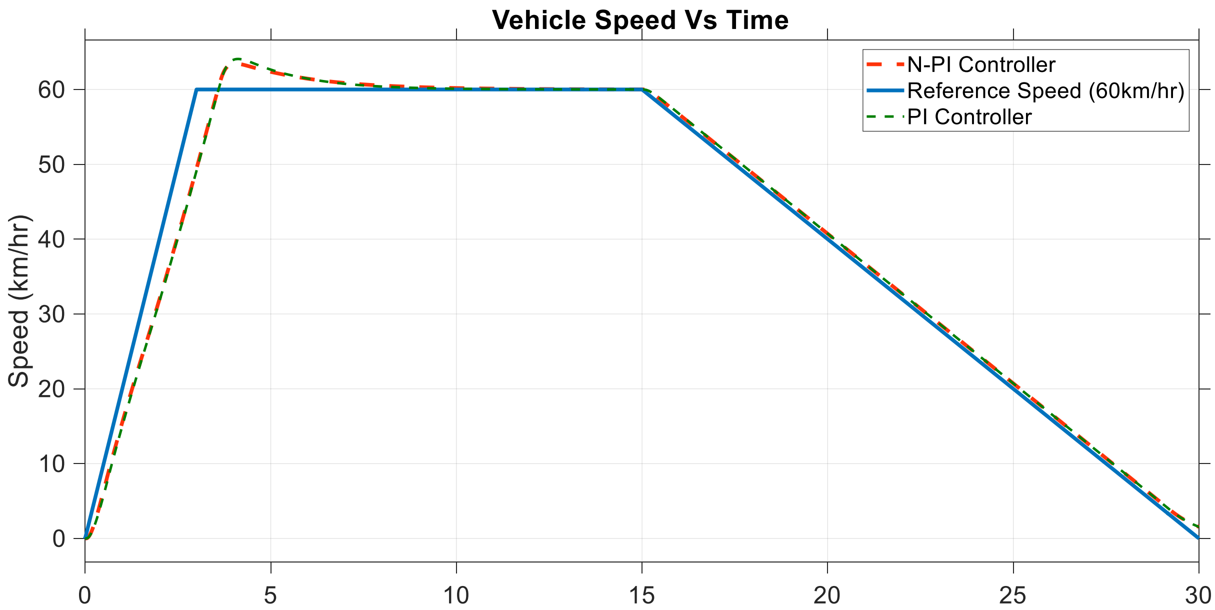
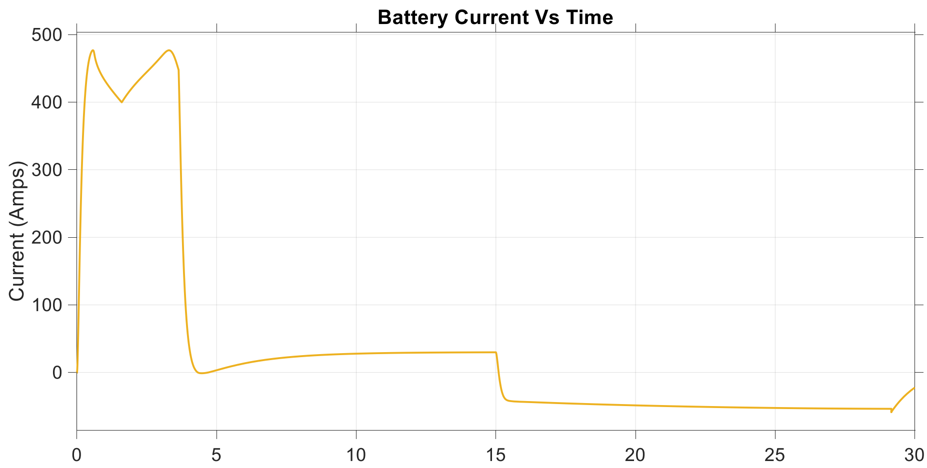
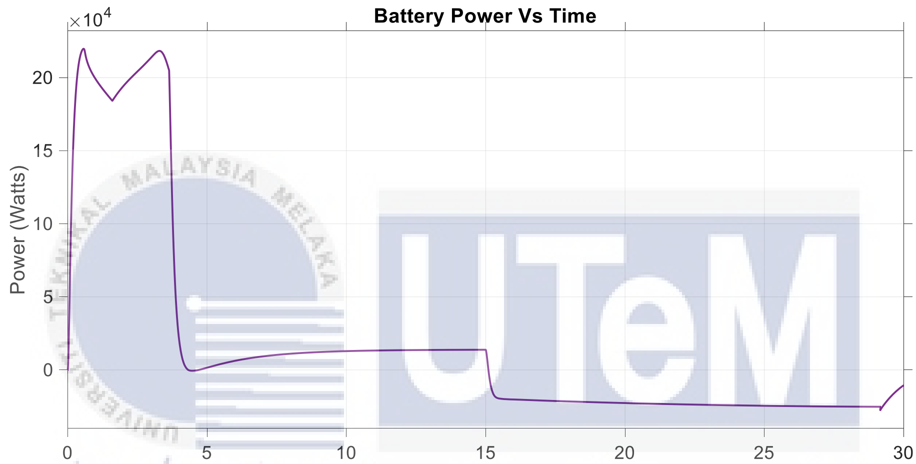


Figure 4.24: Simulation results of reference speed of 60 km/h; Vehicle Speed

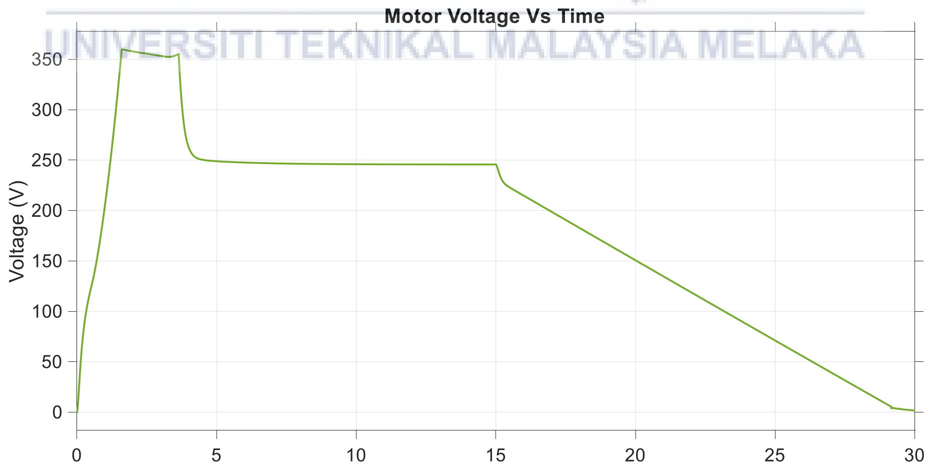
Figure 4.25 (a-b) illustrates the power and current drawn from the battery. The pattern of current and power is fundamentally the same as in the previous simulation. The increase in battery current usage, as shown in Figure 4.25 (a), is due to vehicle acceleration. The battery's voltage curve absorbs power from the battery to the load and returns it to the battery when regenerated. When the voltage and current polarities are equal, the motor operates in standard motoring mode. However, as the current decreased and power flowed in the opposite direction, the motor's function as a generator changed, resulting in regenerative braking mode.



(a)



(b)



(c)

Figure 4.25: Simulation results of reference speed of 60 km/h; (a) Battery Current; (b) Battery Power; (c) Motor Voltage

The charging rate for a battery travelling at 60 km/h is depicted in Figure 4.26. From the diagram, the battery discharge rate at the end of the simulation is 0.1%. In parallel with the battery current rate depicted in Figure 4.25 (a), the discharge rate occurs only during the first 15 seconds, i.e., while the vehicle is driven quickly. However, it is discovered that the battery charging rate increases by 0.03 % while the vehicle is going through the braking phase. This is due to the effects of regenerative braking.

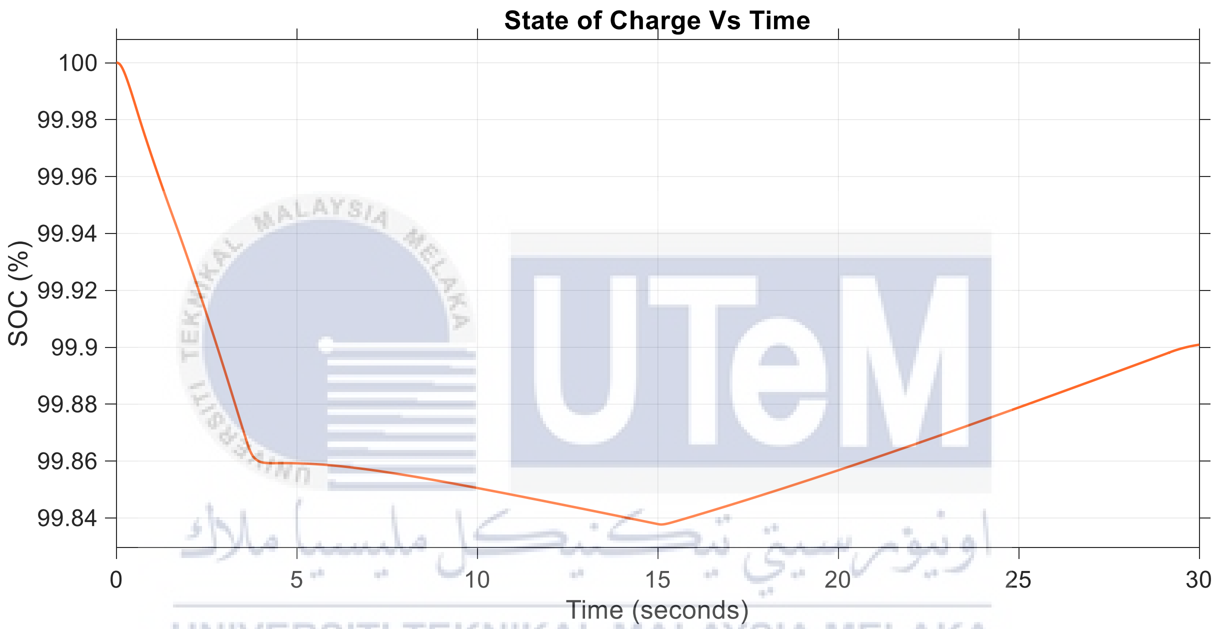


Figure 4.26: Simulation results of reference speed of 60 km/h; State of charge

4.3.3 Simulation result of vehicle in Federal Test Procedure 75 (FTP-75)

Motor performance was the first component that will be analysed. In Figure 4.27, it was illustrated the vehicle speed produced by the motor to complete the drive cycle. The maximum velocity produced by an EVs was 91.25 kilometres per hour at the y-axis with time that was 240.06 second at the x-axis. This result was very similar with the reference drive cycle that means the simulation of this EVs has successfully completed the desired path. After that, the torque of the motor can be measured and illustrated as in Figure 4.28 that shows the positive and negative values. The positive torque means that the vehicle was in forward motoring while the negative torque shows the vehicle was in forward regenerating or braking mode. The maximum and minimum torque that produce by the motor as in Figure 4.28.

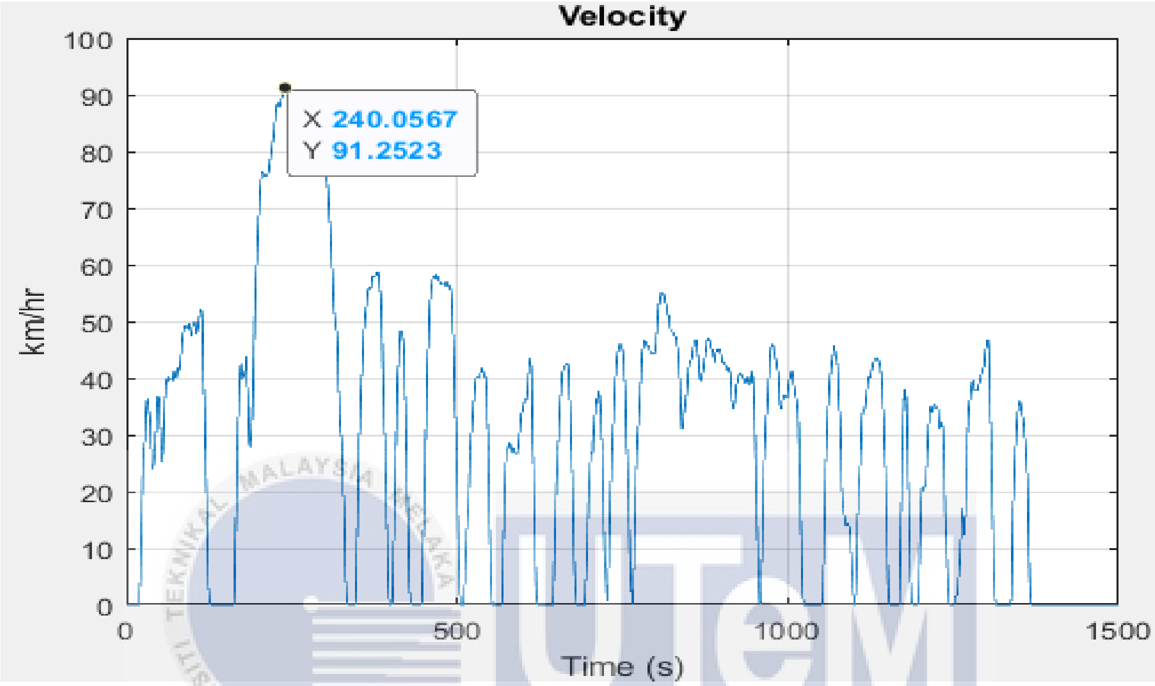


Figure 4.27: Vehicle speed

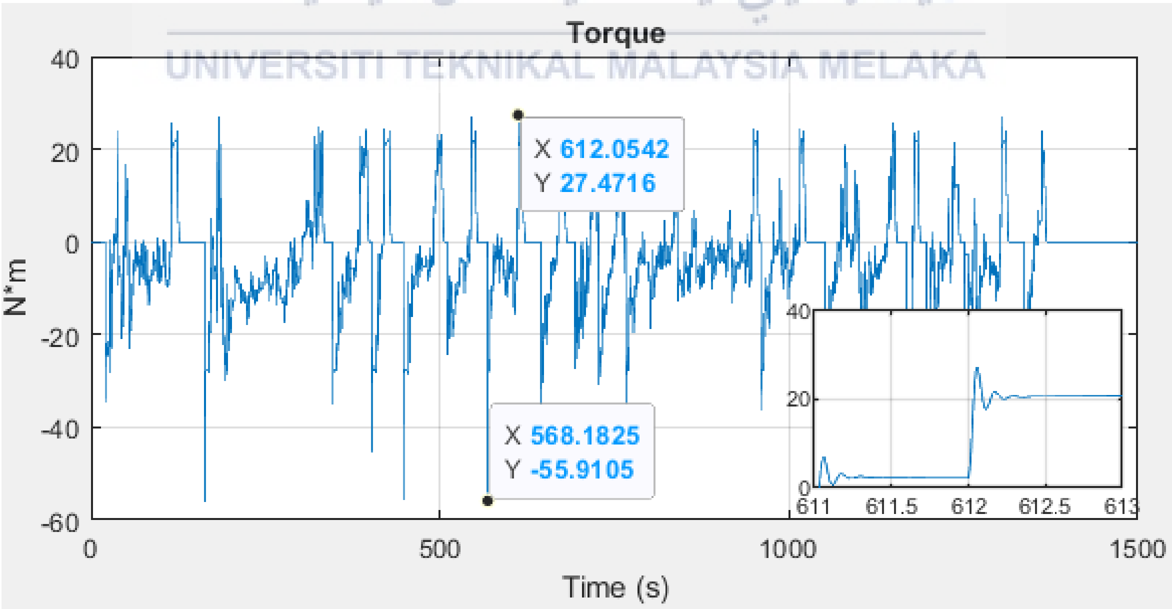


Figure 4.28: Motor Torque

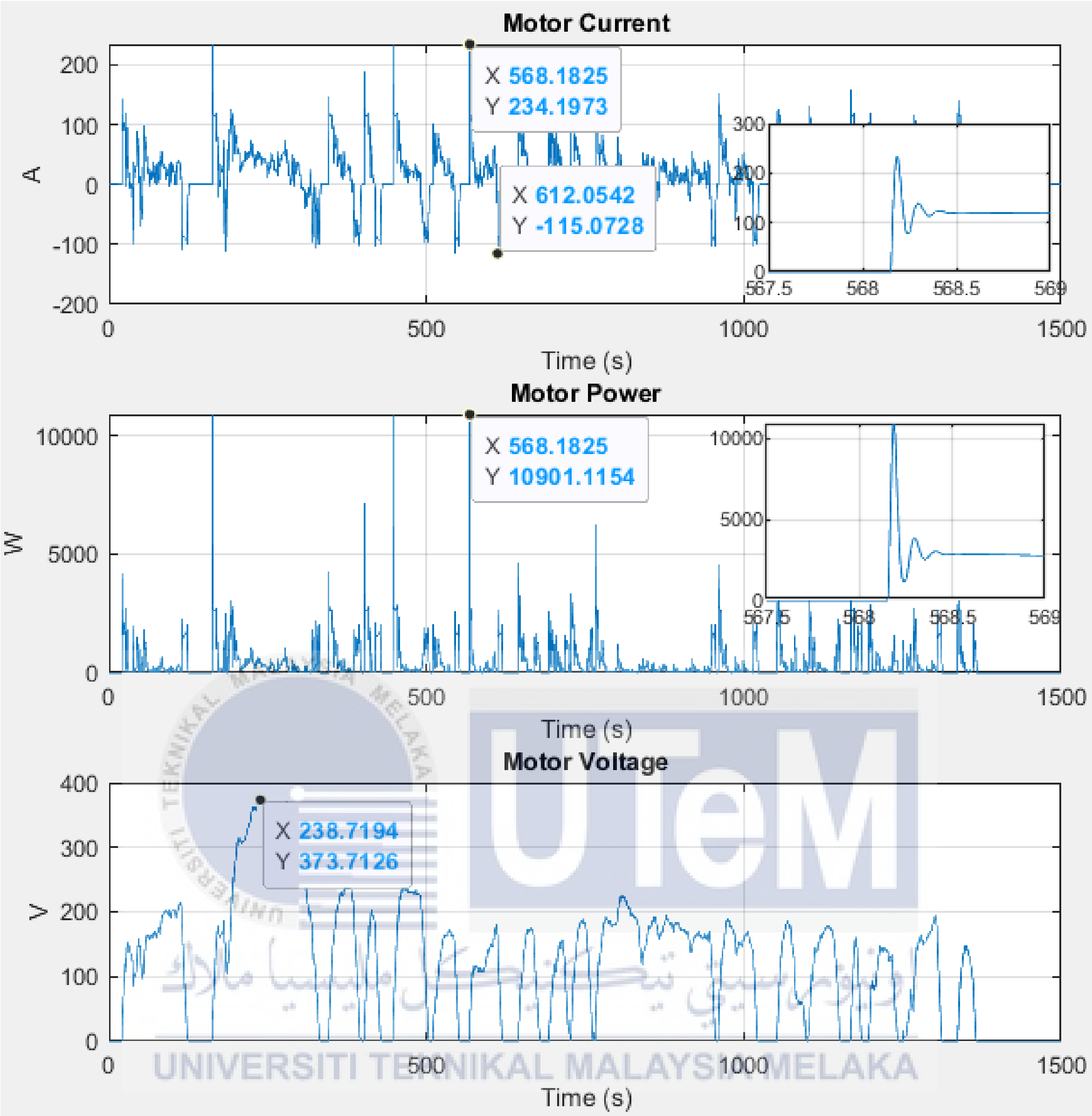


Figure 4.29: Motor Current, Power and Voltage

Figure 4.29 shows about the current, power and voltage developed in the motor. The current curved follows the torque curved in Figure 4.28 while the voltage curved follows the speed curved in Figure 4.27. It causes because of the propotional torque with the current and the voltage developed with the vehicle speed for dc motor. Finally, the power curved in the second plotted once again confirmed that the motor was operated in motoring modes when the curved increased and in regeneration modes when the curved decreased. The power was flow from the battery to the motor during motoring operation and returns back to the battery during regenerative braking.

Figure 4.30 and 4.31 shows the current and state of charge draws from the battery. From the Figure 4.30, the illustration of battery current curved followed the shape of the motor current and the required torque curved. The rise of the battery current causes due to the increased in torque demand in Figure 4.28. The rise of the current causes the motor operated in regular motoring mode. However, the motor operation was switched into regenerative braking mode (generator) when the current turns to negative and the power will flow in the opposited direction. From the Figure 4.31, it shows about the battery state of charge (SOC) after the vehicle travel for 1500 second. At the end of the simulation, the SOC is around 98.28 percent which means that 1.72 percent of the battery was used for 11.99 kilometres distance travelled. From this result, the battery usaged of this vehicle from the full charge until zero can be estimated. A reduction in the battery percentage still occurs even it was equipped with a regenerative mode. This is because not all energy during braking can be converted to recharged the battery but instead is lost in the form of heat.

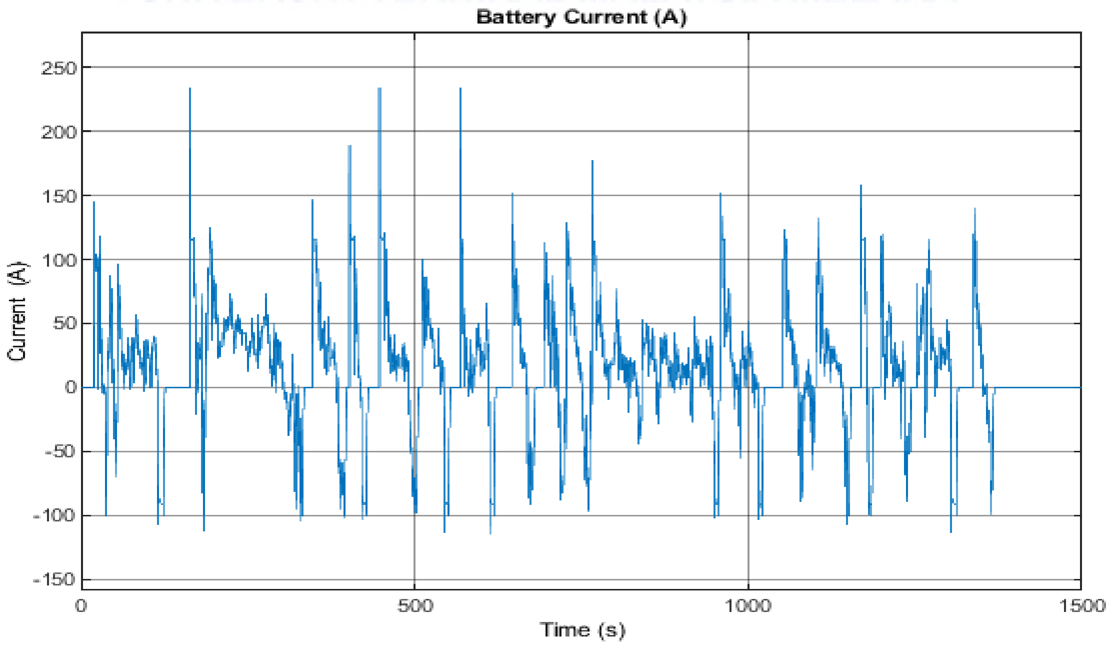


Figure 4.30: Battery Current

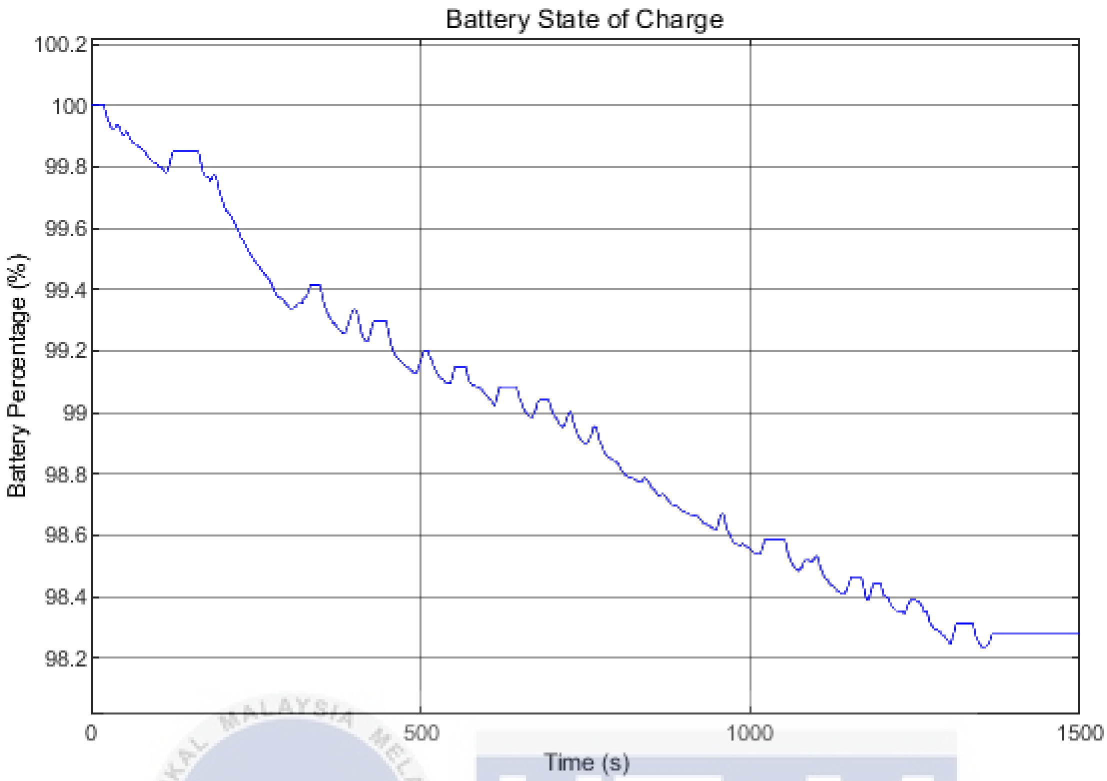


Figure 4.31: Battery State of Charge (SOC)

4.4 Summary

The vehicle model validation results have been discussed, and they show that the simulation model's behaviour agrees with the experimental behavior's responses with an acceptable error of less than 10%, and the simulation results of three tests have been presented. The simulation results for all tests for this vehicle model were found to be satisfactory and succeed to reach the maximum speed of the reference drive cycle which is 91.25 km/h. Finally, the regenerative braking mode operates in the same way as before, with the current reduced and power flowing in the opposite direction.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The validation of the vehicle longitudinal model, which includes modelling the vehicle model, measuring the vehicle model parameters, and conducting experiments with a real vehicle, is presented in this section of the thesis. Conclusions were drawn based on the scope of the study as outlined in this thesis and the detailed explanations provided below.

In this study, some researched and discussion about an EV has been done in order to identify the element of parameters study such as their mass, wheel radius, frontal area, rolling ressistance coefficient and battery capacity. With less than 10% error from the results of this experiment, there is no significant difference between the simulation results and the experimental data. However, by fine-tuning the vehicle and wheel parameters for the vehicle longitudinal model, the error can be reduced. As a result, a vehicle's longitudinal model can be used to represent a real vehicle. Then, the EV drivetrain has been proposed in order to make a simple and a low run time vehicle models using individual components model. The main components found in the EV drivetrain were the controller, electric component, lithium-ion battery, dc motor, simple gear and a vehicle body.

For simulation and analysis, both motoring and regeneration modes were used. The energy transfer from the battery to the load can be investigated using this vehicle model. The performance of the EV is determined by the controller's ability to eliminate system errors. To retain the same battery input, PI controller was used in this researched.

The designed EV's speed control was evaluated under a variety of conditions. The results show that the driving cycles used in this simulation can accurately predict the performance of the electric drive system, batteries, and other components. The simulation findings for this model were found to be strong at all outcomes. Finally, the regenerative braking mode operates in the same way as before, with the current reduced and power flowing in the opposite direction.

5.2 Recommendation

The result that has been obtained in this thesis show a good understanding in speed control of four wheel electric vehicle. However, there are some additional work that would help to improve these investigations knowledge.

Firstly, the experiment on this study has been done only in forward and braking condition. Therefore, the future experiment must be done in different type of the condition which were in moving backward and cornering to find the real performance of the vehicle according to the real condition.

Then, all of the component that have been used in this EV was very simple and basic. For the future improvement, the simulation of an EV must be done by consider a full and complex component which is more advanced.

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