



**PERFORMANCE EVALUATION OF AN ELECTRIC VEHICLE  
USING IN-WHEEL MOTOR IN THE LONGITUDINAL DIRECTION**



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**MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

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**Faculty of Mechanical Technology and Engineering**

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**MUHAMMAD SHUKRI AZIZI BIN RAZAK**

**A thesis submitted  
in fulfilment of the requirements for the degree of  
Master of Science in Mechanical Engineering**



**Faculty of Mechanical Technology and Engineering**

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2024**

## DECLARATION

I declare that this thesis entitled “Performance Evaluation of An Electric Vehicle Using In-Wheel Motor In The Longitudinal Direction” 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 : 

Name : Muhammad Shukri Azizi bin Razak

Date : 28 December 2023

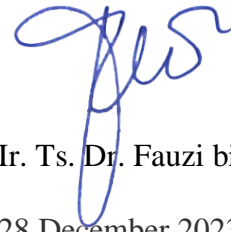


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## APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of the degree of Master of Science in Mechanical Engineering.

Signature :



Supervisor Name : Ir. Ts. Dr. Fauzi bin Ahmad

Date : 28 December 2023



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## DEDICATION

To Prophet Muhammad (S.A.W), my beloved father and mother, family and teachers.



## ABSTRACT

This study explores the latest electric vehicle driving system concept, the in-wheel motor (IWM) on the rear drive to minimize the weight carried by the current dynamic electric vehicle. The current electric vehicle driving system is a single motor integrated with a gearbox and differential mechanism. The integration of these three mechanical systems causes the dynamic performance of the electric vehicle to not be fully exploited. Therefore, the objective of this study is to evaluate the capability of electric vehicles based on in-wheel motors. To achieve this goal, the first step is to develop a mathematical model of the in-wheel motor using MATLAB/Simulink software. This mathematical model uses the actual parameters of the in-wheel motor, controlled by a PID controller, and verified through a series of experiments. Furthermore, to improve the confidence in the capability of the in-wheel motor, it has been applied to a mathematically developed vehicle model. The IWM based vehicle sub-model simulation has been validated in a hardware-in-the-loop simulation (HILS) using a sub-vehicle model integrated with an actual IWM. The IWM test on the sub-vehicle shows good results and increases confidence that it can be used in actual vehicles. Besides, the rear-wheel-based electric vehicle model has been designed using SolidWorks software. This design is done in detail based on the actual hardware dimensions to ensure the feasibility and functionality of the prototype to be fabricated. Subsequently, the in-wheel motor-based electric vehicle has been fabricated in the Autotronic laboratory based on the designed dimensions. At the same time, a 5-DOF longitudinal simulation model of a vehicle integrated with an in-wheel motor has been developed using actual parameters from the fabricated electric vehicle. This simulation model has been verified through a series of experiments conducted on two different road surfaces, flat and uphill with a gradient of  $8.45^\circ$ . Each experimental test was performed at different speeds of 10, 20, and 30 km/h. The results show that the minimum relative absolute error (MRAE) value is less than 5 %, increasing confidence that the developed simulation model is adequate. Therefore, researchers and the industry can utilize the findings of this study for observation and application of in-wheel motor systems on actual vehicles.

## **PENILAIAN PRESTASI KENDERAAN ELEKTRIK MENGGUNAKAN RODA BERMOTOR DALAM ARAH MEMBUJUR**

### **ABSTRAK**

*Kajian ini meneroka sistem pemanduan kenderaan elektrik terkini yang berkonsepkan motor dalam roda pada pacuan belakang bagi meminimumkan berat yang ditampung oleh dinamik kenderaan elektrik pada masa ini. Sistem pemanduan kenderaan elektrik pada masa ini adalah berkonsepkan motor tunggal yang bersepadu dengan kotak gear serta mekanisme pembezaan. Penyepaduan ketiga-tiga sistem mekanikal ini menyebabkan prestasi dinamik kenderaan elektrik tidak dapat dieksploitasikan sepenuhnya. Oleh itu, objektif kajian ini adalah untuk menilai keupayaan kenderaan elektrik berasaskan motor dalam roda. Bagi mencapai matlamat ini, langkah pertama yang diambil adalah membangunkan model matematik motor dalam roda menggunakan perisian MATLAB/ Simulink. Model matematik ini menggunakan parameter motor dalam roda yang sebenar, dikawal menggunakan pengawal PID dan disahkan melalui beberapa siri eksperimen. Selain daripada itu, bagi meningkatkan keyakinan keupayaan motor dalam roda, ia telah diaplikasikan pada model suku kenderaan yang dibangunkan secara matematik. Model simulasi suku kenderaan berasaskan motor dalam roda telah divalidasi secara perkakasan dalam simulasi gegelung menggunakan model suku kenderaan bersepadu dengan motor dalam roda yang sebenar. Pengujian motor dalam roda pada kenderaan suku menunjukkan keputusan yang baik dan meningkatkan kepercayaan bahawa ia mampu untuk digunakan pada kenderaan sebenar. Lanjutan daripada itu, model kenderaan elektrik berasaskan motor dalam roda pada pacuan belakang telah direka bentuk menggunakan perisian SolidWorks. Reka bentuk ini dilakukan secara terperinci berdasarkan ukuran sebenar perkakasan bagi memastikan kebolehlaksanaan dan kefungisian prototaip yang akan difabrikasi. Seterusnya, kenderaan elektrik berasaskan motor dalam roda telah difabrikasi di dalam makmal autotronik berdasarkan ukuran yang telah ditetapkan. Dalam masa yang sama, model simulasi kenderaan membujur 5-DOF bersepadu dengan motor dalam roda telah dibangunkan menggunakan parameter sebenar daripada kenderaan elektrik yang telah difabrikasi. Model simulasi ini telah disahkan melalui beberapa siri eksperimen yang dijalankan pada dua permukaan jalan yang berbeza iaitu jalan rata dan jalan berbukit yang mempunyai kecerunan  $8.45^\circ$ . Setiap pengujian eksperimen dilakukan pada kelajuan yang berbeza-beza iaitu 10, 20 dan 30 km/j. Keputusan menunjukkan nilai minimum ralat mutlak relatif kurang daripada 5 % meningkatkan keyakinan bahawa model simulasi yang dibangunkan adalah mencukupi. Oleh itu, para penyelidik dan industri boleh memanfaatkan penemuan kajian ini untuk pemerhatian dan aplikasi sistem motor dalam roda pada kenderaan sebenar.*

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## TABLE OF CONTENTS

|   | <b>PAGE</b> |
|---|-------------|
| <b>DECLARATION</b>  |             |
| <b>DEDICATION</b>   |             |
| <b>ABSTRACT</b>   | i           |
| <b>ABSTRAK</b>  | ii          |
| <b>ACKNOWLEDGEMENTS</b>   | iii         |
| <b>TABLE OF CONTENTS</b>  | iv          |
| <b>LIST OF TABLES</b>   | vii         |
| <b>LIST OF FIGURES</b>  | viii        |
| <b>LIST OF APPENDICES</b>                                       | xii         |
| <b>LIST OF SYMBOLS</b>  | xiii        |
| <b>LIST OF ABBREVIATIONS</b>                                    | xvi         |
| <b>LIST OF PUBLICATIONS</b>                                     | xix         |
| <br>  |             |
| <b>CHAPTER</b>  |             |
| <b>1. INTRODUCTION</b>  | <b>1</b>    |
| 1.1 Overview  | 1           |
| 1.2 Research Background   | 5           |
| 1.3 Problem Statement   | 8           |
| 1.4 Research Objective  | 8           |
| 1.5 Scope of Research   | 9           |
| 1.6 Contribution of Research                                    | 10          |
| 1.7 Thesis Outline  | 11          |
| <br>  |             |
| <b>2. LITERATURE REVIEW</b>                                     | <b>13</b>   |
| 2.1 Introduction  | 13          |
| 2.2 Internal Combustion Engines Vehicle                         | 13          |
| 2.3 The Rise of Hybrid Vehicles                                 | 14          |
| 2.4 The Fundamental Of Electric Vehicle                         | 16          |
| 2.5 The In-Wheel Motor Electric Vehicle                         | 24          |
| 2.5.1 Modelling Approach of IWM-EV                              | 28          |
| 2.5.2 Development of IWM-EV Control Strategy                    | 29          |
| 2.5.3 The Implementation of In Wheel Motor Vehicle Drive System | 32          |
| 2.6 Design of Electric Vehicle Chassis                          | 33          |
| 2.7 Research Gap  | 35          |
| 2.8 HILS Technique  | 37          |
| 2.8.1 HILS Hardware and Software                                | 39          |
| 2.8.2 Developing Simulation Model for HILS tests                | 41          |
| 2.9 Experimental Tests  | 41          |
| 2.9.1 Experimental hardware and software                        | 43          |
| 2.9.2 Developing Simulation Model for Experimental tests        | 45          |
| 2.10 Simulation Validation                                      | 46          |
| 2.11 Summary  | 47          |
| <br>  |             |
| <b>3. METHODOLOGY</b>   | <b>48</b>   |
| 3.1 Introduction  | 48          |

|           |   |            |
|-----------|---|------------|
| 3.2       | In-Wheel Motor Modelling  | 48         |
| 3.2.1     | In-Wheel Motor Parametric Modelling And Assumption  | 50         |
| 3.2.2     | In-Wheel Motor Control Strategy By Using PPEM   | 52         |
| 3.2.3     | Experimental Procedure For Validation of In-Wheel Motor                                     | 54         |
| 3.3       | Testing of In-Wheel Motor Using The QC With An Anti-Slip Control Structure                  | 57         |
| 3.3.1     | Quarter Car Dynamic Vehicle Model   | 58         |
| 3.3.2     | Effectiveness of In-Wheel Motor Between Anti-Slip and Slip In The Control Scheme            | 60         |
| 3.3.3     | Experimental Procedure of HILS Tests for In-Wheel Motor Based Quarter Electric Vehicle      | 62         |
| 3.4       | Simulation and Experimental of In-Wheel Motor Based Electric Vehicle                        | 63         |
| 3.4.1     | Modelling Assumption of 5-DOF Vehicle Longitudinal Model                                    | 63         |
| 3.4.2     | Mathematical Modelling of 5-DOF In-Wheel Motor Based Electric Vehicle                       | 64         |
| 3.4.3     | In-Wheel Motor Based Electric Vehicle Control Scheme  | 66         |
| 3.4.4     | Development of In-Wheel Motor Based Electric Vehicle  | 67         |
| 3.4.4.1   | Design of In-Wheel Motor Based Electric Vehicle   | 67         |
| 3.4.4.2   | Fabrication of In-Wheel Motor Based Electric Vehicle  | 68         |
| 3.4.4.3   | Vehicle Instrumentation   | 70         |
| 3.4.5     | Experimental procedure of 5-DOF In-Wheel Motor Based Electric Vehicle model                 | 72         |
| 3.5       | Summary   | 76         |
| <b>4.</b> | <b>RESULTS AND DISCUSSION</b>   | <b>78</b>  |
| 4.1       | Introduction  | 78         |
| 4.2       | Simulation and Experimental Result of The In-Wheel Motor Model                              | 78         |
| 4.2.1     | Simulation and Experimental Result of IWM Using square signal                               | 78         |
| 4.2.2     | Simulation and Experimental Result of In-Wheel Motor Using Sine Wave Signal                 | 81         |
| 4.2.3     | Simulation and Experimental Result of In-Wheel Motor Using Sawtooth Signal                  | 84         |
| 4.3       | Simulation and Experimental Result of In-Wheel Motor Based Electric Vehicle for Quarter Car | 86         |
| 4.4       | Simulation and Experimental Result of In-Wheel Motor Based Electric Vehicle Model           | 91         |
| 4.4.1     | Simulation and Experimental Result Acceleration Tests on The Level Pavement                 | 92         |
| 4.4.2     | Simulation and Experimental Result of Acceleration Then Braking Tests on The Level Pavement | 96         |
| 4.4.3     | Simulation and Experimental Result of Road Gradient Tests                                   | 100        |
| 4.5       | Summary   | 104        |
| <b>5.</b> | <b>CONCLUSION AND RECOMMENDATIONS</b>   | <b>106</b> |
| 5.1       | Conclusion  | 106        |
| 5.1.1     | The In-Wheel Motor Electric Vehicle Mathematical Modelling                                  | 106        |

|                   |   |            |
|-------------------|---|------------|
| 5.1.2             | Proposed In-Wheel Motor Based Electric Vehicle Control Structure  | 107        |
| 5.1.3             | Simulation and experimental evaluation of In-Wheel Motor Based Electric Vehicle in Longitudinal Dynamic | 108        |
| 5.2               | Open Problem and Recommendation for Future Works  | 108        |
| <b>REFERENCES</b> |   | <b>110</b> |
| <b>APPENDICES</b> |   | <b>130</b> |



## LIST OF TABLES

| TABLE | TITLE  | PAGE |
|-------|--|------|
| 1.1   | Average temperature statistics in Malaysia                                   | 2    |
| 1.2   | Average annual temperature until 2030 and 2050                               | 2    |
| 3.1   | Controller parameter   | 54   |
| 3.2   | Throttle input value and the speed response of IWM                           | 57   |
| 3.3   | IWM-EV Controller parameter  | 66   |
| 3.4   | Reaction force on IWM-EV   | 73   |
| 4.1   | Speed tracking control performances for step function                        | 80   |
| 4.2   | RMS value of speed tracking control for sine wave function                   | 83   |
| 4.3   | RMS value of speed tracking control for sawtooth function                    | 86   |
| 4.4   | MRAE validation test for bounded signal at a speed of 10 km/h                | 89   |
| 4.5   | MRAE of QCEV validation results at the variant speed                         | 91   |
| 4.6   | MRAE of acceleration performance on the level pavement at different speed    | 96   |
| 4.7   | MRAE of acceleration then braking tests on level pavement at different speed | 100  |
| 4.8   | MRAE of acceleration performance tests on incline roads at different speed   | 104  |

## LIST OF FIGURES

| FIGURE | TITLE   | PAGE |
|--------|---|------|
| 1.1    | API during MCO at Wilayah Persekutuan Putrajaya (Ramli et al. 2021)   | 3    |
| 1.2    | API during MCO at Bandaraya Petaling Jaya (Ramli et al., 2021)  | 4    |
| 1.3    | SMD and DMD configuration   | 6    |
| 2.1    | (a) In- Line Engines, (b) V-Engine, (c) Horizontal Engine (Saif M, 2023)  | 14   |
| 2.2    | Hybrid electric vehicle powertrain configuration (a) Series; (b) Parallel; (c) Series-Parallel (Shrey Verma, 2014)    | 16   |
| 2.3    | Thomas Davenport electric vehicle (Wikimedia Commons, 1838)   | 17   |
| 2.4    | William Morrison vehicle (Wikimedia Commons, 1891)  | 18   |
| 2.5    | Electric taxi in New York City in 1897 (Wikimedia Commons, 1897)  | 19   |
| 2.6    | Citicar electric vehicle (Wikimedia Commons, 2012)  | 20   |
| 2.7    | EV1 electric car (Wikipedia, 1990)  | 21   |
| 2.8    | Tesla Roadster sport electric vehicle (Wikimedia Commons, 2014)   | 22   |
| 2.9    | Nissan "Leaf" EV model (Nissan, 2019)   | 23   |
| 2.10   | First In-wheel motor electric vehicle (Porsche Newsroom, 2019)  | 25   |
| 2.11   | Configuration of IWM: (a) Individual motor; (b) Individual motor integrated with a gearbox system; (c) In-wheel motor | 27   |
| 2.12   | Development of IWM-EV chassis   | 35   |
| 2.13   | HILS method   | 38   |
| 2.14   | HILS testing for QC electric vehicle  | 40   |
| 2.15   | Experimental tests of geared IWM-EV   | 43   |
| 2.16   | IWM experimental electric vehicle   | 45   |
| 3.1    | Flow chart of the research  | 49   |
| 3.2    | IWM vector diagram  | 51   |

|      |  |    |
|------|--|----|
| 3.3  | IWM control scheme   | 53 |
| 3.4  | Experimental setup for performance evaluation of IWM model   | 55 |
| 3.5  | Nexus between throttle input and IWM speed traits  | 56 |
| 3.6  | QC-traction model  | 58 |
| 3.7  | IWM-EV with anti-slip rejection loop   | 61 |
| 3.8  | Experimental setup for IWM-QCEV HILS tests   | 62 |
| 3.9  | Schematic diagram of IWM-EV  | 65 |
| 3.10 | IWM-EV control strategy  | 66 |
| 3.11 | Design of IWM-based Electric Vehicle   | 68 |
| 3.12 | Chassis laser balance  | 69 |
| 3.13 | Fabrication of chassis   | 70 |
| 3.14 | Chassis painting process   | 70 |
| 3.15 | Electric vehicle instrumentation   | 71 |
| 3.16 | Load cell sensor position  | 73 |
| 3.17 | Front vehicle raised up  | 74 |
| 3.18 | Experimental tests of IWM-EV   | 75 |
| 3.19 | Route used to run the experimental tests   | 76 |
| 4.1  | Response of square input speed control with varying speed of 10, 20 and 30 km/h  | 79 |
| 4.2  | Respond of speed tracking control for sine wave function   | 82 |
| 4.3  | Respond of speed tracking control for sawtooth function  | 85 |
| 4.4  | Response of the IWM-QCEV at the speed of: (a) 10 km/h; (b) 20 km/h; (c) 30 km/h; (d) 40 km/h   | 87 |
| 4.5  | The evaluation of IWM-EV acceleration performance on the level pavement at 10 km/h: (a) throttle and braking input; (b) dynamic vehicle characteristics; (c) electrical dynamic characteristics              | 90 |
| 4.6  | The evaluation of IWM-EV acceleration then braking performance on the level pavement at 10 km/h: (a) throttle and braking input; (b) dynamic vehicle characteristics; (c) dynamic electrical characteristics | 93 |

|     |  |     |
|-----|--|-----|
| 4.7 | The evaluation of IWM-EV acceleration performance on incline road at 10 km/h: (a) throttle and braking input; (b) dynamic vehicle characteristics; (c) electrical dynamic characteristics                | 97  |
| 4.8 | The evaluation of IWM-EV acceleration performance on incline road at 10 km/h: (a) throttle and braking input; (b) dynamic vehicle characteristics; (c) electrical dynamic characteristics                | 101 |
| C-1 | The evaluation of IWM-QCEV speed tests at 20 km/h: (a) vehicle dynamic characteristics; (b) electrical dynamic characteristics   | 150 |
| C-2 | The evaluation of IWM-QCEV speed tests at 30 km/h: (a) vehicle dynamic characteristics; (b) electrical dynamic characteristics   | 151 |
| C-3 | The evaluation of IWM-QCEV speed tests at 40 km/h: (a) vehicle dynamic characteristics; (b) electrical dynamic characteristics   | 152 |
| D-1 | The evaluation of IWM-EV acceleration performance on level pavement at 15 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics              | 153 |
| D-2 | The evaluation of IWM-EV acceleration performance on level pavement at 20 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics              | 154 |
| E-1 | The evaluation of IWM-EV acceleration then braking performance on level pavement at 15 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics | 155 |
| E-2 | The evaluation of IWM-EV acceleration then braking performance on level pavement at 20 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics | 156 |
| F-1 | The evaluation of IWM-EV acceleration performance on incline road at 15 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics                | 157 |
| F-2 | The evaluation of IWM-EV acceleration performance on incline road at 20 km/h: (a) throttle and braking input; (b) vehicle dynamic characteristics; (c) electrical dynamic characteristics                | 158 |

## LIST OF APPENDICES

| APPENDIX | TITLE   | PAGE |
|----------|---|------|
| A        | IWM-EV detail drawings and its component  | 130  |
| B        | IWM-EV Circuit Diagram  | 149  |
| C        | Validation Results of IWM-QCEV  | 150  |
| D        | Validation results of IWM-EV: acceleration performance on level pavement              | 153  |
| E        | Validation results of IWM-EV: acceleration then braking performance on level pavement | 155  |
| F        | Validation results of IWM-EV: acceleration performance on incline road                | 157  |
| G        | Basic Circuit Diagram for IWM   | 159  |
| H        | Copyright Variant Pipe Notch  | 160  |
| I        | Copyright the Electronic Wedge Brake Tests Bench                                      | 161  |

## LIST OF SYMBOLS

|           |   |   |
|-----------|---|---|
| $a$       | - | Distance of CG From The Front Axle                              |
| $b$       | - | Distance of CG From The Rear Axle                               |
| $e$       | - | Error   |
| $d$       | - | Distance Travel of the Vehicle                                  |
| $F_d$     | - | Drag Force of the Vehicle                                       |
| $F_x$     | - | Longitudinal Tyre Force   |
| $F_z$     | - | Normal Force  |
| $h_{CG}$  | - | Distance From The CG From The Plane Axis                        |
| $h$       | - | Distance of CG Above the Ground                                 |
| $i_a$     | - | Current on Phase A for Permanent Magnet Synchronous Motor       |
| $i_b$     | - | Current on Phase B for Permanent Magnet Synchronous Motor       |
| $i_c$     | - | Current on Phase C for Permanent Magnet Synchronous Motor       |
| $i_d$     | - | Stator Current on D-Axis for Permanent Magnet Synchronous Motor |
| $I_{IWM}$ | - | IWM Current for In-Wheel Motor                                  |
| $i_q$     | - | Stator Current on Q-Axis for Permanent Magnet Synchronous Motor |
| $J$       | - | Polar Moment of Inertia   |
| $K_b$     | - | Cylinder Pressure Gain  |
| $K_c$     | - | Pressure Gain   |
| $K_i$     | - | Integral Gain   |
| $K_p$     | - | Proportional Gain   |
| $L_{aa}$  | - | Inductance on Phase A-A for Permanent Magnet Synchronous Motor  |
| $L_{ab}$  | - | Inductance on Phase A-B for Permanent Magnet Synchronous Motor  |

|           |   |  |
|-----------|---|--|
| $L_{ac}$  | - | Inductance on Phase A-C for Permanent Magnet Synchronous Motor |
| $L_{bb}$  | - | Inductance on Phase B-B for Permanent Magnet Synchronous Motor |
| $L_{bc}$  | - | Inductance on Phase B-C for Permanent Magnet Synchronous Motor |
| $L_{cc}$  | - | Inductance on Phase C-C for Permanent Magnet Synchronous Motor |
| $L_d$     | - | Inductance on D-Axis for Permanent Magnet Synchronous Motor    |
| $L_q$     | - | Inductance on Q-Axis for Permanent Magnet Synchronous Motor    |
| $L_w$     | - | Width of The Experimental Vehicle                              |
| $m$       | - | Mass of Quarter Car  |
| $m_b$     | - | Body Mass of Quarter Car                                       |
| $m_w$     | - | Wheel Mass of Quarter Car                                      |
| $P$       | - | Number of Pole for In-Wheel Motor                              |
| $P_b$     | - | Brake Pressure Applied   |
| $R_a$     | - | Resistance on Phase A for Permanent Magnet Synchronous Motor   |
| $R_b$     | - | Resistance on Phase B for Permanent Magnet Synchronous Motor   |
| $R_c$     | - | Resistance on Phase C for Permanent Magnet Synchronous Motor   |
| $R_f$     | - | Front Radius of Experimental Vehicle                           |
| $R_r$     | - | Rear Radius of Experimental Vehicle                            |
| $R_s$     | - | Stator Resistance for In-Wheel Motor                           |
| $R_w$     | - | Radius of The Wheel  |
| $t$       | - | Time   |
| $T_{cmd}$ | - | Command Torque   |
| $T_e$     | - | Electromagnetic Torque   |
| $T_{IWM}$ | - | IWM Torque for In-Wheel Motor                                  |
| $u_b$     | - | Brake Setting  |
| $v_x$     | - | Vehicle Velocity   |

|             |   |   |
|-------------|---|---|
| $v_b$       | - | Vehicle Body  |
| $v_w$       | - | Wheel Speed   |
| $\dot{v}$   | - | Vehicle Acceleration  |
| $V$         | - | Voltage   |
| $V_b$       | - | Battery Voltage   |
| $V_a$       | - | Voltage on Phase A for Permanent Magnet Synchronous Motor       |
| $V_b$       | - | Voltage on Phase B for Permanent Magnet Synchronous Motor       |
| $V_c$       | - | Voltage on Phase C for Permanent Magnet Synchronous Motor       |
| $V_d$       | - | Stator Voltage on D-Axis for Permanent Magnet Synchronous Motor |
| $V_q$       | - | Stator Voltage on Q-Axis for Permanent Magnet Synchronous Motor |
| $W$         | - | Weight of The Experimental Vehicle                              |
| $W_f$       | - | Vehicle Weight on The Front                                     |
| $\theta$    | - | Road Inclination Angle  |
| $\lambda^*$ | - | Desired Longitudinal Tyre Slip                                  |
| $\mu$       | - | Road Coefficient of Friction                                    |
| $\tau_a$    | - | Traction Torque   |
| $\tau_b$    | - | Braking Torque  |
| $\tau_{bs}$ | - | Brake Lag   |
| $\psi_a$    | - | Flux on Phase A for Permanent Magnet Synchronous Motor          |
| $\psi_b$    | - | Flux on Phase B for Permanent Magnet Synchronous Motor          |
| $\psi_c$    | - | Flux on Phase C for Permanent Magnet Synchronous Motor          |
| $\psi_d$    | - | Stator Flux on D-Axis for Permanent Magnet Synchronous Motor    |
| $\psi_f$    | - | Stator Flux for Permanent Magnet Synchronous Motor              |
| $\psi_{ma}$ | - | Motor Flux on Phase A for Permanent Magnet Synchronous Motor    |
| $\psi_{mb}$ | - | Motor Flux on Phase B for Permanent Magnet Synchronous Motor    |

|                |   |  |
|----------------|---|--|
| $\psi_{mc}$    | - | Motor Flux on Phase C for Permanent Magnet Synchronous Motor |
| $\psi_q$       | - | Stator Flux on Q-Axis for Permanent Magnet Synchronous Motor |
| $\omega_{act}$ | - | Actual Wheel Angular Speed                                   |
| $\omega_r$     | - | Reference Angular Speed                                      |
| $\omega$       | - | Wheel Angular Velocity                                       |
| $g$            | - | Gravitational Acceleration                                   |
| %              | - | Percentage   |
| C°             | - | Degree Celcius   |



## LIST OF ABBREVIATIONS

|      |   |                                    |
|------|---|------------------------------------|
| AC   | - | Alternating Current                |
| ADC  | - | Analog To Digital Converter        |
| API  | - | Air Pollution Index                |
| AWD  | - | All Wheel Drive                    |
| BEV  | - | Battery Electric Vehicle           |
| CG   | - | Center Of Gravity                  |
| CMCO | - | Conditional Movement Control Order |
| CO   | - | Carbon Monoxide                    |
| CVT  | - | Continuous Variable Transmission   |
| DAC  | - | Digital To Analog Converter        |
| DC   | - | Direct Current                     |
| DMD  | - | Dual Motor Drive                   |
| DOE  | - | Department of Environment          |
| DOF  | - | Degree of Freedom                  |
| DYC  | - | Direct Yaw Control                 |
| EV1  | - | Electric Vehicle 1                 |
| EWD  | - | Electric Wheel Drive               |
| FBD  | - | Free Body Diagram                  |
| FLC  | - | Fuzzy Logic Controller             |
| FWD  | - | Front Wheel Drive                  |
| GM   | - | General Motor                      |
| HDD  | - | Hard Disc Drive                    |
| HEV  | - | Hybrid Electric Vehicle            |

|                 |   |   |
|-----------------|---|---|
| HILS            | - | Hardware-In-The-Loop Simulation                   |
| I/O             | - | Input/Output                                      |
| ICE             | - | Internal Combustion Engine                        |
| IWM             | - | In-Wheel Motor                                    |
| IWM-EV          | - | In-Wheel Motor Electric Vehicle                   |
| JPJ             | - | Jabatan Pengangkutan Jalan                        |
| km/h            | - | Kilometer Per Hour                                |
| MAA             | - | Malaysian Automotive Association                  |
| MCO             | - | Movement Control Order                            |
| MET Malaysia    | - | Meteorologi Malaysia                              |
| MPC             | - | Model Predictive Controller                       |
| MRAE            | - | Mean Relative Absolute Error                      |
| MIMO            | - | Multiple Input and Multiple Output                |
| N/A             | - | Naturally/ Aspirated                              |
| NEP             | - | National Energy Policy                            |
| NiMH            | - | Nickel Metal Hydride                              |
| NNC             | - | Neural Network Controller                         |
| NO <sub>2</sub> | - | Nitrogen Oxide                                    |
| ODE             | - | Ordinary Differential Equation                    |
| OPEC            | - | Organization of The Petroleum Exporting Countries |
| PI              | - | Proportional-Integral                             |
| PID             | - | Proportional-Integral-Derivative                  |
| PMSM            | - | Permanent Magnet Synchronous Motor                |
| PPEM            | - | Physical Parametric Estimation Modelling          |
| QC-EV           | - | Quarter Car Electric Vehicle                      |
| RMS             | - | Root Mean Square                                  |

|                 |   |  |
|-----------------|---|--|
| RWD             | - | Rear Wheel Drive                                     |
| Rx              | - | Signal Receiver                                      |
| SIM             | - | System Identification Method                         |
| SMC             | - | Sliding Model Controller                             |
| SMD             | - | Single Motor Drive                                   |
| SO <sub>2</sub> | - | Sulfur Oxide   |
| SSD             | - | Solid State Drive                                    |
| SSM             | - | State Space Model                                    |
| SUT             | - | System Under Tests                                   |
| SVPWM           | - | Space Vector Pulse Width Modulation                  |
| Tx              | - | Signal Transmitter                                   |
| UNFCCC          | - | United Nation Framework Convention On Climate Change |
| USB             | - | Universal Serial Bus                                 |
| USPTO           | - | United State Patent Trademark Office                 |
| UTeM            | - | Universiti Teknikal Malaysia Melaka                  |
| VLM             | - | Vehicle Longitudinal Model                           |
| ZEV             | - | Zero Emission Vehicle                                |