FINAL YEAR PROJECT
A STUDY OF TORQUE VECTORING AND TRACTION CONTROL FOR AN ALL-WHEEL DRIVE ELECTRIC VEHICLE

By

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Certification of Originality

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or personal.

MOHAMAD NOOR IMAN BIN MOHD NOR

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First and foremost, my deepest gratitude to Allah SWT for His blessing and Guidance in various aspects for me to accomplish my final year project entitled “A Study of Torque Vectoring And Traction Control for an All-Wheel Drive Electric Vehicle”. Not to forget, special thanks to my parent and family members for their continuous support and encouragement towards me all this while completing this project.

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Hopefully this project will provide the readers with more knowledge and understanding towards wear behaviour and wear mechanisms at rail track.

Thank you,

Mohamad Noor Iman Bin Mohd Nor

Mechanical Engineering Department

Abstract

Common vehicle always experience energy loss during cornering manoeuver. Thus, to ensure it did not happened especially at high speed, a study of torque vectoring and traction control need to be made since it can increase the traction control of tyres during cornering at high speed. The study of torque vectoring and traction control for an all-wheel drive electric vehicle was conducted by modelling an all-wheel drive EV in ADAMS/Car software. In addition, an optimal control algorithm will be developed for best performance to minimize energy losses using MATLAB/Simulink software. Furthermore, to prove the effectiveness of the all-wheel drive electric, the torque and traction control simulation of the all-wheel drive electric vehicle will be compared with uncontrolled electric vehicle model. According to the result, torque vectoring and traction control of in-wheel motor in all wheel drive EV can help to increase the performance of the electric vehicle during cornering manoeuver. In conclusion, this study of torque vectoring and traction control for an all-wheel drive electric vehicle will help researchers to improvise the design of the future electric vehicle in term of the vehicle performance during cornering manoeuvre.

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ABBREVIATIONS AND NOMENCLATURES

EV: Electric vehicle

ICE: Internal combustion engine

FYP: Final Year Project

IWM: in- wheel motor

AWD: all-wheel drive

TV: Torque vectoring

PID: proportional-integral-derivative

SLC: single lane change

CG: centre of gravity

CRC: constant radius cornering

SS: step steer

2DOF: two degree-of-freedom

CHAPTER 1: INTRODUCTION

1.1 Problem statement

Torque vectoring is a very important technology that is essential to be used in car because it related to the energy efficiency that being used in electric vehicle (EV). Torque vectoring increases the energy efficiency by transferring the torque from right wheel to left wheel, and vice versa thus it can increase the traction of the wheel to the ground during cornering [6]. Due to the increased traction to the ground, the car equipped with this technology is much safer compared to common car on road [6]. In this project, in-wheel motor (IWM) will be used in the all-wheel drive (AWD) electric vehicle thus, the wheel can be controlled independently and it provides far greater control than any other drive systems like front wheel drive and rear wheel drive. A vehicle dynamic model needs to be developed to characterize the torque vectoring drive system and an optimum control algorithm needs to be developed to provide the best performance and to minimize drivetrain losses. In conclusion, by introducing the torque vectoring and traction control in EV, the usage of energy especially electric energy can be reduced thus the efficiency of the next generation of EV will be increased and most important part is this technology gives great impact towards the sustainability of environment.

1.2 Objectives :

1. To develop a vehicle dynamic model for an electric vehicle with 4 in-wheel motors in ADAMS/Car.
2. To develop an optimal control algorithm for best performance in MATLAB/Simulink.
3. To simulate and characterize the performance of the electric vehicle and compare it to uncontrolled base EV model.

1.3 Scope of Study

The main purpose of the project is to develop a vehicle dynamic model for an EV equipped with 4 in-wheel motor by using ADAMS/Car software. After the base vehicle model generated in ADAMS/Car, an optimal control algorithm will be developed for best performance to minimize energy losses using MATLAB/Simulink software. Besides that, the performance of the electric vehicle will be simulated and characterized so that it can be compared to uncontrolled electric vehicle model using co-simulation of ADAMS/Car and MATLAB/Simulink strategy. The vehicle controller will be generated using MATLAB/Simulink and the simulation will be compare with uncontrolled electric vehicle model to prove that the effectiveness of torque vectoring and traction of the all-wheel drive electric vehicle.

CHAPTER 2: LITERATURE REVIEW AND/OR THEORY

2.1 Electric Vehicle

Electric vehicle is a vehicle that use stored electric power mainly from on-board battery to propel one or more electric motor for propulsion. There are three main type of electric vehicle such as; powered by stored electricity originally from an external power source, powered by on-board electrical generator such as hydrogen fuel cell or internal combustion engine (hybrid electric vehicle) and powered directly from external power station like trains.

Electric vehicle always relates with green technology because it emits less pollution to the environment compared to internal combustion engine (ICE). According to [1], the efficiency of electric vehicle is much higher compare to internal combustion engine vehicle where electric vehicle convert about 59-62% of the electrical energy from the grid to power at the wheels rather than 17-21% for internal combustion engine. By using electric motor, electric vehicle can perform in quiet and smooth operation while can provide stronger acceleration and required less maintenance compared to internal combustion engine.

In the other side, electric vehicle also has their own disadvantages which are limited driving range for example the Mitsubishi i-MiEV can only travel up to 160 Kilometres [2]. In addition, in case of electric vehicle (EV), recharging of the battery consume a lot of time. Even at level 3 public quick-charge port charge took approximately 30 minutes to 80% charge [3]. The battery of an electric vehicle is made of rare earth metal (Lithium) thus make the battery packs to be expensive. Furthermore, the rechargeable battery may need to be replaced from time to time and the battery itself is heavy and bulky thus need a lot of space. Apart from these disadvantages, EV still the best solution for next generation transportation because these advantages may be solved or improved from time to time as the generation continue to discover new technology.

2.2 In-wheel Motor in All-wheel Drive Electric Vehicle

In-wheel motor is basically an electric motor that directly attached into the wheel to drive and propel the wheel. According to research made by researchers in Rome, Italy, up to 79% of energy efficiency that can be produced by using in-wheel motor in all wheel drive electric vehicle and 30% for a series hybrid electric vehicle [4].

By introducing this method, the energy losses through gearboxes drive shafts and axels can be eliminated thus make the car to be more energy efficient compared to conventional hybrid electric vehicle which still used gearboxes, drive shafts and axels. Plus, by eliminate the gearboxes, drive shafts and axels, the manufacturing cost of a model of electric car can be reduced and can provides significant weight saving thus, decreasing the environmental impact of the product.

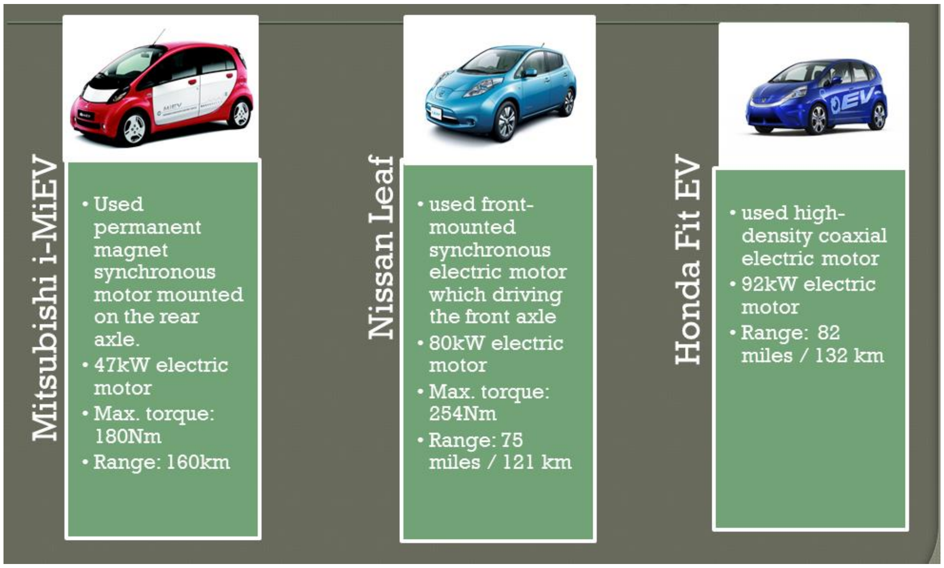
According to [7], there are 2 main types of IWM which are high speed inner-rotor motor and low speed outer-rotor type. High speed inner-rotor can reach up to 10000rpm and it has fixed speed reduction where it utilized planetary gear set for realistic wheel speed while for low speed outer-rotor motor, the rotor is designed as the rim itself [8]. Figure 1 shows an in-wheel electric motor designed by Protean Electric.

Figure 1: **Example of in-wheel motor by Protean Electric [13].**

2.3 Existing Electric Vehicle in the Market

Due to the ICE produce very less power output efficiency, the demand of study of EV increases, thus, several existing company came out with their own concept of electric vehicle. There are several EV in the market for example:

1. Mitsubishi i-MiEV - EV that used permanent magnet synchronous motor mounted on the rear axle [2].
2. Nissan Leaf – EV that used front-mounted synchronous electric motor which driving the front axle [9].
3. Honda Fit EV – EV that used high-density coaxial electric motor [10].



Mitsubishi i-MiEV

- Used permanent magnet synchronous motor mounted on the rear axle.
- 47kW electric motor
- Max. torque: 180Nm
- Range: 160km

Nissan Leaf

- used front-mounted synchronous electric motor which driving the front axle
- 80kW electric motor
- Max. torque: 254Nm
- Range: 75 miles / 121 km

Honda Fit EV

- used high-density coaxial electric motor
- 92kW electric motor
- Range: 82 miles / 132 km

Figure 2: **Specification of Mitsubishi i-Miev, Nissan Leaf and Honda Fit EV.**

2.4 Torque Vectoring and the Existing Implementation

Torque vectoring (TV) is a process that translates input from the driver (brake, steering angle, acceleration pedal signals) into torque commands to the wheels of the vehicle which means with the individual torque distribution, the performance and traction control of the vehicle can be enhanced [5]. In other words, while TV system monitors steering angle, wheel speed, yaw rate, vehicle speed and other inputs, it splits engine's torque from front to back and distributed it from side to side on a given axle by using control unit deferential [14].

According to [14], when the vehicle is turning left with under steer, TV drive automatically transmits the input torque, T_d of the driveshaft from left rear wheel to right rear wheel with vectoring torque, $T_{v,}$ by engaging clutches. Thus, it results in additional driving force T_v / R acting on right rear wheel and extra braking force -T_v / R acting on left rear wheel. Finally, the differential longitudinal driving force ΔF between the right and left wheel is produced, which generates yaw moment, M, helping the vehicle bend into the corner more sharply. When the vehicle is driving straight, TV behaves like an ordinary open differential with the input torque T_d equally distributed to the left and right rear wheels, which means $T_v = 0$.

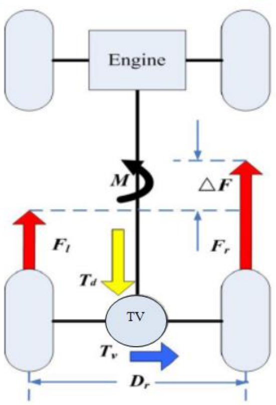


Figure 3: **Definition of torque vectoring [14].**

Some car manufacturer has already implemented this technology to improve the performance of their cars. Quattro, xDrive, and Active Yaw Control are among the most popular torque vectoring technologies that has been implemented by Audi, BMW and Mitsubishi respectively.

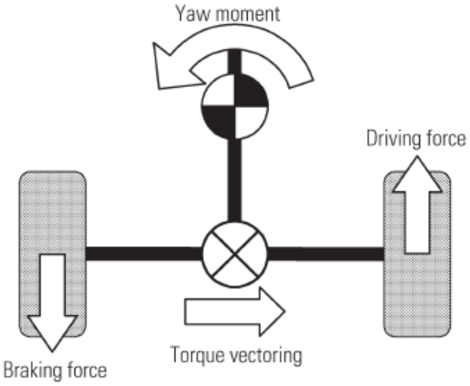


Figure 4: **Left-right torque vectoring concept in Mitsubishi's Active Yaw Control [15].**

For instant, the Active Yaw Control introduced by Mitsubishi shown in Figure 4, the left-right torque vectoring concept involves vectoring torque between the left and right wheels such that braking force is produced on the left side and driving force of the same magnitude is generated on the other. This technology has given two benefits toward the vehicle control. Firstly, it enhanced the cornering performance by means of tire load equalization between the left and right rear wheels. Secondly, it also improved the cornering performance by means of tire load equalization between the front and rear wheels as a result of direct yaw moment control [15].

According to [16] in his book, "Fundamental of Vehicle Dynamics', there are three possibilities exist in vehicle steer, which are neutral steer, understeer and oversteer. Neutral steer means when on a constant radius turn, no change of in steer angle required as the speed is varied. While understeer means the steer angle have to increase as the speed is increased in constant radius cornering (CRC) where the lateral acceleration at the center gravity (CG) causes the front wheels to slips away to a greater extent than at the rear wheels, thus making the vehicle to follow path larger than intended. For oversteer, the steer angle will have to decrease as the speed is increased in CRC event. Oversteer also causes the slip angles of the rear wheels to increase more compared to the front. The outward drift at the rear of the vehicle will turn the front wheels inward, thus decreases the radius of turn.

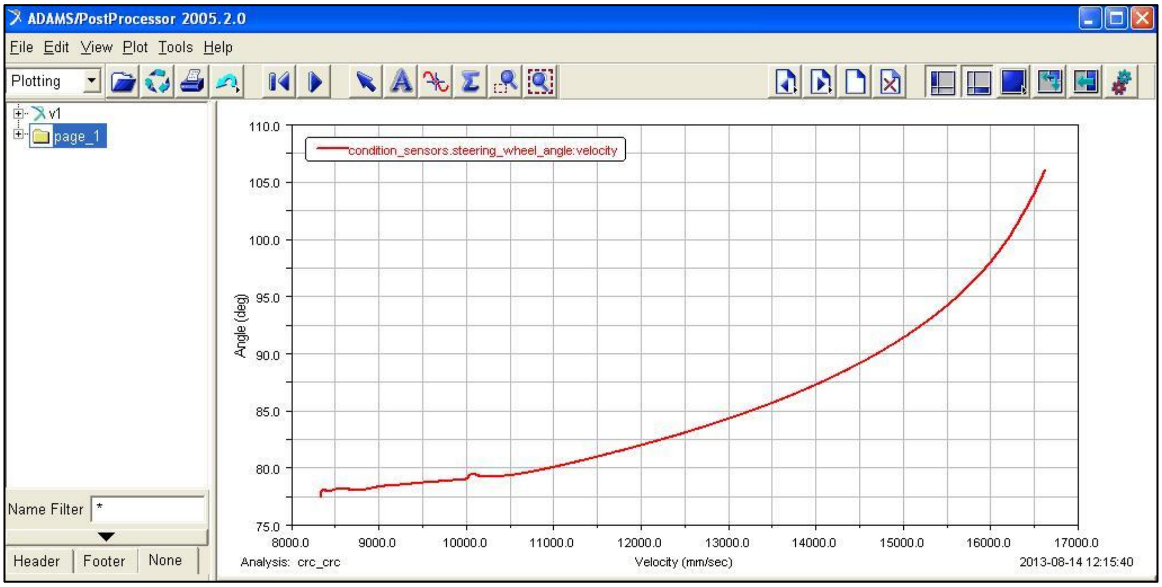


Figure 5: **EV steer characteristic.**

As shown in the figure above, the vehicle steer characteristic of the electric vehicle of this project is understeer.

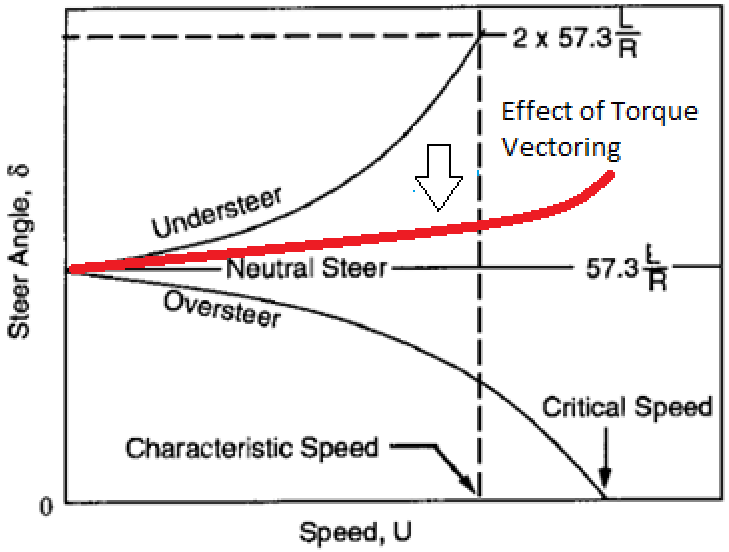


Figure 6: **The effect of Torque Vectoring towards understeer characteristic of vehicle.**

By applying torque vectoring, the steer angle needed for vehicle can be reduced as the vehicle increasing its speed thus prolong the vehicle to stay near the neutral steer characteristic as the speed is increased.

As stated before, in this project four in-wheel electric motors will be used to propel the Electric Vehicle. Thus the EV can perform torque vectoring concept can be applied at both front and rear wheels. For example, to generate yaw moment to the left (anti-clockwise), torque output at the left wheels of the vehicle must be higher compare to the right wheels.

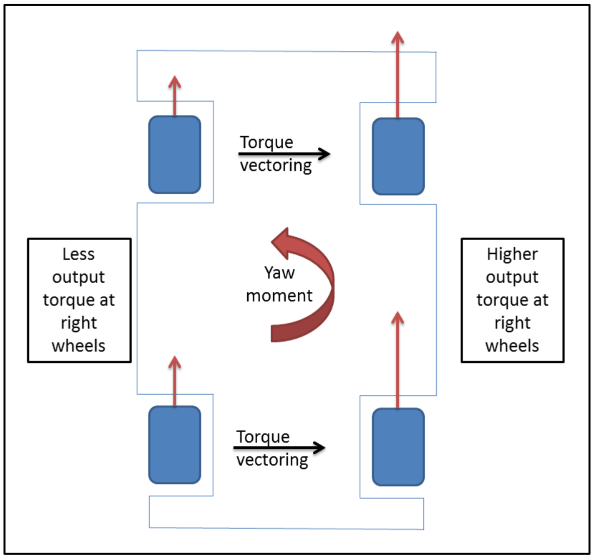


Figure 7: **Torque vectoring of 4 In-wheels All wheel Drive Electric Vehicle (anti-clockwise turning)**

Figure 7 above shows the torque vectoring concept that can be applied in this project using 4 in-wheel motors.

Torque vectoring is very much related to control system which will translate the input signal from vehicle user demand into vehicle control output. Thus, the control system that will be used in this project will be explained in the next sub chapter.

2.5 Control and Control System

Control is the process of causing a system variable to perform some desired value. While control system in other hand, is an interconnection of components forming a system configuration that will provide a desired system respond [10].There are more than 95% of the control loops based on proportional-Integral-Derivative (PID) controllers are yet still be used in the industrial processes [11]. This is due to the simplicity in principle.

There are 2 main type of element or pathway within control system which are feed-forward and feed-backward. A feed-forward controller uses information from measurable disturbances to improve the control performance; theoretically it is possible to eliminate the disturbances, but in reality, the disturbances will not perfectly eliminate. On the other hand, feed-backward control system calculation is based on measurements of the controlled output; where feed-backward control systems normally give better attenuation of low-frequency process disturbances and that they give better robustness (less sensitivity to parameter changes) when compared to systems without feedback [11]. Among the most widely used feed-backward control mechanism in industrial control systems is a PID controller.

Another popular logic controller is fuzzy logic. It can control complex continuously-varying systems. It can approximate any continuous functions on a compact set to a given accuracy so it can be considered as a universal approximator. The advantages of using fuzzy model are the model structure is easy to understand and sometimes interpretable and various types of knowledge can be integrated in the model, including statistical objects and empirical knowledge [12]. It also found that fuzzy controller was simpler and easier to develop compare to PID controllers [8].

Fuzzy controller type will used in this final year project to develop an optimal control algorithm for best performance and to minimize energy losses in MATLAB/Simulink. The fuzzy controller model and block diagram of the Fuzzy controller system used will be further discussed in the result and discussion part.

2.6 Reference Model

Bicycle model is the simplest method in determining lateral vehicle response which has two degree of freedom. The model combined the right and left tires at the front and rear of the car into equivalent tire which located at the centre line. The slip angles on the inside and outside wheels are approximately the same. The degree-of-freedom for constant forward speed are yaw rate, r, and lateral velocity u_y (or sideslip angle, α). In addition, this model neglects body roll and load transfer. The longitudinal speed of travel is assumed to be constant. The steer and slip angles are assumed to be thus, the tire forces may be assumed to vary linearly with slip angles [17].

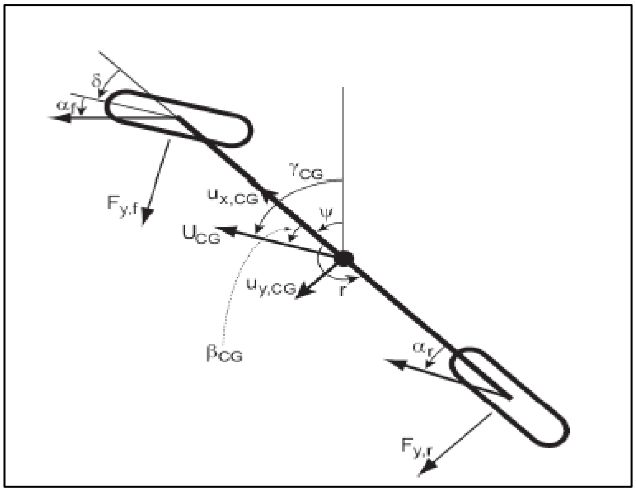


Figure 8: Bicycle model [17]

In Figure 8, u_x and u_y are the longitudinal and lateral components of the vehicle velocity, δ is the steering angle, α_f and α_r are the tire slip angles and F_{yf} and F_{yr} are the lateral tire forces.

The mathematical model to be use in this project is using the same approach as researcher [8]. The state equation for the project electric vehicle bicycle model is written as:

$$\dot{x} = Ax + B\delta_f \tag{2.1}$$

$$x = [\beta, \gamma]^t \tag{2.2}$$

$$A = \begin{bmatrix} -2\frac{C_f + C_r}{mV} & -1 - 2\frac{l_f C_f - l_r C_r}{mV^2} \\ -2\frac{l_f C_f + l_r C_r}{IV} & -2\frac{l_f^2 C_f + l_r^2 C_r}{IV} \end{bmatrix} \tag{2.3}$$

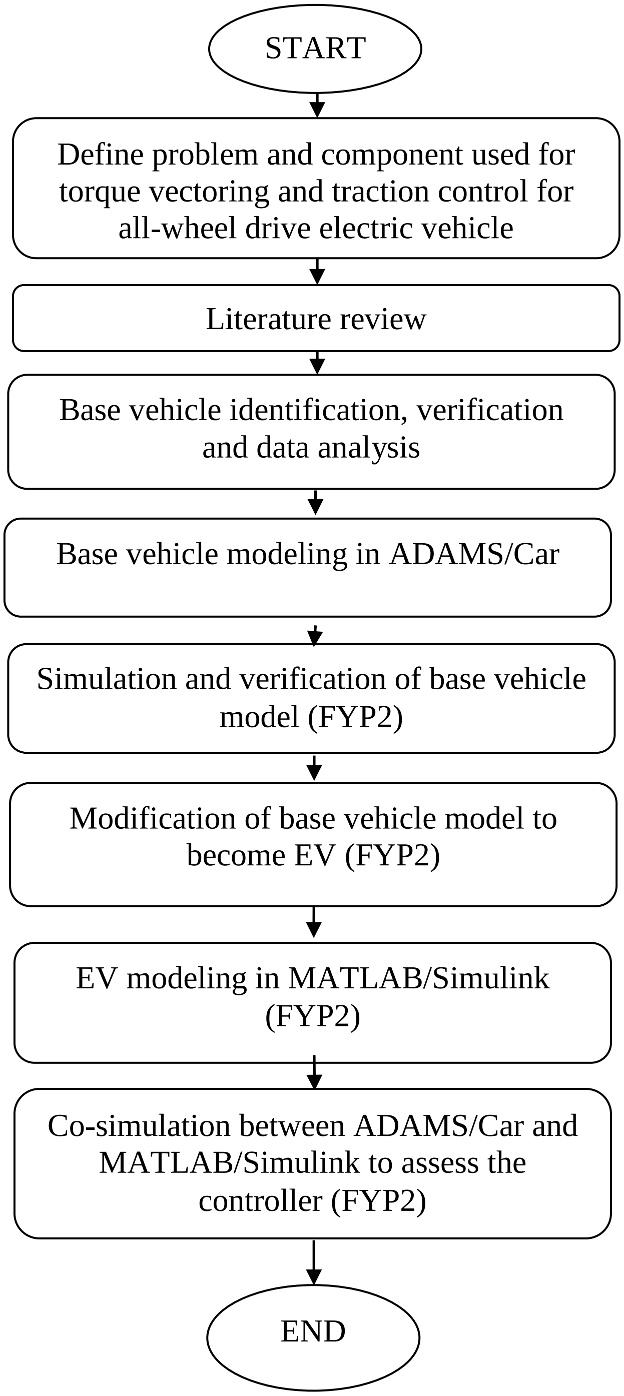
$$B = \begin{bmatrix} \frac{2C_f}{mV} & \frac{2l_f C_f}{I} \end{bmatrix} \tag{2.4}$$

Where β is side slip angle, δ_f is front steer angle, γ is yaw rate, m is mass, l_f is length between center of the car and front tire, l_r length between center of the car and rear tire, I is the vehicle inertia, C_f is front cornering stiffness, and C_r is rear cornering stiffness.

When the vehicle is experiencing several manoeuvers such as changing lane, making j-turn or steer change there is possibility that the vehicle to experience oversteer or understeer. During this moment, the vehicle will give slight different in term of lateral acceleration, and yaw rate as compare to the reference model. Thus, the bicycle model is introduced in this project as reference model which is generated in MATLAB/Simulink model for the EV to assist in controlling the torque vectoring and traction control of the IWM during co-simulation between MATLAB/Simulink model and ADAMS/Car model.

CHAPTER 3: METHODOLOGY/PROJECT WORK

3.1 Research Methodology



3.1.1 Explanation of Methodology

3.1.1.1 Define problem and component used for torque vectoring and traction control for all-wheel drive electric vehicle:

Define problems statement and all the components used for AWD EV such as in-wheel motors, controller, type of vehicle parts and battery used.

3.1.1.2 Literature review:

Find articles, paper works and previous study related to torque vectoring and traction control for an all-wheel drive electric vehicle

3.1.1.3 Base vehicle identification, verification and data analysis:

Identify the base model for the electric vehicle. Verify the type of parts that need to be used such as double wishbone suspension.

3.1.1.4 Base vehicle modeling in ADAMS/Car:

The base model of the electric car will be generated using ADAMS/Car; all the measurements are according to the chassis specification.

3.1.1.5 Simulation and verification of base vehicle model (FYP2):

Generate similar vehicle model that using internal combustion engine (ICE) and compare the Single Lane Change (SLC) simulation in ADAMS/Car with the base EV model.

3.1.1.6 Modification of base vehicle model to become EV (FYP2):

Add torque at each wheel of the base EV model using ADAMS/View interface so that it can simulate the motor rotation torque and modify the input so that it can be co-simulate with MATLAB/Simulink.

3.1.1.7 EV modeling in MATLAB/Simulink (FYP2):

Define motor sizing and generate electric motor controllers, driver controller, and reference model controller using MATLAB/Simulink.

3.1.1.8 Co-simulation between ADAMS/Car and MATLAB/Simulink to assess the controller (FYP2):

Fuzzy controller of the motor controllers will be tune so that the best performance of torque vectoring and traction control is achieved in

MATLAB/Simulink. Then, co-simulate the simulation done in MATLAB/Simulink and ADAMS/Car to assess the controller.

3.2 Project Activities

Several activities related to the project were done in order to complete this project. The activities are as mention below:

3.2.1 Extract chassis measurement from CATIA file

3.2.2 ADAMS/Car software:

- Generate subassemblies using templates
- Generate ICE vehicle and electric vehicle full assemblies.
- Define appropriate coordinate for wheel centre, suspension parts, and centre of gravity of the vehicle models based on chassis measurement specification
- Verify and simulate vehicle models using “single lance change” (SLC) simulation command
- Verify simulation result data of ICE vehicle and electric vehicle.
- Apply torque on each wheel by using ADAMS/View interface.
- Define Torque input so that it can co-simulate with MATLAB/Simulink
- Save SLC simulation data into “m-file” which can be read by MATLAB/Simulink.

3.2.3 Define Motor sizing, battery sizing and vehicle mass using appropriate equation.

3.2.4 MATLAB/Simulink software:

- Export ADAMS/Car SLC simulation data so that it can be used in MATLAB/Simulink.
- Construct and link block model of electric motor controller, driver controller, and reference model controller.
- Generate and tune fuzzy controller for each motor to gain optimized vehicle traction control.
- Co-simulate MATLAB/Simulink with ADAMS/Car.

3.3 Gantt chart

Table 1: Gantt chart of FYP 1 and FYP 2

Activity (FYP1)	**Week of January 2013 Semester**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Title & Supervisor Allocation	/	/					S							
Overview basic of the project			/	/			E							
Study on literature, technical paper & extended proposal				/	/	/	M							
Extended proposal submission						/								
Proposal defense/Progress preparation and evaluation							B R	/	/					
ADAMS/Car vehicle modeling							E A			/	/	/		
Interim Report preparation and submission							K				/	/	/	/
Activity (FYP2)	**Week of May 2013 Semester**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Simulation and verification with conventional ICE vehicle	/	/	/	/										
Modification of base model to become EV				/	/	/	/	/						
EV modelling in MATLAB/Simulink							/	/	/	/				
Co-simulation between ADAMS/Car and MATLAB/Simulink to assess the controller									/	/	/	/	/	
Final Report									/	/	/	/	/	/

3.3 Proposed Project Milestone

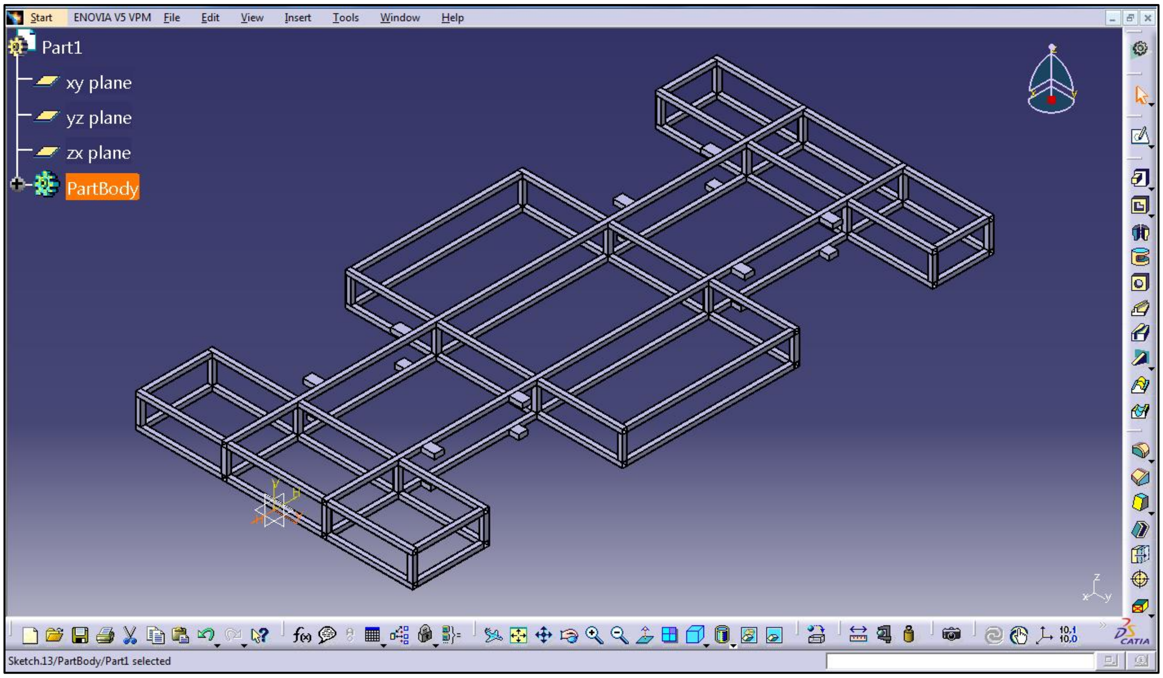
Table 2: Project milestone for FYP 1 and FYP 2

No	MILESTONES (FYP 1)	Jan 2013 Semester Week
1	Acquisition of primary information	W6
2	Submission of Extended Proposal	W6
3	Completion of base model modeling task	W12
4	Completion of Interim Report	W14
	MILESTONES (FYP 2)	**May 2013 Semester Week**
5	Completion of all ADAMS/Car modeling task	W8
6	Completion of control system modeling	W10
7	Completion of co-simulation between base model and control system model	W12
8	Submission of Final Year Project Report	W14

CHAPTER 4: RESULT AND DISCUSSION

4.1 Base vehicle identification, verification and data analysis

Base model identification, verification and data analysis was done before generating the base model using ADAMS/Car. Thus, the subsystems of vehicle used by the EV were identified and the measurements of each part were corrected to get an accurate result. The subsystems needed are chassis (vehicle body), suspensions, steering, wheels and brakes. In this project, flat chassis need to be used to simulate the vehicle body. Prior to vehicle modeling, the measurements of chassis were done and modeled in CATIA to ease the coordinate point's identification and mass estimation of the chassis.



Sketch.13/PartBody/Part1 selected

Figure 9: Overview of flat chassis model modeling using CATIA

Figure 9 shows the overview of CATIA model of the flat chassis that is used in the project. This CATIA model was made based on the real measurement of the flat chassis that has been built by UTP students in other previous research.

4.2 Base vehicle modeling in ADAMS/Car

Prior to vehicle modeling in ADAMS/Car, there are several subsystems need were identified such as chassis, suspensions, steering, handling tires, and braking system as shown below:

4.2.1 Chassis

For vehicle body subsystem, template of "_rigid_chassis_lt" (light version of rigid chassis) in the ADAMS/Car is used to simulate the flat chassis that being used for the EV.

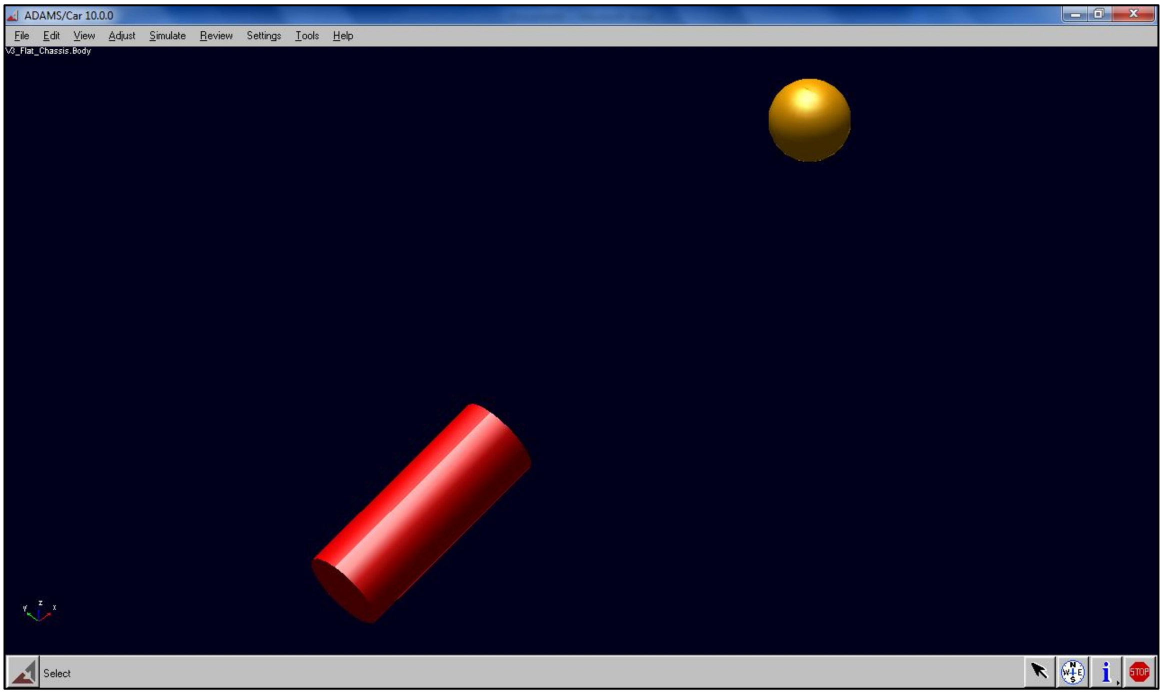


Figure 10: light version of rigid chassis used in ADAMS/Car

Figure 10 shows the rigid chassis that used to model the flat chassis in ADAMS/Car. The red cylinder indicates the steering column housing and the yellow sphere indicate the overall chassis body.

4.2.2 Suspensions

For suspension subsystems, templates of "_double_wishbone" were used for both front and rear suspension.

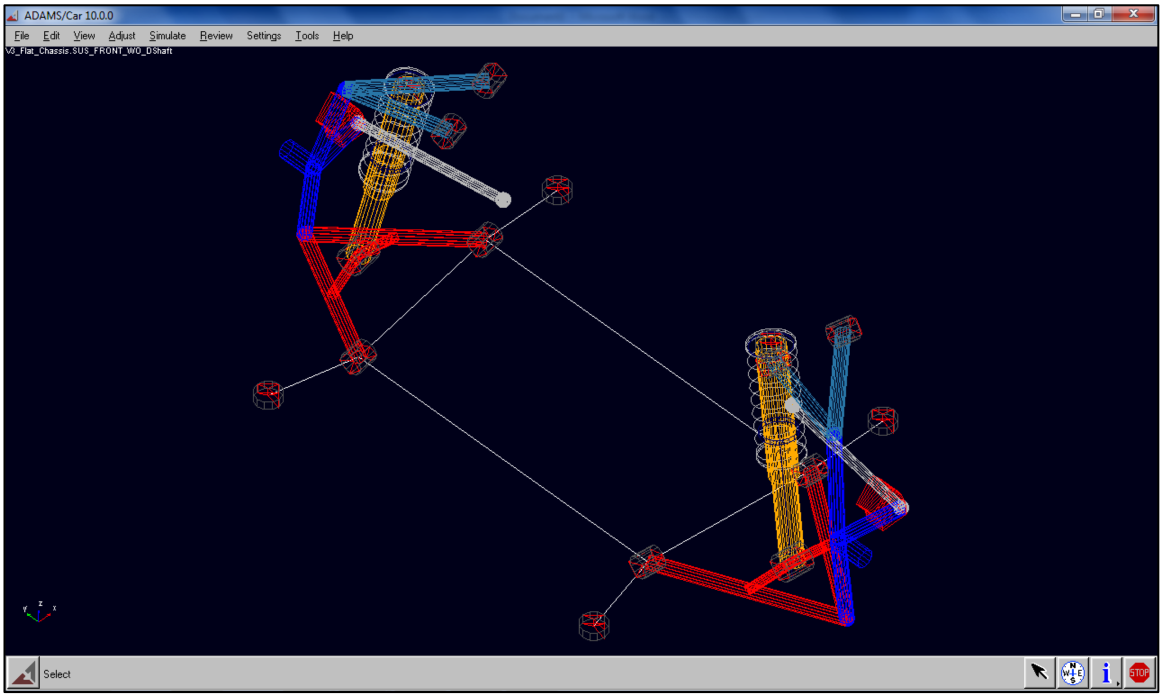


Figure 11: Double wishbone suspension used by front and rear suspension subsystem

Figure 11 shows that the type suspension used at both front and rear wheels. The drive shafts of both suspensions were deleted because; in this project the vehicle will be propelled by four in-wheel motor instead of an ICE.

4.2.3 Steering

For steering, pinion and rack type of steering will be used so, the template that used was “_rack_pinion_steering”.

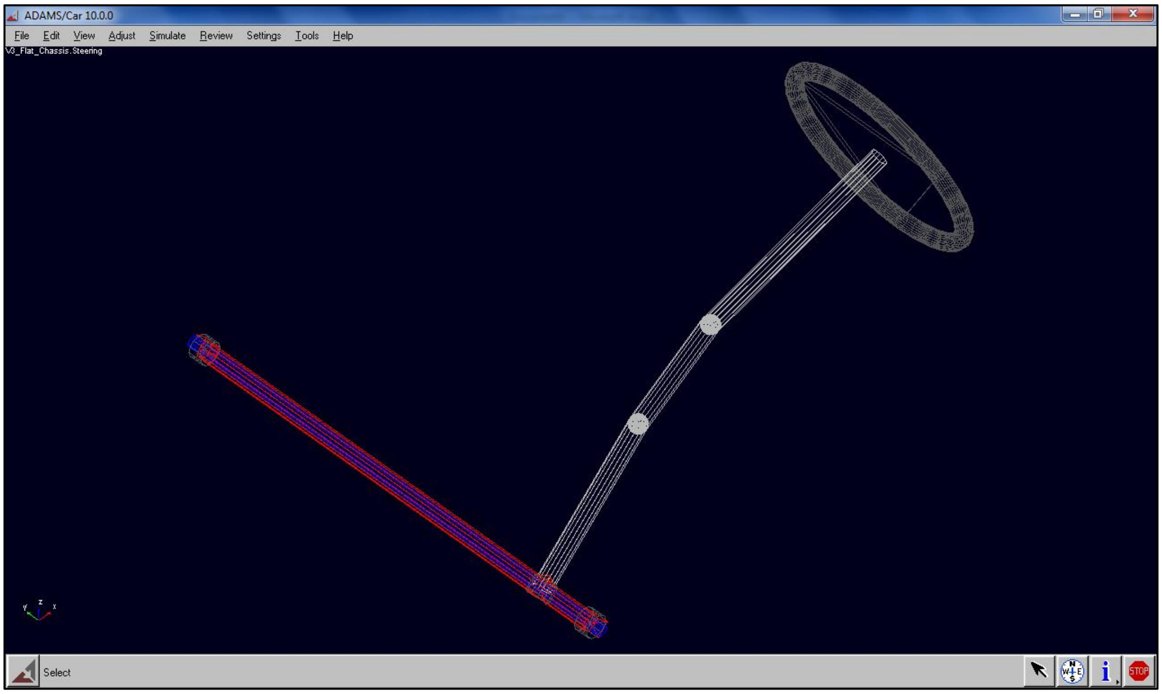


Figure 12: Pinion and rack type of steering

Figure 12 shows the pinion and rack type of steering subsystem used in this project. This steering minor role is “front” because the steering will navigate the front wheels for left and right maneuver.

4.2.4 Handling tires

In other hand, normal type of handling tires and wheels were used for both wheels subsystems, thus, template used for the wheels is "_handling_tire"

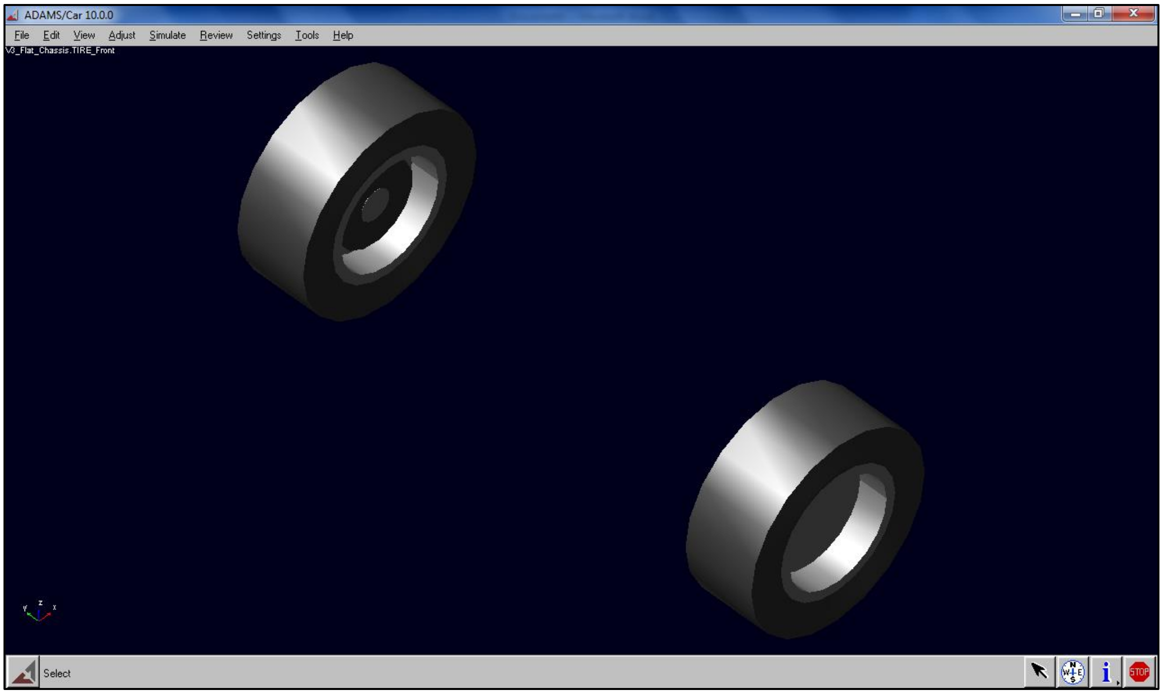


Figure 13: Wheel system used in the project

Figure 13 shows the pair of wheels used by front and rear wheel subsystem. In this project motors will be used to propel the vehicle, thus, torque force will be applied at each wheel to simulate the motor torque using ADAMS/View after the EV model is verified.

4.2.5 Braking system

Brake subsystem used for this project is brake disk type. The template used is "_brake_system_4Wdisk".

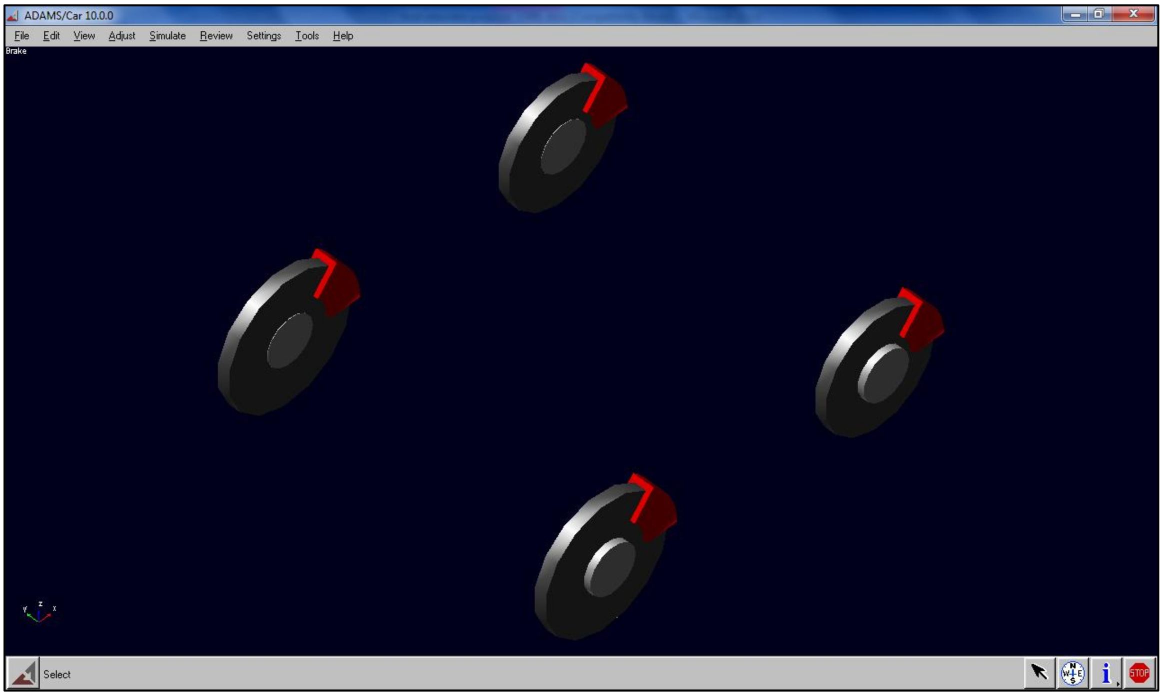
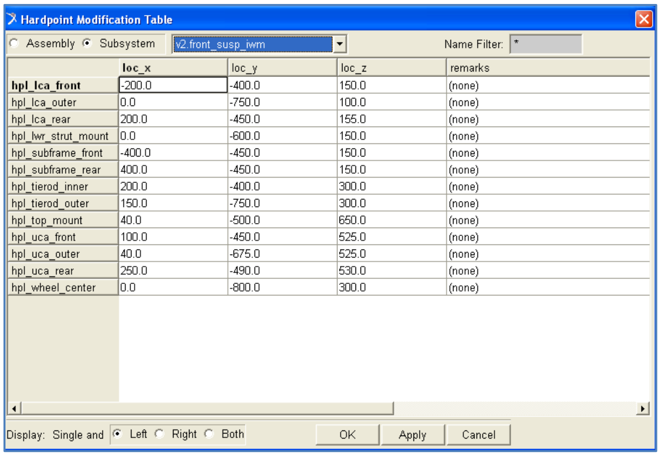


Figure 14: Disk type of brake system.

Figure 14 shows that the disk type of brake subsystem used in the project.

Before all the templates of the subsystem save as subsystem file (.sub), the coordinate of the front and rear suspensions need were defined and modified according to the right coordinate generated in CATIA to get an accurate result of ADAMS/Car modeling.

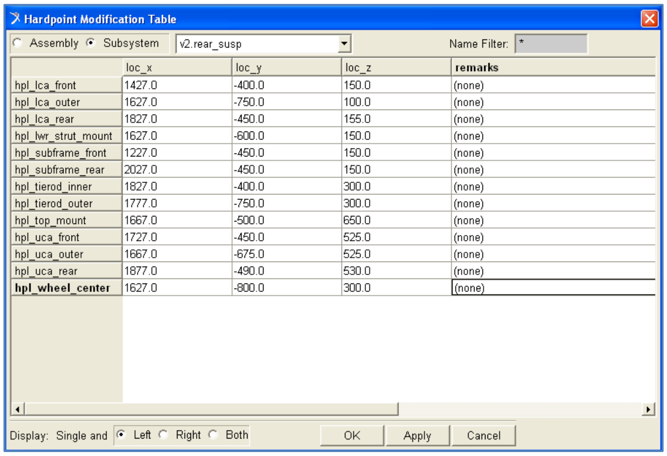


○ Assembly ● Subsystem v2.front_susp_iwm Name Filter: *

	loc_x	loc_y	loc_z	remarks
hpl_lca_front	-200.0	-400.0	150.0	(none)
hpl_lca_outer	0.0	-750.0	100.0	(none)
hpl_lca_rear	200.0	-450.0	155.0	(none)
hpl_lwr_strut_mount	0.0	-600.0	150.0	(none)
hpl_subframe_front	-400.0	-450.0	150.0	(none)
hpl_subframe_rear	400.0	-450.0	150.0	(none)
hpl_tierod_inner	200.0	-400.0	300.0	(none)
hpl_tierod_outer	150.0	-750.0	300.0	(none)
hpl_top_mount	40.0	-500.0	650.0	(none)
hpl_uca_front	100.0	-450.0	525.0	(none)
hpl_uca_outer	40.0	-675.0	525.0	(none)
hpl_uca_rear	250.0	-490.0	530.0	(none)
hpl_wheel_center	0.0	-800.0	300.0	(none)

Display: Single and ● Left ○ Right ○ Both

Figure 15: Hard point coordinates of front suspension



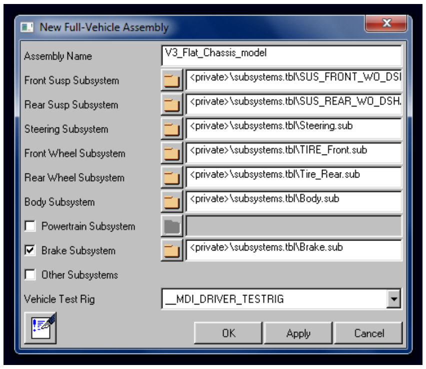
○ Assembly ● Subsystem v2.rear_susp Name Filter: *

	loc_x	loc_y	loc_z	remarks
hpl_lca_front	1427.0	-400.0	150.0	(none)
hpl_lca_outer	1627.0	-750.0	100.0	(none)
hpl_lca_rear	1827.0	-450.0	155.0	(none)
hpl_lwr_strut_mount	1627.0	-600.0	150.0	(none)
hpl_subframe_front	1227.0	-450.0	150.0	(none)
hpl_subframe_rear	2027.0	-450.0	150.0	(none)
hpl_tierod_inner	1827.0	-400.0	300.0	(none)
hpl_tierod_outer	1777.0	-750.0	300.0	(none)
hpl_top_mount	1667.0	-500.0	650.0	(none)
hpl_uca_front	1727.0	-450.0	525.0	(none)
hpl_uca_outer	1667.0	-675.0	525.0	(none)
hpl_uca_rear	1877.0	-490.0	530.0	(none)
hpl_wheel_center	1627.0	-800.0	300.0	(none)

Display: Single and ● Left ○ Right ○ Both

Figure 16: Hard point coordinates of rear suspension

Lastly, each subsystems needed were attached together to model the full assembly design.



Assembly Name	V3_Flat_Chassis_model
Front Susp Subsystem	<private>\subsystems.tbl\SUS_FRONT_WO_DSI
Rear Susp Subsystem	<private>\subsystems.tbl\SUS_REAR_WO_DSH.
Steering Subsystem	<private>\subsystems.tbl\Steering.sub
Front Wheel Subsystem	<private>\subsystems.tbl\TIRE_Front.sub
Rear Wheel Subsystem	<private>\subsystems.tbl\Tire_Rear.sub
Body Subsystem	<private>\subsystems.tbl\Body.sub
☐ Powertrain Subsystem	
☑ Brake Subsystem	<private>\subsystems.tbl\Brake.sub
☐ Other Subsystems	
Vehicle Test Rig	__MDI_DRIVER_TESTRIG

Figure 17: New full vehicle assembly command in ADAMS/Car

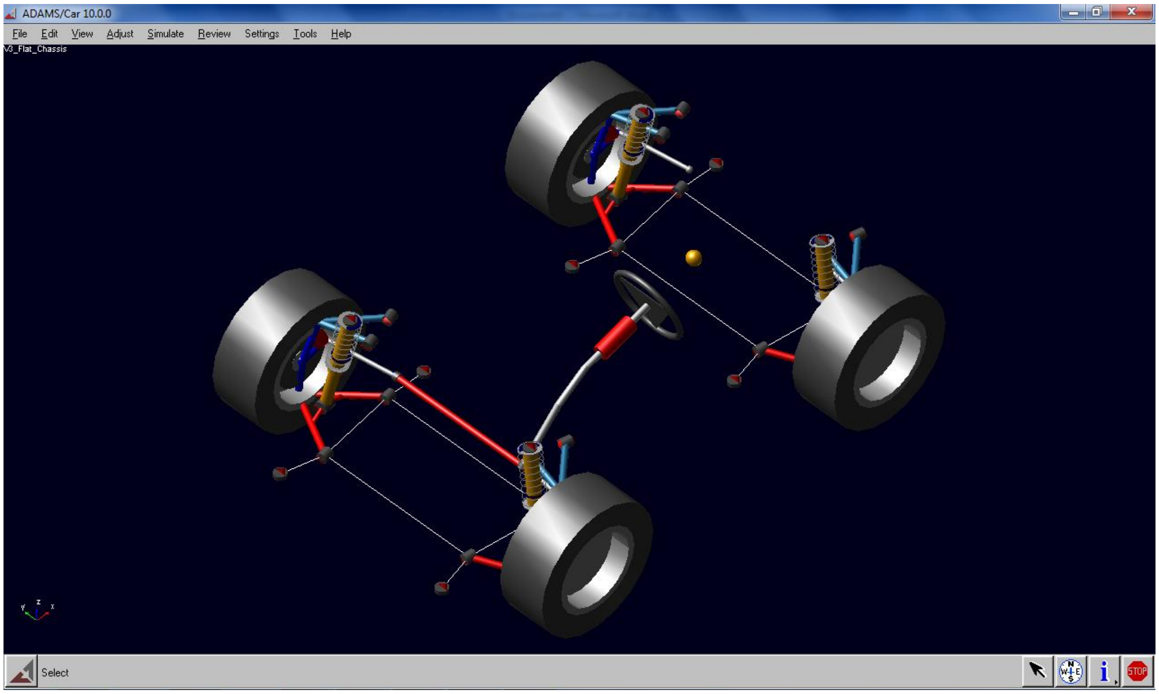


Figure 18: vehicle dynamic model for an electric vehicle with 4 in-wheel motors in ADAMS/Car

Figure 18 above shows the full assembly design vehicle model of the electric vehicle that used 4 in-wheel motors in this project. Next step is to simulate and characterize the performance of the electric vehicle and compare it to base EV model.

4.3 Simulation and Verification of Base Vehicle Model

Prior to modification of base vehicle model to become EV, some validation is required in order to validate the ADAMS/Car EV model with stock vehicle model. For comparison purposes, single lane change (SLC) simulation was selected. Single Lane Change simulation is basically to simulate vehicle that change lane at certain speed as shown in figure 19 below.

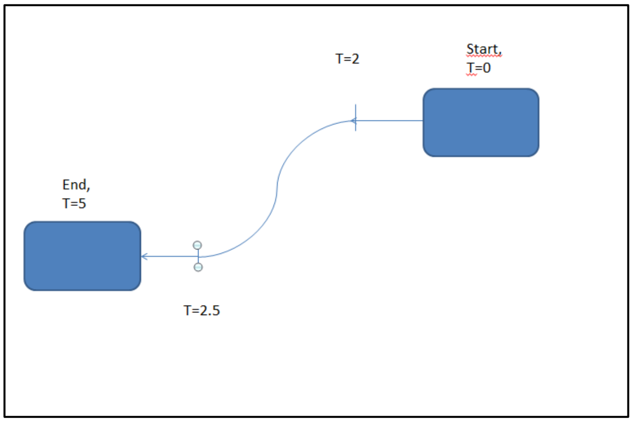
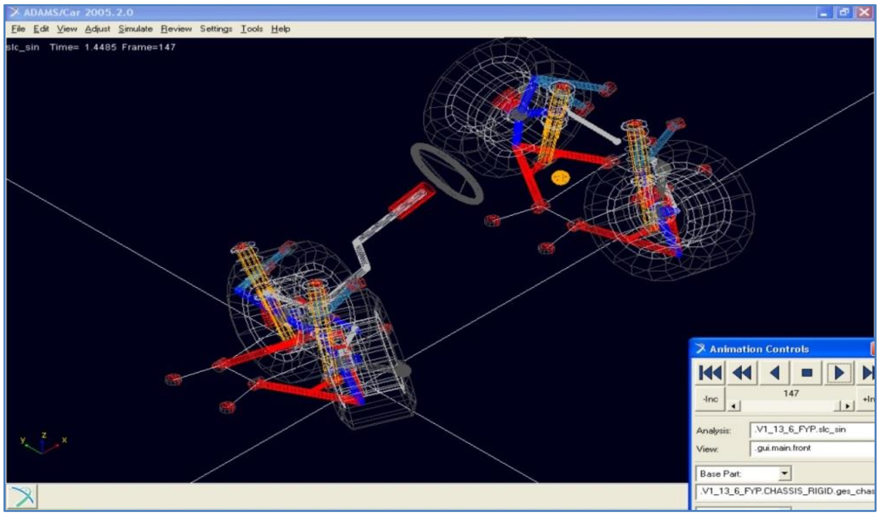


Figure 19: Overview of single lane change

This simulation also held to verify if the structures of the model are strong enough to handle all forces exist during the simulation. If the structures of the vehicle failed, modification of subsystems hard point coordinates must be done.



slc_sin Time= 1.4485 Frame=147

Analysis: .V1_13_6_FYP.slc_sin
View: .gui.main.front
Base Part:
.V1_13_6_FYP.CHASSIS_RIGID.ges_chas

Figure 20: structures of the model vehicle failed

Figure 20 shows vehicle structure failed due to suspension could not withstand the applied forces experience by the vehicle during SLC simulation.

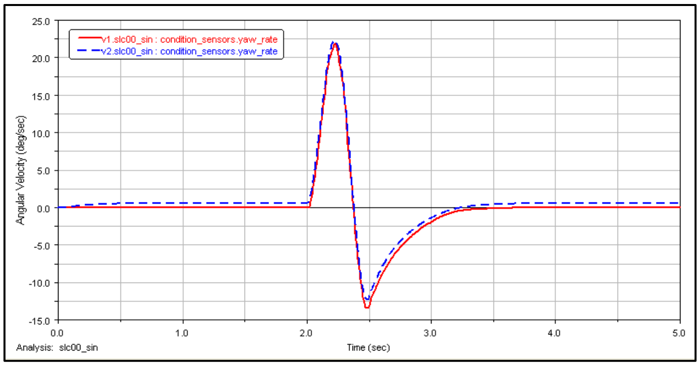


Figure 21: stock car vs. EV car SLC performance verification

As shown in Figure 21 above, the result of the yaw rate of both models were compared and if the SLC percentage error result was minor, thus it is concluded that the EV is verified and modification of base model can be done to become all-wheel drive EV.

4.4 Modification of Base Model to Become Electric Vehicle

To modify the base model to become EV, a torque must be applied at the centre of each of the subsystems tyres. To apply the torque, the interface of the ADAMS/Car was switch into ADAMS/View. Then, torque is inserted at the centre of each tyre and defined the input accordingly so that it can communicate with MATLAB/Simulink during the ADAMS/Car and MATLAB/Simulink Co-simulation stage.

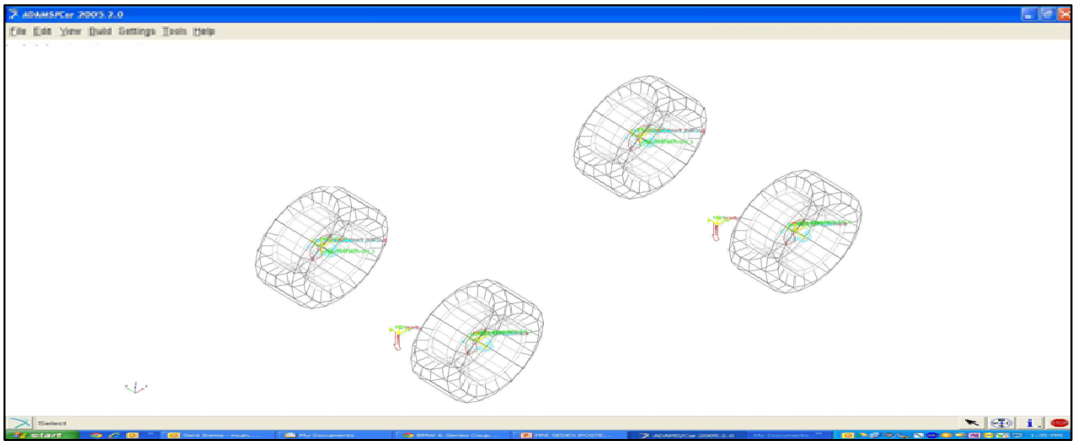
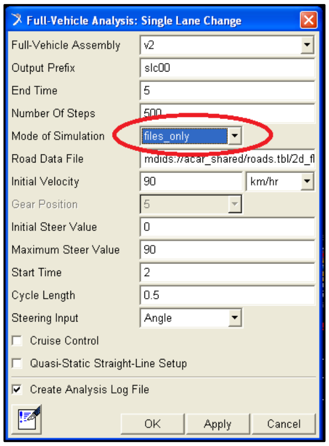


Figure 22: torque forces added at each wheel.

4.5 Electric Vehicle Controller modelling in MATLAB/Simulink

Prior to controller modelling in MATLAB/Simulink, the ADAMS/Car model simulation was save in m-file so that the EV model could be generated in MATLAB/Simulink and to ensure it can co-simulate with MATLAB/Simulink. SLC simulation that was saved into m-file and ADAMS/Car model that generated by MATLAB/Simulink from the m-file are as shown in Figure 23 and Figure 24 respectively.



Full-Vehicle Assembly: v2
Output Prefix: slc00
End Time: 5
Number Of Steps: 500
Mode of Simulation: files_only
Road Data File: mdids://acar_shared/roads.tbl/2d_fl
Initial Velocity: 90 km/hr
Gear Position: 5
Initial Steer Value: 0
Maximum Steer Value: 90
Start Time: 2
Cycle Length: 0.5
Steering Input: Angle
☐ Cruise Control
☐ Quasi-Static Straight-Line Setup
☑ Create Analysis Log File

Figure 23: Saving ADAMS/Car SLC simulation model into m-file.

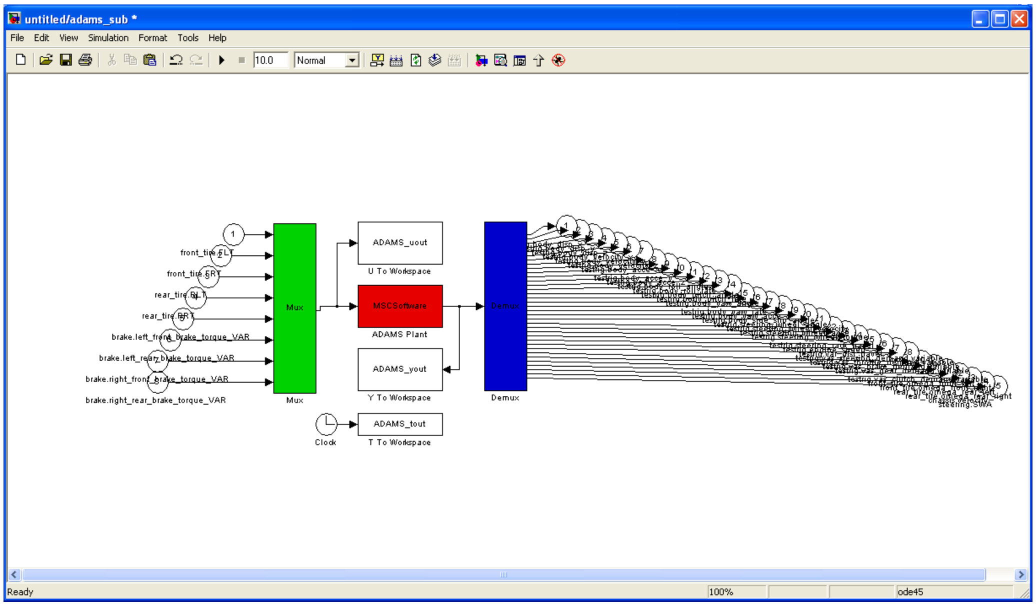


Figure 24: ADAMS/Car model in MATLAB/Simulink.

Some calculations also need to be done in order to determine the component sizes. The component includes in-wheel motor, battery and the electrical vehicle mass. The equation that governing each of the components is as shown below:

4.5.1 In-Wheel Motor Sizing

The motor sizing is based on normal driving condition which is at 90km/h (25m/s) and on flat asphalt surface.

Power required:

$$P = V\,[F_w + F_g + F_r + M\tfrac{dv}{dt}] \tag{4.1}$$

$$P = 25\,[0.5\rho C_D A V^2 + f_r mg.\cos\theta]$$

$$P = 25\,[0.5(1.23)(0.3)(1.75)(25^2) + 0.013(400)(9.81)$$

$$P = 6320\,W = 6.32\,kW$$

Power required per motor:

$$P_m = \frac{6.320}{4} = 1.580\,kW$$

Thus, Motor with 2kW is selected.

4.5.2 Battery Sizing

Condition: full charged, travelled distance of 80km at 90km/h. State of charge = 80%, motor efficiency = 90%, lead acid (35Wh/kg)

Energy Required:

$$E = \tfrac{P\times T}{\pi} \tag{4.2}$$

$$T = \frac{D}{V} = \frac{80km}{90km/h} = 0.89h$$

$$\pi = \pi_m\, x\, SOC = 0.8\, x\, 0.9 = 0.72 \tag{4.3}$$

$$E = \frac{6.32kW \times 0.89h}{0.72}$$

$$E = 7.81kWh$$

Thus, the battery capacity for the EV: 7.81 kWh

Voltage of battery, at current = 300A

$$P = IV \tag{4.4}$$

$$V = \frac{6320}{300}$$

$$V = 22V$$

Battery mass,

$$M_b = \frac{7810Wh}{35wh/kg}$$

$$M_b = 220kg$$

4.5.3 Additional Electric Vehicle Model Mass

Mass:

Chassis (steel) = 40kg

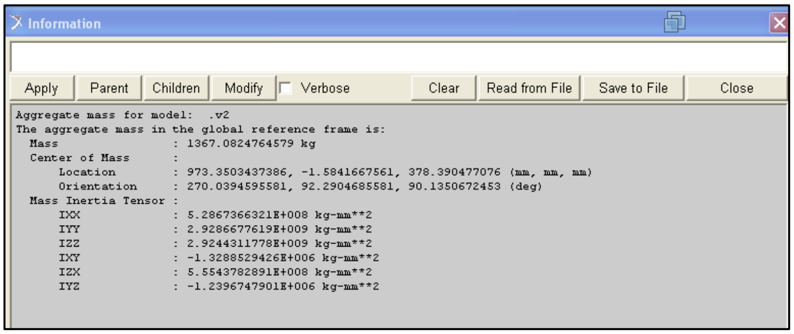
Electric motor = 14kg x 4 = 56kg

Controller = 2kg x 4 = 8kg

Battery = 220kg

Additional lump mass = 382 kg

Additional lump mass was added in the ADAMS/Car vehicle model located approximately in between rear tires. Figure below shows the total mass of the EV.



```
Aggregate mass for model:  .v2
The aggregate mass in the global reference frame is:
  Mass                : 1367.0824764579 kg
  Center of Mass      :
      Location        : 973.3503437386, -1.5841667561, 378.390477076 (mm, mm, mm)
      Orientation     : 270.0394595581, 92.2904685581, 90.1350672453 (deg)
  Mass Inertia Tensor :
      IXX             : 5.2867366321E+008 kg-mm**2
      IYY             : 2.9286677619E+009 kg-mm**2
      IZZ             : 2.9244311778E+009 kg-mm**2
      IXY             : -1.3288529426E+006 kg-mm**2
      IZX             : 5.5543782891E+008 kg-mm**2
      IYZ             : -1.2396747901E+006 kg-mm**2
```

Figure 25: Total mass of the car generated by ADAMS/Car.

The vehicle mass is needed by MATLAB/Simulink which used by reference model to produce reference yaw rate value for every simulations needed.

4.5.4 Electric Vehicle Controller Model

EV Controller model was constructed using MATLAB/Simulink. The overall EV model is as shown in figure below:

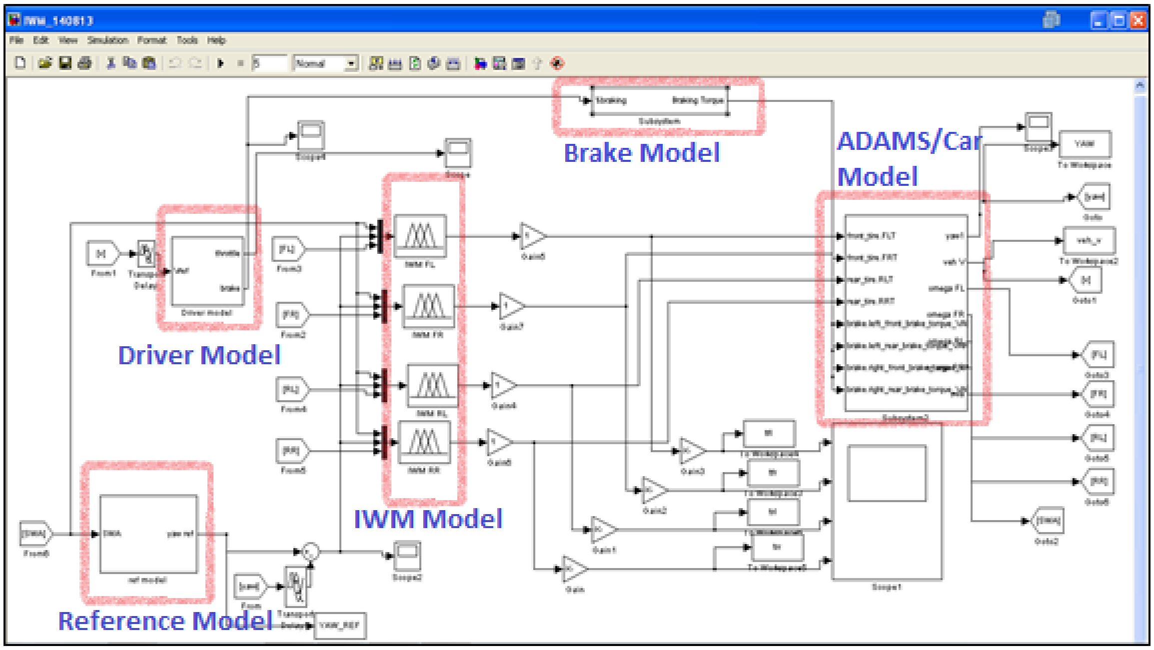


Figure 26: Overall EV model in MATLAB/Simulink.

Inside the model shown in Figure 26, there were several sub-model constructed such as reference model, in-wheel motor models, driver model and ADAMS/Car model. The main purpose of model the EV in MATLAB/Simulink is to control the amount output in each in-wheel motor modelled in ADAMS/Car. The torque output is the function of torque constant and current given out by the battery which is retrieved from the IWM torque map (refer appendix 1). The description of the sub-model is as shown below:

4.5.4.1 Reference Model

Reference model is an abstract framework consisting of an interlinked set of clearly defined concepts produced in order to encourage clear communication between the input and output function of the controller that generated in MATLAB/Simulink. The reference model is created based on the 2 degree of freedom bicycle model stated in (Chapter 2.6). For this project, Steering wheel angle of the vehicle will be the input of the reference model and the model will generate reference yaw rate as the output. The reference yaw rate next will be compare with the actual yaw rate of the EV and the yaw rate error of the vehicle will be calculated to give input to IWM model.

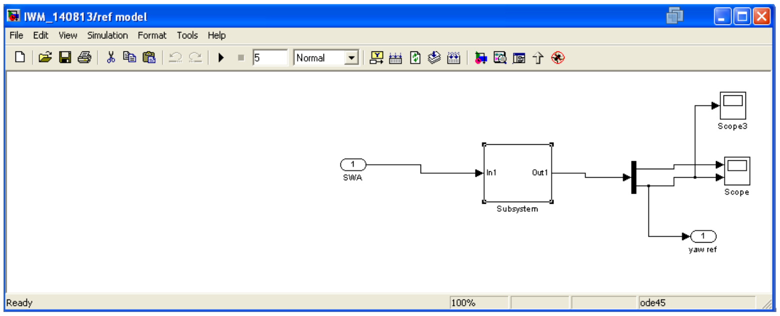
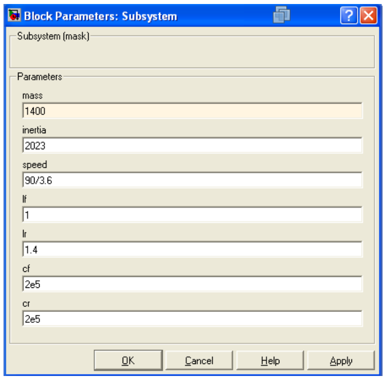


Figure 27: reference model in MATLAB/Simulink



mass
1400
inertia
2023
speed
90/3.6
lf
1
lr
1.4
cf
2e5
cr
2e5

Figure 28: Reference model input

4.5.4.2 In-Wheel Electric Motor Model

Four Fuzzy IWM controller models needed to simulate the behaviour of the motors during co-simulation process which are for front left, front right, rear right and rear left. When several manoeuver that making the steer angle to change, the vehicle may gone through either understeer of oversteer steer characteristic which will give slight difference in term of yaw rate. Thus, the yaw rate error was used as one of the input of the fuzzy controller. Other input data for the controllers are steering wheel angle and vehicle speed. The fuzzy logic controller will control the amount of torque (output) produced by the IWM so that it can improve the vehicle cornering performance based on the fuzzy logic controller strategy. The strategy to control the IWM fuzzy logic controller is summarized as table shown below:

Table 3: IWM fuzzy logic controller strategy

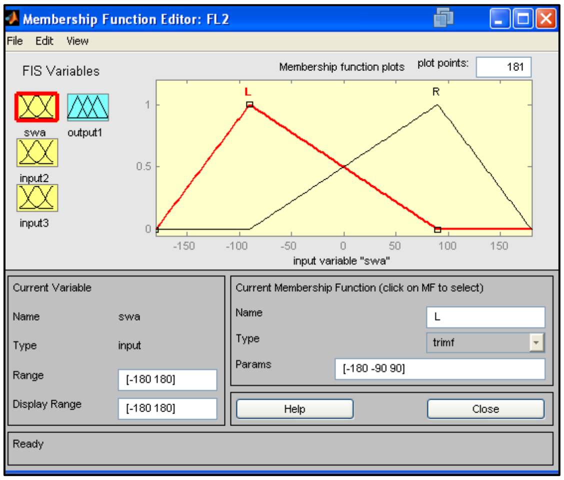
Input	**Input**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**
Steering wheel angle	**Yaw rate error**	**Vehicle velocity**	**Front Left Torque**	**Vehicle velocity**	**Rear Left Torque**	**Vehicle velocity**	**Front Right Torque**	**Vehicle velocity**	**Rear Right Torque**
L	-	Low	Low	Low	Low	High	High	High	High
L	+	Low	High	Low	High	High	Low	High	Low
R	-	High	High	High	High	Low	Low	Low	Low
R	+	High	Low	High	Low	Low	High	Low	High

L – steering wheel angle towards left (0^o to -90^o)

R – steering wheel angle towards right (0^o to 90^o)

"-" – negative yaw rate error as compared to actual`

"+" – positive yaw rate error as compared to actual



plot points: 181

Current Variable

Name swa

Type input

Range [-180 180]

Display Range [-180 180]

Current Membership Function (click on MF to select)

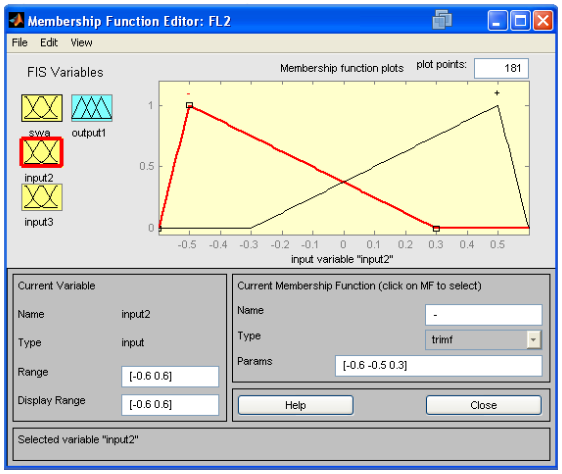
Name L

Type trimf

Params [-180 -90 90]

Ready

Figure 29: Steering wheel angle as input 1 in fuzzy logic controller



plot points: 181

Name: input2

Type: input

Range: [-0.6 0.6]

Display Range: [-0.6 0.6]

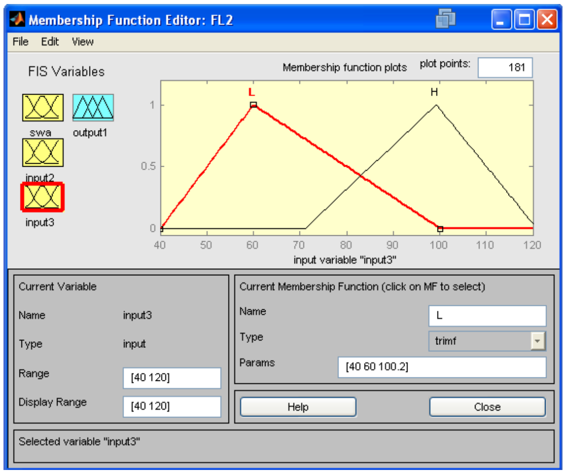
Name: -

Type: trimf

Params: [-0.6 -0.5 0.3]

Selected variable "input2"

Figure 30: Yaw rate error as input 2 in fuzzy logic controller



plot points: 181

Name: input3

Type: input

Range: [40 120]

Display Range: [40 120]

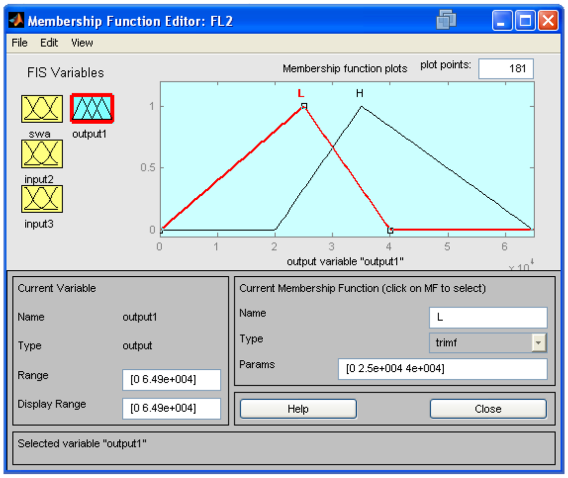
Name: L

Type: trimf

Params: [40 60 100.2]

Selected variable "input3"

Figure 31: vehicle velocity as input 3 in fuzzy logic controller



plot points: 181

Current Variable

Name: output1

Type: output

Range: [0 6.49e+004]

Display Range: [0 6.49e+004]

Current Membership Function (click on MF to select)

Name: L

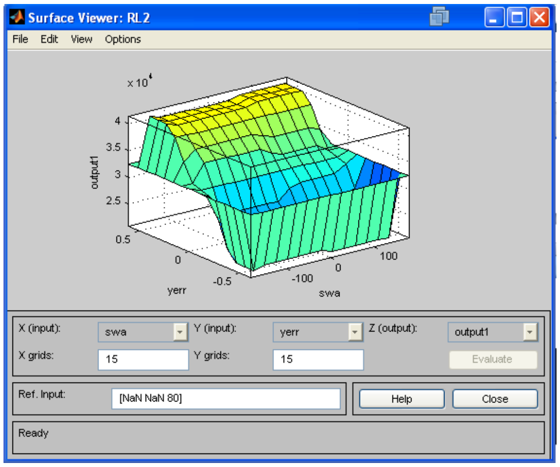
Type: trimf

Params: [0 2.5e+004 4e+004]

Selected variable "output1"

Figure 32: motor torque as output of the fuzzy logic controller

The motor torque output range was retrieved from real specification of 2kW in-wheel motor design by Kelly Control, LLC [18] (refer Appendix 1).



X (input): swa

Y (input): yerr

Z (output): output1

X grids: 15

Y grids: 15

Ref. Input: [NaN NaN 80]

Ready

Figure 33: Input and output map of the fuzzy logic controller

4.5.4.3 Driver Model

Driver model simulate the throttle and brake demand during the co-simulation process and the output will be sent to the ADAMS/Car controller to be processed.

4.5.4.4 The EV ADAMS/Car Model

The EV ADAMS/Car model is a model where generated by ADAMS/Car software which simulate the behaviour of the EV when it received input from the IWM fuzzy logic controller model and from the driver model.

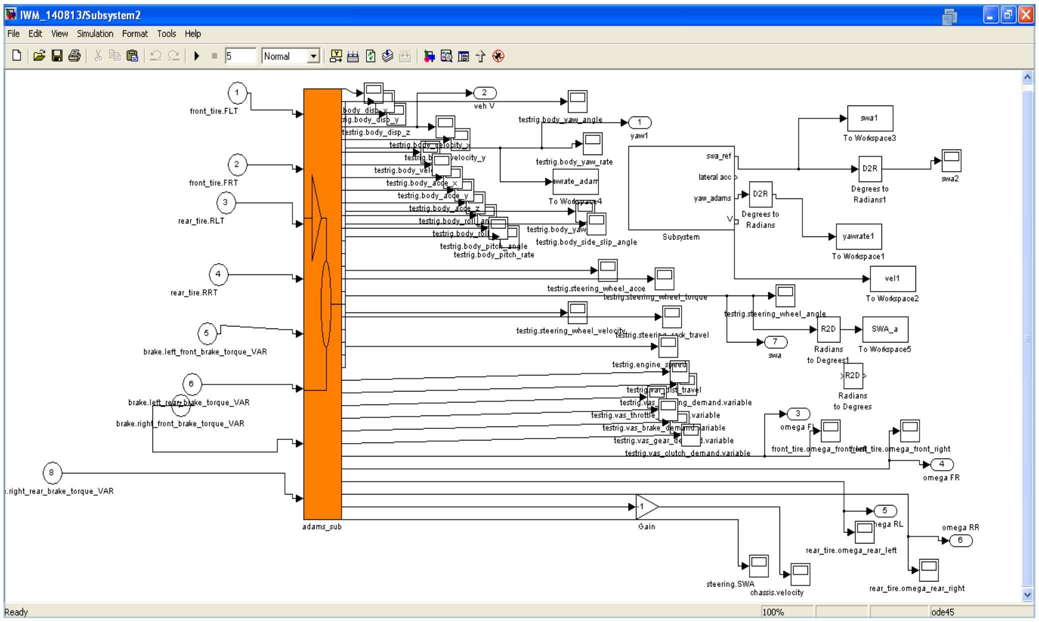


Figure 34: Adams/Car model

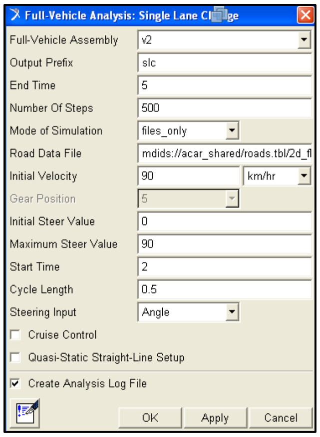
From the input, it will generate the output which needed for the reference model, driver model and IWM fuzzy logic controller model thus, complete the closed loop MATLAB/Simulink block model.

4.6 Co-Simulation between ADAMS/Car and MATLAB/Simulink to Assess the Controller

To assess the controller so that it will improve the cornering performance of the EV several vehicle cornering event simulation were held which are single lane change (SLC), steep steer (SS) and constant radius cornering (CRC). The results will be comparison of performance of EV model with controlled IWMs and EV model with uncontrolled IWMs. The results are compared based on the yaw rate characteristic which gives information on how stable the electric vehicle undergoes the manoeuvre since yaw rate is related to side slip angle (refer equation in chapter 2.6). The result and discussion of the simulations are as shown below:

4.6.1 Single lane change simulation:

As stated before, SLC is to simulate vehicle that changing lane at certain given speed. The vehicle input condition for the SLC simulation is given as shown below:



Full-Vehicle Assembly	v2
Output Prefix	slc
End Time	5
Number Of Steps	500
Mode of Simulation	files_only
Road Data File	mdids://acar_shared/roads.tbl/2d_fl
Initial Velocity	90 km/hr
Gear Position	5
Initial Steer Value	0
Maximum Steer Value	90
Start Time	2
Cycle Length	0.5
Steering Input	Angle

☐ Cruise Control
☐ Quasi-Static Straight-Line Setup
☑ Create Analysis Log File

Figure 35: SLC simulation condition.

Time taken for the SLC simulation is 5 second, and the SLC manoeuver will start at T= 2sec where the steering wheel angle started to turn from 0 to 90 degree for 0.5sec and turn back from 90 to 0 degree for another 0.5sec. The vehicle speed was set constant at 90 km/h.

Single Lane Change Result:

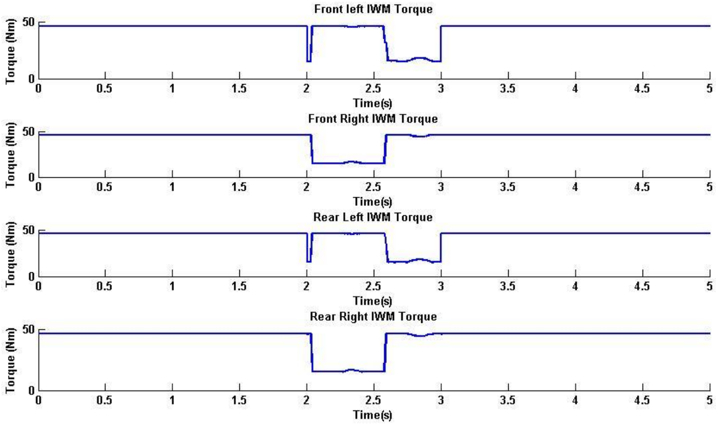


Figure 36: Torque vs. Time graph for SLC

Based on torque versus time graph above, the output torque at the front right and rear right wheel were lowered down by the controller at T=2s until T=2.5s. This shows that the torque vectoring system was applied thus assisting the vehicle to have a resultant moment towards the right (clockwise). At T=2.5s until T=3.0s, the torque at front left and rear left were lowered down by the controller. The torque vectoring system assisted the car to get the resultant moment toward the left. Thus, it completed the single lane change manoeuver.

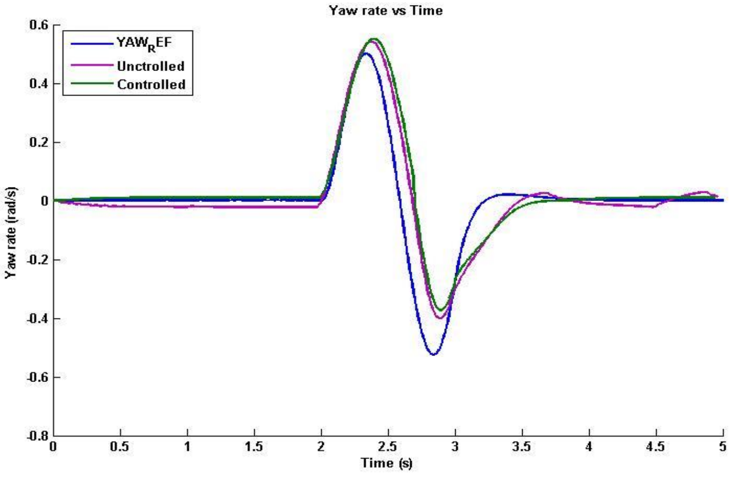
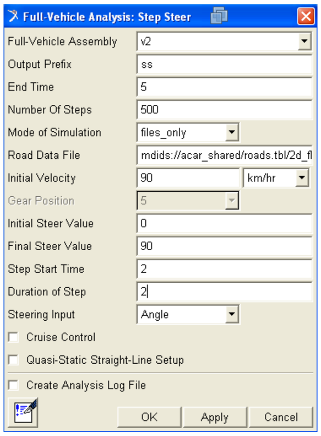


Figure 37: Yaw rate vs. time for SLC.

Based on Figure 37 above shows the plot of yaw rate versus time for yaw reference based on two degree-of freedom (2DOF) bicycle model, uncontrolled and controlled EV model. Yaw reference plot shows that there will be slight overshoot at T=3s to T=3.5s. By controlling the IWMs of EV model, the yaw rate was found has improved the slight overshoot. In the other hand, the uncontrolled EV model still experiencing change in yaw rate after T=3.5s. Based on the plot, it can be conclude that controlling IWMs can improve the stability of the EV model during SLC manoeuver.

4.6.2 Steep steer simulation:

SS simulation is j-turn simulation of a vehicle at a certain speed. The input condition of the simulation is as shown below:

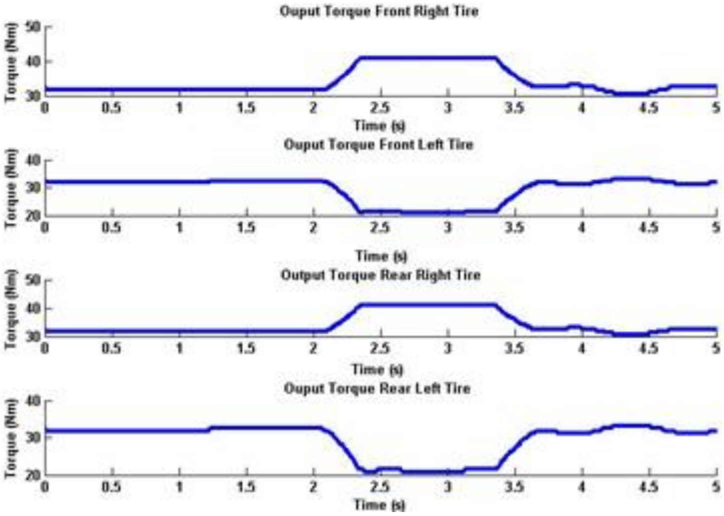

Full-Vehicle Analysis: Step Steer

Full-Vehicle Assembly: v2
Output Prefix: ss
End Time: 5
Number Of Steps: 500
Mode of Simulation: files_only
Road Data File: mdids://acar_shared/roads.tbl/2d_fl
Initial Velocity: 90 km/hr
Gear Position: 5
Initial Steer Value: 0
Final Steer Value: 90
Step Start Time: 2
Duration of Step: 2
Steering Input: Angle
☐ Cruise Control
☐ Quasi-Static Straight-Line Setup
☐ Create Analysis Log File

Figure 38: SS simulation condition.

The vehicle speed was set constant at 90 km/h. Time taken for the SS simulation is 5 seconds, and the SS manoeuver will start at T= 2sec where the steering wheel angle started to turn from 0 to 90 degree for 2 seconds and stay at 90 degree until the end of the simulation (5 seconds).

Step Steer Result:


Ouput Torque Front Right Tire

Ouput Torque Front Left Tire

Output Torque Rear Right Tire

Ouput Torque Rear Left Tire

Figure 39: Torque vs. Time graph for SS.

Based on torque versus time graph above, the output torque at the front right and rear right wheel were increased by the controller at T=2s until T=3.5s. This shows that the torque vectoring system assisted the vehicle to have a resultant moment towards the left (anti-clockwise) at the beginning of the j-turn. At T=3.5s until T=5.0s, the torque were lowered down and controlled by the controller at about 30Nm. At this point, the torque vectoring system tried to assist the car to balance the yaw rate according to the reference model developed before to complete the j-turn or SLC manoeuver.

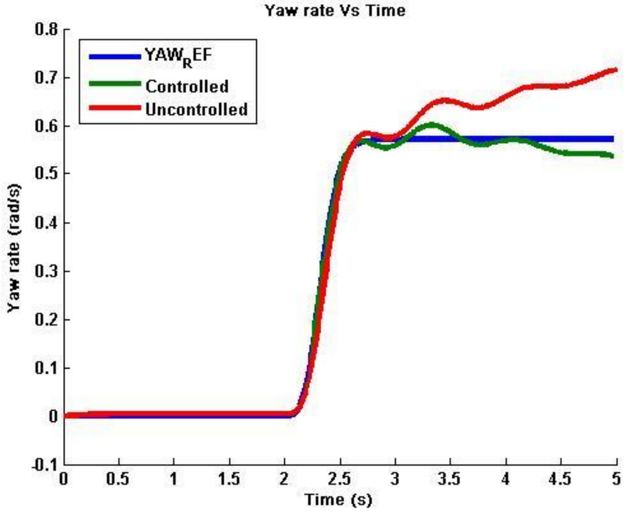
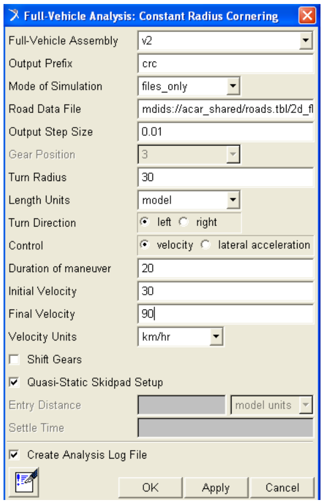


Figure 40: Yaw rate vs. time for SS.

Based on Figure 40, the result shows the plot of yaw rate versus time for yaw reference based on two degree-of freedom (2DOF) bicycle model, uncontrolled and controlled EV model for SS simulation. Clearly spotted that uncontrolled EV model unable to maintain its yaw rate as the vehicle start the j-turn at T=2s. While the EV model with controlled IWMs tries to follow the reference yaw rate line as the vehicle experienced the j-turn in step steer simulation. Thus, by controlling IWMs can improve the vehicle stability in Step steer.

4.6.3 Constant radius cornering simulation:

CRC simulation is where the vehicle is to turn at a certain constant radius with increasing speed. In this project, the radius set for CRC simulation was 30 meters and the speed of the vehicle was increased from 30km/h to 90km/h. The turn direction is toward the left (anti-clockwise), the input condition of the simulation is as shown below:



Full-Vehicle Assembly: v2
Output Prefix: crc
Mode of Simulation: files_only
Road Data File: mdids://acar_shared/roads.tbl/2d_fl
Output Step Size: 0.01
Gear Position: 3
Turn Radius: 30
Length Units: model
Turn Direction: ● left ○ right
Control: ● velocity ○ lateral acceleration
Duration of maneuver: 20
Initial Velocity: 30
Final Velocity: 90
Velocity Units: km/hr
☐ Shift Gears
☑ Quasi-Static Skidpad Setup
Entry Distance: model units
Settle Time
☑ Create Analysis Log File

Figure 41: CRC simulation condition.

Constant Radius Cornering Result:

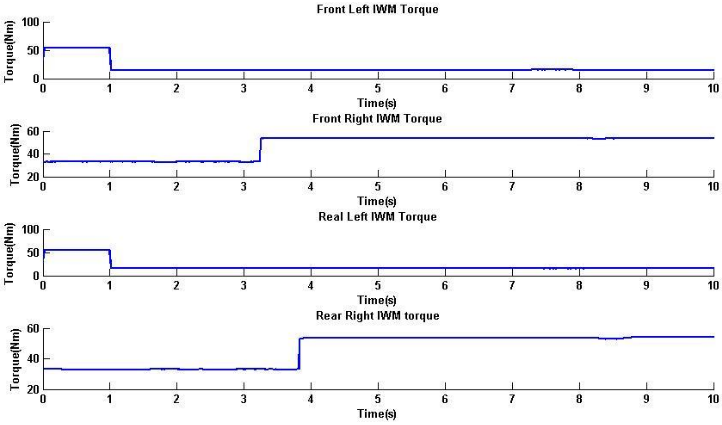


Figure 42: Torque vs. Time graph for CRC.

Based on torque versus time graph above, the output torque at the front right and rear right wheel were start at about 30Nm by the controller at T=0s. While, the torque values at front left and rear left were start higher which is at about 50Nm. This shows that the torque vectoring system assisted the vehicle to have a resultant moment towards the right (clockwise) at the beginning of the anti-clockwise constant radius cornering turn for 1 second. This is shows that the controller tried to lower down the yaw rate error that experienced by the EV model according to the reference model.

At T=1s, both output torque at the front left and rear left wheel were lowered down at about 10Nm until the end of the CRC manoeuver finish while torque output at front right and rear right is remain constant at 30Nm up until T=3.2s and T=3.9s respectively. As the speed increased, the torque output at front right and rear right were further increased to 50Nm at T=3.2s and T=3.9s respectively until the CRC manoeuver finish. This shows that as the speed increased, the EV model experienced understeer, thus torque vectoring system assisted the EV model to ensure it stays at the correct CRC path.

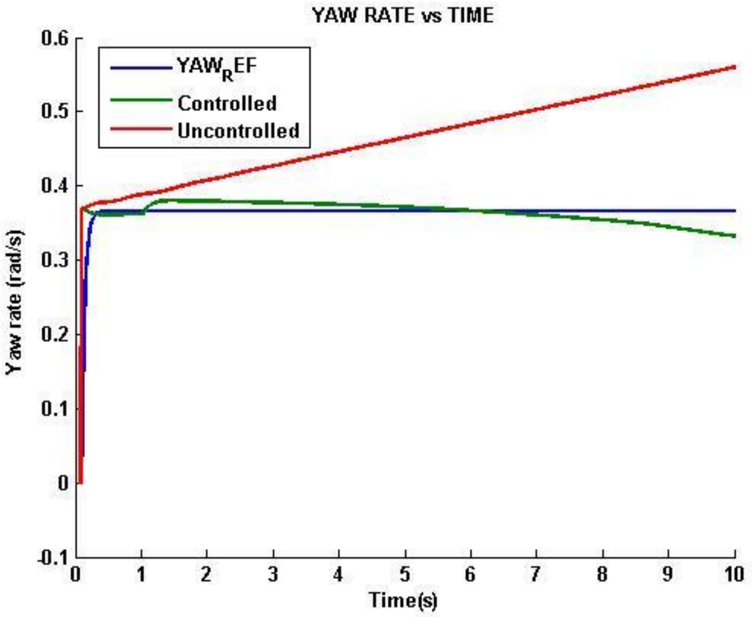


Figure 43: Yaw rate vs. time for CRC.

Figure 43 shows the plot of yaw rate versus time for yaw reference based on two degree-of freedom (2DOF) bicycle model, uncontrolled and controlled EV model for CRC simulation. As the vehicle increase its velocity through 30m radius cornering, the controlled EV model tries to maintain its yaw rate according to the reference plot. While the uncontrolled EV model unable to maintain the yaw rate thus, making the model undergoes understeer characteristic and may came out from the cornering path (30m radius). Hence, by controlling the IWMs in the EV model, the cornering performance of the EV model can be improved.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The initial step in study of torque vectoring and traction control for an all-wheel drive electric vehicle was to develop base model in ADAMS/Car which include several subsystem such as front and rear double wish bone suspensions, chassis, steering, brake, and wheels. Prior to modification of base model to become EV model, the base model without ICE cornering characteristic is compare with base model with ICE to validate its performance and body model structure. Once the base model is validated, IWM is added at each wheel to become dynamic model in ADAMS/Car. Up to this point, the first objective which is to develop a vehicle dynamic model for an electric vehicle with 4 IWMs in ADAMS/Car is achieved.

Prior to simulate and characterize the performance of the EV, Some set-up in the ADAMS/Car model was done so that it can communicate with MATLAB/Simulink for the co-simulation purposes. Next, sizing of IWM, Battery and vehicle mass was made to determine the value for the component sizing in the MATLAB/Simulink EV controller Model. Several subcomponents of vehicle model were generated in MATLAB/Simulink to ensure the co-simulation with the ADAMS/Car model such as reference model, IWM model and driver model.

Next, simulation and characterization of the performance of the EV and compare it to uncontrolled EV model was made. The simulations involved are single lane change, step steer and constant radius cornering. According to the result, torque vectoring and traction control of in-wheel motor in all wheel drive EV can help to increase the performance of the electric vehicle during cornering manoeuver. At this stage, the second and third objective which are to develop an optimal control for vehicle best performance and to simulate and characterize the performance of the electric vehicle and compare it to uncontrolled EV model were done.

In conclusion, torque vectoring using this approach has the potential to improve response and stability where the tuning of the control model enabling vehicle behavior to meet driver expectations.

5.2 RECOMMENDATION

The result of the study concluded that the modeling and simulation of the EV is a success. The simulation performed shows that torque vectoring and traction control capable to improve the vehicle performance in term of vehicle handling.

To improve the study for future work, the modelling of ADAMS/Car and MATLAB/Simulink can be done in detail manner. For example, in ADAMS/Car modelling, the suspensions model used were simplified with several assumptions. While in MATLAB/Simulink, reference model accuracy was up to 2 degree of freedom to improve the accuracy of the result, the degree of freedom should be increased.

In this project, the result of the electric vehicle model cornering performance improved by controlling the IWMs but is not very smooth where the controller still lacking in term of giving the best output torque. To improve the results, researcher can use other type of controller which can give out better and smooth output such as Neuro-fuzzy logic controller which combining human-like reasoning style of fuzzy systems and structure of neutral networks.

Simulation alone will not give a very accurate result towards the realistic vehicle that will be built. Thus, to ensure that all wheel drive of electric vehicle is possible and the torque vectoring and traction control is really improving the handling of the electric vehicle, experimental base on real electric vehicle is needed so that the technology can be proved in real life.

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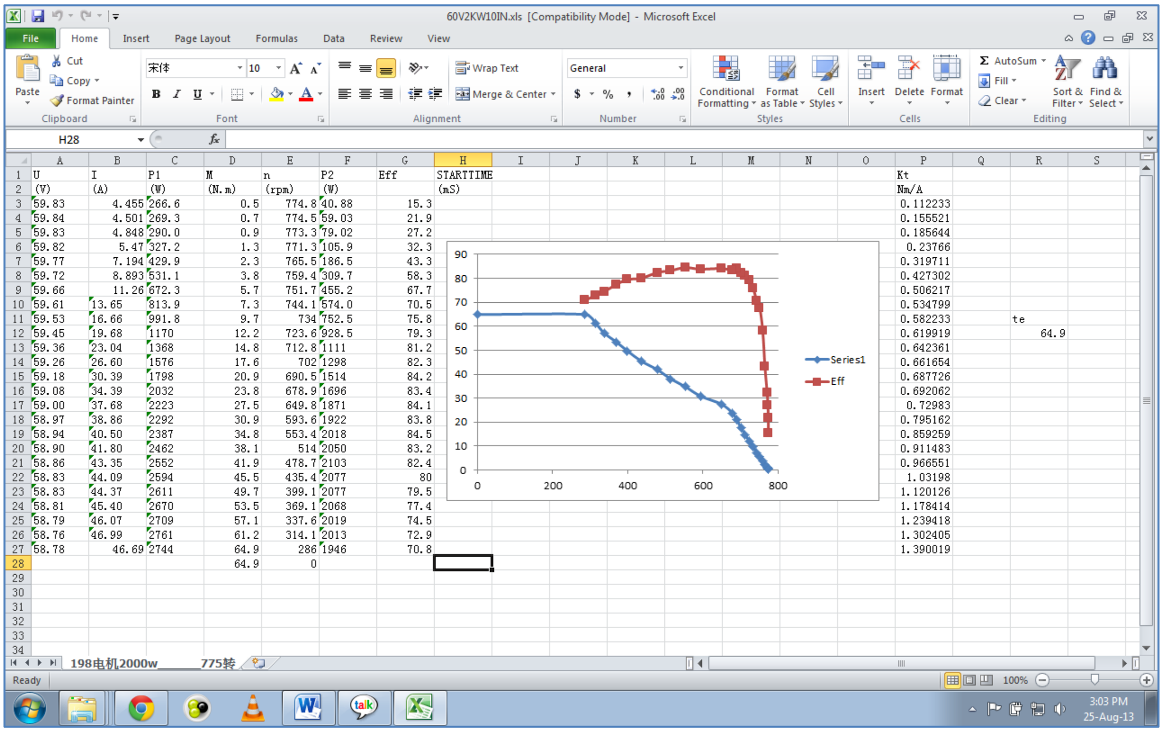
Appendix

1. Appendix 1: Motor Map [18]



	A	B	C	D	E	F	G	H	P	R
1	U	I	P1	M	n	P2	Eff	STARTTIME	Kt	
2	(V)	(A)	(W)	(N.m)	(rpm)	(W)		(mS)	Nm/A	
3	59.83	4.455	266.6	0.5	774.8	40.88	15.3		0.112233	
4	59.84	4.501	269.3	0.7	774.5	59.03	21.9		0.155521	
5	59.83	4.848	290.0	0.9	773.3	79.02	27.2		0.185644	
6	59.82	5.47	327.2	1.3	771.3	105.9	32.3		0.23766	
7	59.77	7.194	429.9	2.3	765.5	186.5	43.3		0.319711	
8	59.72	8.893	531.1	3.8	759.4	309.7	58.3		0.427302	
9	59.66	11.26	672.3	5.7	751.7	455.2	67.7		0.506217	
10	59.61	13.65	813.9	7.3	744.1	574.0	70.5		0.534799	
11	59.53	16.66	991.8	9.7	734	752.5	75.8		0.582233	te
12	59.45	19.68	1170	12.2	723.6	928.5	79.3		0.619919	64.9
13	59.36	23.04	1368	14.8	712.8	1111	81.2		0.642361	
14	59.26	26.60	1576	17.6	702	1298	82.3		0.661654	
15	59.18	30.39	1798	20.9	690.5	1514	84.2		0.687726	
16	59.08	34.39	2032	23.8	678.9	1696	83.4		0.692062	
17	59.00	37.68	2223	27.5	649.8	1871	84.1		0.72983	
18	58.97	38.86	2292	30.9	593.6	1922	83.8		0.795162	
19	58.94	40.50	2387	34.8	553.4	2018	84.5		0.859259	
20	58.90	41.80	2462	38.1	514	2050	83.2		0.911483	
21	58.86	43.35	2552	41.9	478.7	2103	82.4		0.966551	
22	58.83	44.09	2594	45.5	435.4	2077	80		1.03198	
23	58.83	44.37	2611	49.7	399.1	2077	79.5		1.120126	
24	58.81	45.40	2670	53.5	369.1	2068	77.4		1.178414	
25	58.79	46.07	2709	57.1	337.6	2019	74.5		1.239418	
26	58.76	46.99	2761	61.2	314.1	2013	72.9		1.302405	
27	58.78	46.69	2744	64.9	286	1946	70.8		1.390019	
28				64.9	0					