UNIVERSITI TEKNIKAL MALAYSIA MELAKA

# PROJECT COMPLETION REPORT
# FOR
# (SHORT TERM) RESEARCH GRANT

# DEVELOPMENT OF VEHICLE ROLLOVER PREVENTION SYSTEM USING ACTIVE BRAKING

**Principal Researcher : Amrik Singh A/L Phuman Singh**

**Co-Researchers : 1. Engr. Dr. Mohd Azman Bin Abdullah (Faculty of Mechanical Engineering)**
**2. Ranjit Singh A/L Sarban Singh (Faculty of Electronics and Computer Engineering)**

**Project Code No. : PJP/2012/FKM(1C)/S01006**

**Report Submission Date : 26 September 2014**

**Department of Automotive**

**FACULTY OF MECHANICAL ENGINEERING**

## ABSTRACT

This research focuses on the development of the vehicle rollover prevention system using active braking. Vehicle rollover occurs typically in vehicles with a high center of gravity, such as sport utility vehicle when it is driven by extreme steering input at high speed. Active braking is one of the methods that could be used to avoid vehicle rollover. Vehicle dynamics model made up of eight degrees of freedom coupled with Dugoff's tire model is first developed mathematically and then built in the Matlab / SIMULINK environment. Both reduced scale instrumented vehicle and CarSim software were used to validate the vehicle dynamic performance. From the validation results, the proposed vehicle model was able to produce responses similar to that of reduced scale instrumented vehicle and CarSim software. In this project, the active braking system with both PID and Fuzzy controllers were used to control the untripped rollover which occurs due to high lateral acceleration resulting from extensive steering maneuvers. Fishhook and J-turn tests with different longitudinal speed were utilized for control performance evaluation. The implementation of the active braking system with PID and Fuzzy control strategies demonstrated improvement by decreasing the magnitude of the roll angle and rate as well as rollover index. The proposed control strategies were proven to be capable of reducing the roll angle and hence avoiding the vehicle rollover.

# TABLE OF CONTENTS

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $C_{\sigma}$ | = | Longitudinal tire stiffness |
| $C_{\alpha}$ | = | Tire cornering stiffness |
| $c_s$ | = | Suspension damping |
| $c_{\phi f}$ | = | Front equivalent roll damping |
| $c_{\phi r}$ | = | Rear equivalent roll damping |
| $F_s$ | = | Spring forces |
| $F_d$ | = | Damping forces |
| $F_t$ | = | Tire forces |
| $F_{xfl}$ | = | Front left tire longitudinal force |
| $F_{xfr}$ | = | Front right tire longitudinal force |
| $F_{xrl}$ | = | Rear left tire longitudinal force |
| $F_{xrr}$ | = | Rear right tire longitudinal force |
| $F_{yfl}$ | = | Front left tire lateral force |
| $F_{yfr}$ | = | Front right tire lateral force |
| $F_{yrl}$ | = | Rear left tire lateral force |
| $F_{yrr}$ | = | Rear right tire lateral force |
| $F_{zfl}$ | = | Front left tire normal force |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $F_{zfr}$ | = | Front right tire normal force |
| $F_{zrl}$ | = | Rear left tire normal force |
| $F_{zrr}$ | = | Rear right tire normal force |
| $g$ | = | Gravitational acceleration |
| $I_w$ | = | Rotational moment of inertia of each wheel |
| $I_x$ | = | Roll moment of inertia |
| $I_z$ | = | Yaw moment of inertia |
| $k_s$ | = | Suspension spring stiffness |
| $k_t$ | = | Tire stiffness |
| $k_{\phi f}$ | = | Front equivalent roll stiffness |
| $k_{\phi r}$ | = | Rear equivalent roll stiffness |
| $l_f$ | = | Distance of vehicle C.G from the front axle |
| $l_r$ | = | Distance of vehicle C.G from the rear axle |
| $l_w$ | = | Track width |
| $m_t$ | = | Total mass of vehicle |
| $m_b$ | = | Sprung mass of the vehicle body |
| $m_{ufl}$ | = | Front left unsprung mass of the vehicle |
| $m_{ufr}$ | = | Front right unsprung mass of the vehicle |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $m_{url}$ | = | Rear left unsprung mass of the vehicle |
| $m_{urr}$ | = | Rear right unsprung mass of the vehicle |
| $R$ | = | Tire effective radius |
| $T_d$ | = | Wheel drive torque |
| $T_{bfl}$ | = | Front left wheel brake torque |
| $T_{bfr}$ | = | Front right wheel brake torque |
| $T_{brl}$ | = | Rear left wheel brake torque |
| $T_{brr}$ | = | Rear right wheel brake torque |
| $v_x$ | = | Longitudinal velocity |
| $\dot{v}_x$ | = | Longitudinal acceleration |
| $v_y$ | = | Lateral velocity |
| $\dot{v}_y$ | = | Lateral acceleration |
| $\omega_{fl}$ | = | Front left angular velocity of wheel |
| $\omega_{fr}$ | = | Front right angular velocity of wheel |
| $\omega_{rl}$ | = | Rear left angular velocity of wheel |
| $\omega_{rr}$ | = | Rear right angular velocity of wheel |
| $\dot{\omega}_{fl}$ | = | Front left angular acceleration of the wheel |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $\dot{\omega}_{fr}$ | = | Front right angular acceleration of the wheel |
| $\dot{\omega}_{rl}$ | = | Rear left angular acceleration of the wheel |
| $\dot{\omega}_{rr}$ | = | Rear right angular acceleration of the wheel |
| $\sigma_x$ | = | Slip ratio |
| $\delta$ | = | Front wheel steering angle |
| $\mu$ | = | Coefficient of friction of road surface |
| $h$ | = | Height of vehicle C.G from ground level |
| $\alpha_f$ | = | Front wheel side slip angle |
| $\alpha_r$ | = | Rear wheel side slip angle |
| $\phi$ | = | Roll angle |
| $\dot{\phi}$ | = | Roll rate |
| $\psi$ | = | Yaw angle |
| $\dot{\psi}$ | = | Yaw rate |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ABS | Antilock Braking System |
| DOF | Degree of freedom |
| EBD | Electronic Brake Force Distribution |
| ESP | Electronic Stability Program |
| FBD | Free Body Diagram |
| LQR | Linear-Quadratic Regulator |
| NHTSA | National Highway Traffic Safety Administration |
| PID | Proportional-Integral-Derivative |
| PSM | Projek Sarjana Muda |
| SUV | Sport Utilities Vehicle |
| TTR | Time-To-Rollover |
| VDC | Vehicle Dynamic Control |
| VSC | Vehicle Stability Control |

# CHAPTER I

# INTRODUCTION

## 1.1 OVERVIEW

Recently, computer simulation is a very useful tool which utilized the user for designing, analyzing and developing a vehicle dynamic model in the automotive field. These virtual dynamic simulations proved to be effective, efficient and precise methods that can be used to assess or predict vehicle behavior for different operating conditions. In order to evaluate the vehicle dynamic behavior with traditional full-scale vehicle testing, it may involve high cost and also endanger the driver safety. Likewise, the test in simulation can be repeated at infinite times. For actual testing, this may be the limitation in which a long duration may require to set up and operate for a real vehicle testing. In real world testing, the test vehicle must be modified or rebuild by the engineers if there are requirements to change the vehicle parameters. However, for the development process, a full-scale vehicle testing will not be eliminated, but being postponed from the beginning stage to the final stage of evolution in order to validate the model design (Longoria et al., 2004).

From the report of NHTSA, there is approximately 90% of the first harmful events of non-collision fatal crashes due to rollover. The average percentage of rollover occurrence in fatal crashes was significantly higher than other types of crashes (Chen and Peng, 2001). Sport Utility Vehicles (SUV) had the highest rollover rates due to higher ground clearance. The star rating for a passenger car is between 4 and 5 stars while for SUV’s, the range is between 1 and 3 stars (Garrick and Garrott, 2002). The lateral acceleration and roll angle of a vehicle is the main consideration for rollover prevention. There are various types of actuation mechanism which had been promoted by different researchers in automotive industries that being utilized as a rollover prevention system. Some of the examples of active system are four wheel steering, active suspension, active stabilizer, and differential braking or known as active braking (Chen and Peng, 2001).

For yaw and roll control, there are three types of stability control systems which have been suggested and produced by several researchers. First, the differential braking systems which utilize the anti-lock braking system (ABS) on the vehicle by applying different braking forces between the right and left wheels in order to control the roll and yaw moment. The second stability control system namely steer-by-wire which modify the driver’s steering angle input and also add correction to the steering angle of wheel helps to prevent yawing motion. Thirdly, the active torque distribution system which utilizes active differentials and all-wheel drive technology to independently control the drive torque distributed to each wheel and thus provide active control for both traction and yaw moment (Rajamani, 2012).

Most of the researchers are interested in using differential braking system as a rollover prevention method such a way of reducing the yawing moment and the speed of the vehicle. In order to prevent rollover, active or semi-active suspension systems can also be used. An active suspension system is more likely to be effective in rollover prevention than steer-by-wire or differential braking systems. However, the hardware price for the development of active suspension is expensive. The new vehicles in the U.S. and Europe starting in the year of 2012 have been implemented differential braking systems as their vehicle safety system in most of the manufactured vehicles (Phanomchoeng and Rajamani, 2013).

## 1.2 PROBLEM STATEMENT

Rollover is one of the most life threatening crash accidents compared to another type of vehicle crashes. Even though vehicle rollover results in only 3% of vehicle accidents, it contributes to 33% of all fatalities. Therefore, extensive research is being done on the development of vehicle rollover prevention systems. Active suspension, active steering, and active braking are among the control strategies that have been investigated by the researchers to enhance the vehicle rollover resistance. It is important that the vehicle roll motion is reduced to avoid rollover risk and hence increase the safety of the vehicle occupant. There is possibility that the vehicle rollover can be recovered if the driver is skillful enough, but it is more than impossible for a normal driver to avoid rollover when the vehicle is driven at its handling limits. For example, stunt drivers enable to maintain the vehicle on two wheels without allowing the vehicle to rollover, but this is impossible for an ordinary driver. For this reason, vehicle rollover prevention system which is able to detect the possibility to vehicle rollover and takes the corrective action to avoid the impending vehicle rollover should be developed.

## 1.3 OBJECTIVES

The objectives of this project are:

i. To develop an eight degrees of freedom vehicle model which is capable of predicting the roll behavior of the vehicle
ii. To design the control strategies for the vehicle rollover prevention system using active braking

## 1.4 SCOPES

The scope of this project is as follows:

i. Development of mathematical and SIMULINK models for eight degrees of freedom vehicle model
ii. Validation of full vehicle model with validated vehicle dynamics software and reduced scale instrumented vehicle for fishhook and J-Turn tests
iii. Controller design by simulation of the vehicle rollover prevention system using active braking

## 1.5 REPORT OUTLINE

This report is divided into five chapters. Chapter 2 presents the literature review related to vehicle dynamics and modeling concepts. The vehicle modeling can be classified into vehicle handling model and full vehicle model. This chapter also discusses about the rollover resistance dynamic tests, rollover detection, rollover prevention methods, and rollover prevention control strategies. Chapter 3 presents the methodology used for completing this project such as flow charts, development of the mathematical and SIMULINK models, brake torque tracking control, and two types of control strategies. Chapter 4 presents the results from the validation of SIMULINK model using CarSim which include the roll angle, roll rate, yaw rate and the lateral acceleration for different test and speed. In this chapter, it also contains the results of improvement for roll angle, rollover index and roll rate after implementing further control strategies to avoid rollover possibility. Lastly, Chapter 5 presents the conclusion and recommendation of this project.

# CHAPTER II

# LITERATURE REVIEW

## 2.1 VEHICLE MODELING

The safety, performance, and comfort of vehicles have improved rapidly nowadays as compared to the 19th century. The manufacturers relied on the vehicle modeling and simulation method to achieve their target in improving the quality of the vehicle. There is a lot of advanced industry standard vehicle dynamic simulation software nowadays in the market such as CarSim, Adams/Car, and etc. Those advance software is widely used to model and evaluate the vehicle dynamic behavior throughout various operating conditions in automotive industries. With this software, manufacturers are able to develop and generate new design vehicle in a shorter period, and improve the development cost reduction of the automotive industry market. Moreover, the development cost and time saved can be utilized for optimizing other vehicle systems such as antilock braking system (ABS), electronic brake force distribution (EBD) and etc.

The simulations of a full vehicle model are much complicated than quarter vehicle models which required a longer duration of model development. The vehicle model complexity can be reduced to some degree depending on the vehicle dynamic scope that needs to be considered. The vehicle model can be subdivided into ride model and handling model. Both of the ride model and handling model can be simplified into a lower degree of freedom (DOF) for analysis and depend on the findings to be obtained.

### 2.1.1 Vehicle Handling Model

The longitudinal acceleration, lateral acceleration and yaw motion of the vehicle is used to determine vehicle handling model performance. In the analysis or simulation process, the rotational motion of the wheels is also considered as one of the vehicle handling model. The roll and pitch motions will be included in the vehicle handling model because load transfer is an important factor which influence the tire performance.

The vehicle handling could be divided into two categories which are linear and nonlinear. In order to evaluate the stability of the system and showing the fundamental dynamics of the vehicle that may exist, linear vehicle handling model can be used. For more accurate studies, the nonlinear model is used as compared to the linear model because it may have various operating ranges. However, for nonlinear model, it required a more complicated system representation.

The four types of vehicle handling model are:

i. 2 DOF vehicle handling model (Arikan, 2008)
ii. 3 DOF vehicle handling model (Bolhasani and Azadi, 2004)
iii. 7 DOF vehicle handling model (Fauzi et al., 2009)
iv. 8 DOF vehicle handling model (Ghike et al., 2008)

#### 2.1.1.1 2 DOF Vehicle Handling Model

For investigating the vehicle handling dynamics such as lateral displacement and yaw motion, a linear bicycle model of 2 DOF can be used. For a lower DOF model, it has greater limitations as compared to the higher DOF model. For instance, the lower DOF model provides low lateral acceleration which is below 0.3g's. However, the model gives the valuable information about the basic handling behavior of a vehicle without extensive measurements. A more complicated nonlinear model will be required to simulate the motion of the vehicle at higher lateral accelerations (Arikan, 2008). Besides, the tire cornering stiffness effects of a vehicle can be deduced by a 2 DOF vehicle handling model. The FBD of a linear bicycle model can be illustrated as in Figure 2.1.

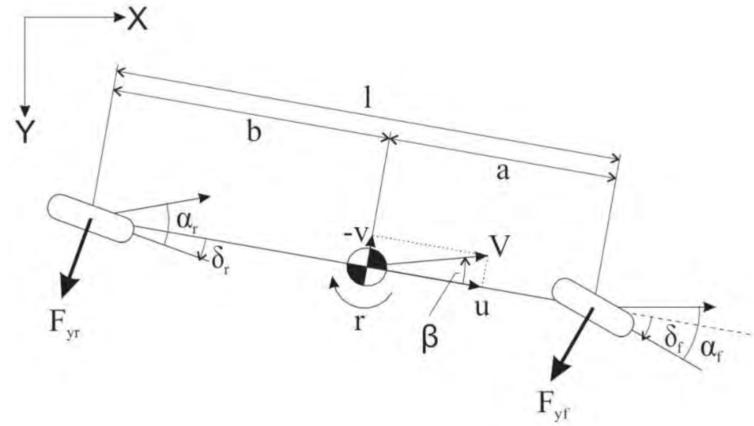


Figure 2.1: The bicycle model
(Source: Veldhuizen, (2007))

There are several assumptions made to linearize the system in development of the bicycle model such as:

i. The front and rear axle traction forces are assumed to be concentrated at a single patch.
ii. The longitudinal velocity is considered to be constant (Veldhuizen, 2007).
iii. Lateral tire forces are assumed to be directly proportional to slip angle at small slip angle (Veldhuizen, 2007).
iv. The application only for lateral accelerations less than 0.3 g (Arikan, 2008).
v. The suspension effect and geometry is neglected
vi. The track width is neglected

These conditions cause the generation of linear tire cornering forces with the following relations (Arikan, 2008). The subscript $f$ indicated front and $r$ indicated rear.

$$F_{yf} = C_f \alpha_f \tag{2.1}$$

$$F_{yr} = C_r \alpha_r \tag{2.2}$$

where,

$C_f, C_r =$ tire cornering stiffness

$\alpha_f, \alpha_r$ = slip angle

2.1.1.2 3 DOF Vehicle Handling Model

A 3 DOF vehicle handling model can also be known as quadricycle model. This model is an extension from the simple 2 DOF linear bicycle model. The vehicle roll dynamic is added as the third degree of freedom other than the consideration of lateral acceleration and yaw dynamic (Veldhuizen, 2007). In order to investigate the lateral velocity, roll rate and yaw rate of the model, a simple 3 DOF vehicle model can be used (Bolhasani and Azadi, 2004). Bolhasani and Azadi (2004) have conducted a research on vehicle parameter estimation of the vehicle handling model by developing 3 DOF vehicle handling model.

2.1.1.3 7 DOF Vehicle Handling Model

The three degrees of freedom for vehicle body motions and four degrees of freedom for rotational motion of each wheel can produce a full 7 DOF vehicle handling model. In order to study the longitudinal acceleration, lateral acceleration and yawing motion of the vehicle, a 7 DOF vehicle handling model can be generated (Fauzi et al., 2009). Normally, the 7 DOF vehicle handling model is used to study the vehicle motion which moving on a flat surface. The FBD of top view model is illustrated in Figure 2.2 while the FBD of wheel rotational dynamics is shown in Figure 2.3.

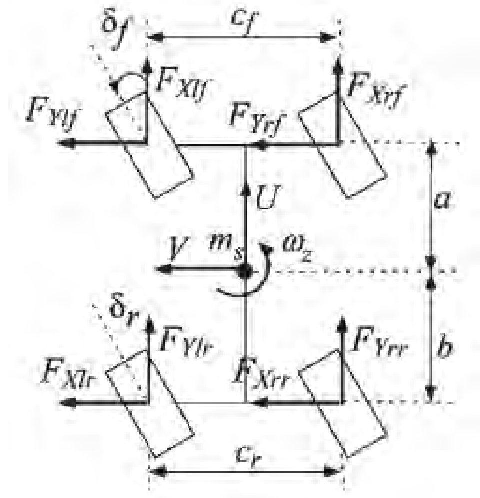


Figure 2.2: The FBD of top view vehicle handling model
(Source: Ghike et al., (2008))

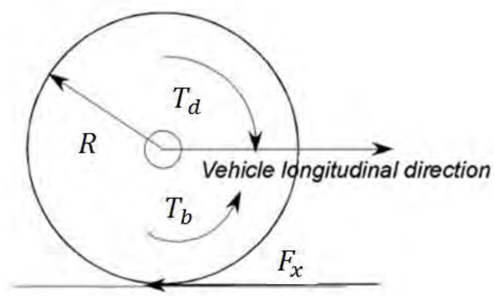


Figure 2.3: The FBD of wheel rotational dynamics
(Source: Shim et al., (2008))

The Equations 2.3, 2.4, 2.5, and 2.6 show the longitudinal dynamic, lateral dynamic, yaw dynamic, and wheel rotational dynamic of the vehicle model.

$$m_t\left(\dot{v}_x - v_y\dot{\psi}\right) = \sum F_{xij} \tag{2.3}$$

$$m_t\left(\dot{v}_y + v_x\dot{\psi}\right) = \sum F_{yij} \tag{2.4}$$

$$I_z\ddot{\psi} = \sum M_z \tag{2.5}$$

$$I_w\dot{\omega}_{ij} = T_{dij} - T_{bij} - F_{xij}\cdot R \tag{2.6}$$

The subscripts *i* denotes the front or rear vehicle wheel while *j* denotes the left or right vehicle wheel.

#### 2.1.1.4 8 DOF Vehicle Handling Model

In order to investigate the vehicle handling dynamics such as longitudinal acceleration, lateral acceleration, yaw rate and roll motion, an 8 DOF vehicle handling model can be used. The load transfer is an important factor which influences the vehicle handling performance in an 8 DOF model. The 8 DOF model is made up from four degrees of freedom for vehicle body motions and four degrees of freedom for rotational motion at each wheel. A research on improvement or enhancement of vehicle handling and stability was conducted by Ghike et al. (2008) by using 8 DOF vehicle handling model. In this research, the vehicle longitudinal and lateral dynamics were controlled by integrated control of wheel drive-brake torque.

### 2.1.2 Full Vehicle Model

The development of a full vehicle model will consist of 7 DOF ride model, and 7 DOF handling model which including the tire model. Generally, there are three types of tire model that have been utilized for vehicle handling models which are Dugoff's tire model, Calspan tire model and Magic Formula tire model. The Dugoff's tire model was chosen for this project due to the ease of understanding the equations which are simpler than Calspan tire model and Magic Formula tire model. Various vehicle dynamic behaviors can be evaluated by using a full vehicle model such as longitudinal acceleration, lateral acceleration, vehicle body displacement, roll rate, pitch rate, yaw rate and etc.

Various researchers have developed 14 DOF mathematical models such as (Shim and Ghike, 2006) which investigating the dynamic behavior of full vehicle, (Lee et al., 2008) which had conducted full vehicle dynamic model for the designing chassis controls, and (Randy et al., 2004) had conducted a study on rollover propensity of a vehicle due to the effect of various vehicle parameters. Therefore, the 14 DOF vehicle model in SIMULINK environment can be used to investigate the rollover possibility and the validation is done by comparing the results with CarSim software.

### 2.1.3 Tire Model

There are several types of tire model which can be known as Dugoff's tire model, Magic formula tire model, and Calspan tire model that commonly used by researchers in their vehicle handling performance studies.

#### 2.1.3.1 Dugoff's Tire Model

Dugoff's tire model is an alternative to the elastic foundation analytical tire model developed by Fiala in 1954 for lateral force generation and by Pacejka and Sharp in 1991 for combined lateral and longitudinal force generation (Rajamani, 2012). The longitudinal and lateral tire force generation as functions of the vertical force, slip ratio and slip angle can be obtained from a tire model. For a Dugoff's tire model, the vertical pressure distribution acted on the tire contact patch is assumed to be uniform.

The Dugoff's tire model has more advantages as compared to the Magic Formula tire model. One of the advantages of this tire model is the independent values of tire longitudinal stiffness and tire cornering stiffness. This could be one of the advantages, since the longitudinal stiffness in a tire could be quite different from the lateral stiffness. It has the advantage of being an analytically derived model developed from force balance calculations where the lateral and longitudinal forces are directly related to the tire road friction coefficient in more transparent equations (Rajamani, 2012).

#### 2.1.3.2 Magic Formula Tire Model

In order to identify larger slip angles and larger slip ratios condition, a more complicated model is required. The Magic Formula tire model provides a technique to calculate the longitudinal tire force, $F_x$, lateral tire force, $F_y$, and aligning moment, $M_z$ for larger slip angle and slip ratio condition. The results obtained from this model can rival experimental data of pure lateral or longitudinal force generation. However, the analytical models do not always lead to quantitatively accurate results. There will be dissimilarity between experimental data, especially at large slip and at combined slip.

There are some criteria which are not included in the simple brush model causing the dissimilarity to happen, such as the unequal stiffness in $x$ and $y$ directions, non-symmetric and non-constant pressure distribution, and non-constant friction coefficient, including a difference between static and kinetic friction coefficients

These factors could be accounted by introducing them into the physical model which would highly increase model complexity. An alternate way to obtain a more accurate mathematical model is to use empirical expressions. A widely used semi - empirical tire model is the so-called Magic Formula Tire Model. This tire model required more experimental coefficient and having complicated equation (Osborn and Shim, 2006). This model yields realistic tire behavior (Rajamani, 2012).

2.1.3.3 Calspan Tire Model

It is very important to describe the real behavior of a vehicle in various types of driving scenario, including during cold or wet weather driving conditions which may require extensive maneuver, braking, acceleration, and etc. In order to simulate the full vehicle operational range, it is important to develop a proper model which generates tire forces containing the interactions of longitudinal and lateral forces from small levels of saturation. With Calspan tire model, it is capable to simulate pure cornering, pure braking, combined braking and cornering maneuvers of vehicle including various conditions (Osborn and Shim, 2006).

However, this tire model involves a greater number of parameters and more equations. The Calspan tire model developed provides a useful force producing element for a full vehicle model, especially the tire aligning moment which not provided by other tire model.

## 2.2 SIMULATION OF VEHICLE MODEL

Matlab/SIMULINK is advanced software developed by MathWorks. It is one of the software or known as a tool for modeling, simulation and analyzing purposes. It can solve complex mathematical equations and dynamic systems which are being constructed by the user in a short period of time. SIMULINK is a user friendly computational tool which provides a graphical editor, editable block libraries, and solvers for modeling and simulating dynamic systems. Those complicated mathematical models can be converted into a SIMULINK block in an easy manner. Model assessments only take a few seconds by inserting the input or known as parameters. The graph of simulated results is displayed just by double clicking scope that connected to the output.

## 2.3 VEHICLE MODEL VALIDATION

Model validation is very important for determining either the model is reliable or not. In order to produce a reliable simulation result, the simulation environment must be practical and validation of the model by using acceptable practices (Pasquier et al. 2007). Model validation should achieve at least the lowest confidence level and supported by simulation data which taken from advance vehicle dynamics simulation software.

Validation can be conducted by comparing the SIMULINK model result with the advance industry standard vehicle dynamic simulation software result. For example, in this project, it will be using the comparison between SIMULINK model results and CarSim software results. The confidence level of the model should be assessed based on the accuracy of model results relative to advance software results and repeatability under different operating conditions.

Vehicle model validation can be done by using advanced vehicle dynamics simulation software such as CarSim, Adams/Car and IPG CarMaker. This software consists of database for various types of testing and vehicle parameter. Many researchers would like to validate the vehicle model developed by using software instead of experimentation due to it is more convenience just by using computer, save cost in term of developing the real vehicle model, repeatability of testing can be carried out and etc. For example, Shim and Ghike (2007) are using the advance simulation software of