# IDENTIFICATION OF VEHICLE ROLLOVER CONDITIONS AND ACTIVE ROLL CONTROL STRATEGIES

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# IDENTIFICATION OF VEHICLE ROLLOVER CONDITIONS AND ACTIVE ROLL CONTROL STRATEGIES

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To my beloved mum and family

Thank you for all kindness and sacrifices you made for me.

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# ABSTRACT

This research presents the development of active roll control strategies to prevent vehicle rollover. The dynamic model representing the vehicle behaviour was first developed and then modelled in Matlab/SIMULINK environment. The tire model integrated to the vehicle model was represented using look up table method. The validity of the vehicle model was verified using CarSim software for double lane change and fishhook manoeuvres. The validation results show strong agreement between the vehicle model and CarSim software. Parametric study was done to investigate the effect of the driver inputs and vehicle parameters on the roll behavior of the vehicle. The effect of the variation of these properties on the vehicle roll angle and load transfer ratio was discussed. Two fuzzy logic based active roll control schemes were developed using active suspension and active front steering. For active roll control using active suspension, the effectiveness of feedforward fuzzy and combination of feedback and feedforward fuzzy in reducing the rollover propensity were evaluated. For active front steering, feedback fuzzy control was incorporated with the vehicle model to assess the performance of the active front steering in reducing vehicle rollover propensity for fishhook and step steer manoeuvres. Both of the proposed control strategies had shown significant enhancement in avoiding vehicle rollover and hence improving the safety of vehicle occupants.

# ABSTRAK

Kajian ini membentangkan pembangunan strategi kawalan gulingan aktif untuk mengelakkan golekan kenderaan. Pada permulaan kajian, model dinamik yang mewakili kelakuan kenderaan dibangunkan dan kemudian dimodelkan dalam pperisian Matlab/ SIMULINK. Model tayar digabungkan dengan model kenderaan diwakili dengan menggunakan kaedah jadual carian. Model kenderaan disahkan dengan menggunakan perisian CarSim untuk gerakan perubahan lorong dua kali dan gerakan mata kail. Keputusan pengesahan menunjukkan persetujuan yang kuat antara model kenderaan dan perisian CarSim. Kajian parametrik dilakukan untuk mengkaji kesan input pemandu dan parameter kenderaan ke atas kelakuan gulingan kenderaan. Dua skim kawalan gulingan aktif berasaskan logik kabur telah dibangunkan dengan menggunakan sistem gantungan aktif dan sistem kemudi depan yang aktif. Untuk kawalan guling yang aktif menggunakan sistem gantungan aktif, keberkesanan logik kabur suapan ke hadapan dan gabungan logik kabur maklum balas dan logik kabur suapan ke hadapan dalam mengurangkan kecenderungan golekan dinilai. Untuk sistem kemudi depan yang aktif, kawalan logik kabur maklum balas telah diperbadankan dengan model kenderaan untuk menilai prestasi sistem kemudi depan yang aktif dalam mencegah golekan kenderaan. Kedua-dua strategi kawalan yang dicadangkan telah menunjukkan peningkatan yang ketara dalam mengelakkan golekkan kenderaan dan dengan itu meningkatkan keselamatan pengguna kenderaan.

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| | | |
|---|---|---|
| ARC | - | Active Roll Control |
| AFS | - | Active Front Steering |
| DOF | - | Degree of Freedom |
| ISO | - | International Organization for Standardization |
| NCAP | - | New Car Assessment Program |
| NHTSA | - | National Highway Traffic Safety Administration |
| PD | - | Proportional Derivative |
| PI | - | Proportional Integral |
| PID | - | Proportional Integral Derivative |
| SSF | - | Static Stability Factor |
| SUV | - | Sport Utility Vehicle |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $a$ | - | Distance of sprung mass C.G. from front axle |
| $a_y$ | - | Lateral acceleration at C.G |
| $C_{sfl}$ | - | Front left suspension damping coefficient |
| $C_{sfr}$ | - | Front right suspension damping coefficient |
| $C_{srl}$ | - | Rear left suspension damping coefficient |
| $C_{srr}$ | - | Rear right suspension damping coefficient |
| $F_{afl}$ | - | Front left actuator force |
| $F_{afr}$ | - | Front right actuator force |
| $F_{arl}$ | - | Rear left actuator force |
| $F_{arr}$ | - | Rear right actuator force |
| $F_{sfl}$ | - | Front left suspension force |
| $F_{sfr}$ | - | Front right suspension force |
| $F_{srl}$ | - | Rear left suspension force |
| $F_{srr}$ | - | Rear right suspension force |
| $F_{tfl}$ | - | Front left tire force |
| $F_{tfr}$ | - | Front right tire force |
| $F_{trl}$ | - | Rear left tire force |
| $F_{trr}$ | - | Rear right tire force |
| $F_{xfl}$ | - | 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 |
| $F_{zfr}$ | - | Front right tire normal force |
| $F_{zrl}$ | - | Rear left tire normal force |
| $F_{zrr}$ | - | Rear right tire normal force |
| $g$ | - | Acceleration due to gravity |
| $h$ | - | Height of vehicle C.G. from ground |
| $I_w$ | - | Tire moment of inertia |
| $I_x$ | - | Roll moment of inertia |
| $I_y$ | - | Pitch moment of inertia |
| $I_z$ | - | Yaw moment of inertia |
| $K_{sfl}$ | - | Front left suspension stiffness |
| $K_{sfr}$ | - | Front right suspension stiffness |
| $K_{srl}$ | - | Rear left suspension stiffness |
| $K_{srr}$ | - | Rear right suspension stiffness |
| $K_{tfl}$ | - | Front left tire stiffness |
| $K_{tfr}$ | - | Front right tire stiffness |
| $K_{trl}$ | - | Rear left tire stiffness |
| $K_{trr}$ | - | Rear right tire stiffness |
| $m$ | - | Total mass of vehicle |
| $m_s$ | - | Sprung mass |

| | | |
|---|---|---|
| $m_{ufl}$ | - | Front left unsprung mass |
| $m_{ufr}$ | - | Front right unsprung mass |
| $m_{url}$ | - | Rear left unsprung mass |
| $m_{urr}$ | - | Rear right unsprung mass |
| $M_{zfl}$ | - | Front left tire aligning moment |
| $M_{zfr}$ | - | Front right tire aligning moment |
| $M_{zrl}$ | - | Rear left tire aligning moment |
| $M_{zrr}$ | - | Rear right tire aligning moment |
| $R$ | - | Tire radius |
| $S_{fl}$ | - | Front left tire longitudinal slip |
| $S_{fr}$ | - | Front right tire longitudinal slip |
| $S_{rl}$ | - | Rear left tire longitudinal slip |
| $S_{rl}$ | - | Rear right tire longitudinal slip |
| $T_{bfl}$ | - | 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 |
| $T_{dfl}$ | - | Front left wheel drive torque |
| $T_{dfr}$ | - | Front right wheel drive torque |
| $T_{drl}$ | - | Rear left wheel drive torque |
| $T_{drr}$ | - | Rear right wheel drive torque |
| $V_x$ | - | Vehicle longitudinal velocity at C.G |
| $V_y$ | - | Vehicle lateral velocity at C.G |
| $w$ | - | Track width |
| $Z_{rfl}$ | - | Front left road profile |
| $Z_{rfr}$ | - | Front right road profile |

| | | |
|---|---|---|
| $Z_{rrl}$ | - | Rear left road profile |
| $Z_{rrr}$ | - | Rear right road profile |
| $Z_s$ | - | Sprung mass vertical displacement at body C.G. |
| $Z_{sfl}$ | - | Front left sprung mass displacement |
| $Z_{sfr}$ | - | Front right sprung mass displacement |
| $Z_{srl}$ | - | Rear left sprung mass displacement |
| $Z_{srr}$ | - | Rear right sprung mass displacement |
| $Z_{ufl}$ | - | Front left unsprung mass vertical displacement |
| $Z_{ufr}$ | - | Front right unsprung mass vertical displacement |
| $Z_{url}$ | - | Rear left unsprung mass vertical displacement |
| $Z_{urr}$ | - | Rear right unsprung mass vertical displacement |
| $\alpha_{fl}$ | - | Front left tire sideslip angle |
| $\alpha_{fr}$ | - | Front right tire sideslip angle |
| $\alpha_{rl}$ | - | Rear left tire sideslip angle |
| $\alpha_{rr}$ | - | Rear right tire sideslip angle |
| $\delta$ | - | Steering angle at road wheel |
| $\omega_{fl}$ | - | Front left wheel angular velocity |
| $\omega_{fr}$ | - | Front right wheel angular velocity |
| $\omega_{rl}$ | - | Rear left wheel angular velocity |
| $\omega_{rr}$ | - | Rear right wheel angular velocity |
| $\theta$ | - | Pitch angle at the body C.G. |
| $\phi$ | - | Roll angle at the body C.G. |
| $\psi$ | - | Yaw angle at body C.G. |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Rollover is one of most life threatening crash incident compared to other type of vehicle crashes. Vehicle roll motion occurs when there is normal load transfer from the inner wheel to the outer wheel. The wheel normal load transfer is due to the lateral force that comes from severe driving inputs especially in cornering with high speed, from impact with other road vehicle, curbs, and from lamp post or sign boards. Generally, vehicle rollover may be divided to two types, namely untripped and tripped rollover. Tripped rollover takes place when the vehicle skid of the road and make a contact with obstacles such as curb and guardrail or the wheel hitting a port hole which yields a roll moment that may cause the vehicle to rollover. In contrast, untripped rollover occurs on the road under severe driving condition such as high speed obstacle avoidance test manoeuvre.

In the assessment of vehicle safety in terms of rollover resistance, the vehicle type is the plays important role. In Figure 1.1, the rollover resistance rating for different types of vehicles given that the vehicle is involved in single vehicle crash by the NCAP are presented. It can be seen that vehicles with higher center of gravity such as sport utility vehicles have lower rollover resistance rating and hence this type of vehicles are more prone to rollover. Although, the vehicle type plays main contribution in rollover, other factors such as the driver behaviour, road condition, and environment should not be neglected.

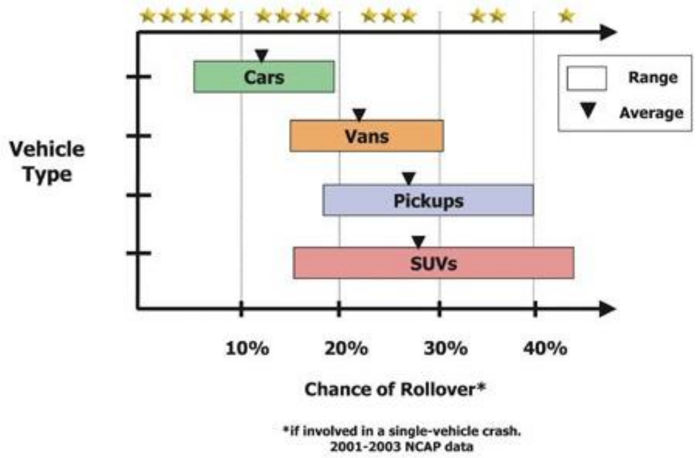


**Figure 1.1** Rollover resistance rating

In an effort to avoid vehicle rollover, passive rollover avoidance system was introduced at first. Passive rollover avoidance system is the when the vehicle detects the possibility of vehicle rollover and gives warning to the driver so that the driver could take corrective action to prevent vehicle rollover. Some of the passive rollover avoidance systems are early warning safety device (Rakheja and Piche, 1990), dynamic rollover threshold (Dahlberg, 2000), and time to rollover metric (Chen and Peng, 1999). The passive rollover avoidance system was still driver dependent. As an improvement to this, active roll control system was introduced. Active roll control system is where the vehicle detects the possibility to vehicle rollover and the vehicle itself takes the corrective to avoid the impending vehicle rollover. Various types of control system have been developed to enhance vehicle roll dynamics and prevent rollover. Active suspension (Hudha *et al*., 2008; Sorniotti and D'Alfio, 2007), active steering (Shim, T. *et al*., 2008; Ackerman *et al*., 1999), and active braking (Wielenga, 1999; Solmaz *et al*., 2006) are among the control strategies that have been investigated by the researchers to enhance the vehicle rollover resistance.

## 1.2 Problem Statement

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 skilful 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 are enable to maintain the vehicle on two wheels without allowing the vehicle to rollover but this is not possible for a normal driver. For this reason, the active roll control system should be incorporated during the development phase in automotive industry. In this thesis, two types of active roll control system, namely active suspension control and active front wheel steering will be implemented on a vehicle dynamics model to evaluate their capabilities to prevent vehicle rollover.

## 1.3 Objectives of the Research

This research focuses on the development of the vehicle roll control strategies. The two objectives of this thesis are as follows:

- To develop vehicle model and identify the conditions that cause the vehicle to rollover.

- To develop active roll control strategies based on active suspension and active front steering using fuzzy control scheme.

## 1.4 Scope of the Research

The scope of this thesis is as follow:

- Development of the vehicle model in Matlab/SIMULINK to represent the rollover behavior of the vehicle.

- Validation of vehicle model with CarSim software for double lane change and fishhook maneuvers.

- Identify the causes that lead to vehicle rollover, e.g., the driver steering wheel angle, vehicle speed, vehicle and suspension properties.

- Development of active roll control strategies:
    - Active roll control system based on active suspension using feedforward fuzzy control, and combination of feedback and feedforward fuzzy control schemes.
    - Active roll control system based on active front steering using feedback fuzzy control scheme.

## 1.5 Research Methodology

The research methodology considered in this thesis is described in Figure 1.2. First, the literature study of previous works is done on vehicle rollover, vehicle modeling, active roll control strategies and fuzzy logic control schemes. A vehicle model that is capable in accurately predicting the vehicle roll behavior is developed in Matlab/SIMULINK. The vehicle model is then validated CarSim software for double lane change and fishhook maneuvers. The vehicle responses in terms of the vehicle roll angle, roll rate, lateral acceleration, yaw rate and vehicle trajectory for both simulation of the vehicle model and CarSim software were compared to present the validity of the vehicle model used in this thesis. Parametric studies are done using the validated vehicle model to indentify the conditions that may lead to vehicle rollover. The parameters that investigated are stiffness of the suspension spring, height of vehicle center of gravity, track width, vehicle longitudinal speed, and driver steering wheel angle input. Two active roll control strategies were developed based on active suspension system and active front wheel steering using fuzzy logic control scheme. The proposed control strategies are implemented on the vehicle model and simulation test were done. The performance evaluation was carried out for both proposed control strategies.

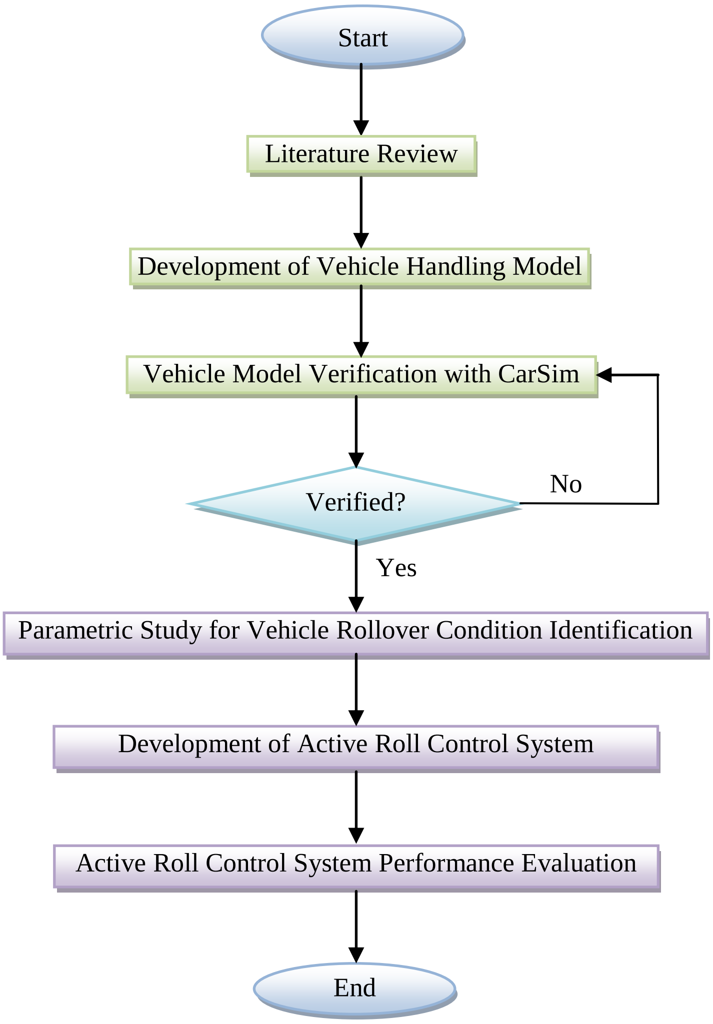


**Figure 1.2** Research procedure flowchart

The Gantt chart for Master Project 1 and Master Project 2 are presented in Figure 1.3.

| | Semester II 2010/2011 | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | W10 | W11 | W12 | W13 | W14 | W15 | W16 | W17 | W18 |
| **1.Literature Review** | | | | | | | | | | | | | | | | | | |
| a.Vehicle Rollover Review | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| b.Study on Vehicle Dynamics Modeling | | | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | |
| c.Study on Active Roll Control Strategies | | | | | | | | | | | | | | | | | | |
| **2.Development of Vehicle Model** | | | | | | | | | | | | | | | | | | |
| a.Development of Mathematical Model for Vehicle Handling | | | | | ■ | ■ | ■ | ■ | | | | | | | | | | |
| b.Development of Simulink Model for Vehicle Handling | | | | | | | ■ | ■ | ■ | | | | | | | | | |
| **3. Verification of Model** | | | | | | | | | | | | | | | | | | |
| a. Selection of Test for Vehicle Rollover | | | | | | | | | | ■ | ■ | | | | | | | |
| b. Verification of Model with CarSim Software | | | | | | | | | | | ■ | ■ | | | | | | |
| **4. Parametric Study to Identify the Conditions for Vehicle Rollover** | | | | | | | | | | | | | ■ | ■ | | | | |
| **5. Development of Active Roll Control** | | | | | | | | | | | | | | | | | | |
| a.Conceptual design of Active Roll Control | | | | | | | | | | | | | | | | | | |
| b.Implemention of Controller on Vehicle Model | | | | | | | | | | | | | | | | | | |
| **6. Active Roll Control Performance Evaluation** | | | | | | | | | | | | | | | | | | |
| **7.Project 1/2 Report Writing** | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

| | Semester I 2011/2012 | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | W10 | W11 | W12 | W13 | W14 | W15 | W16 | W17 | W18 |
| **1.Literature Review** | | | | | | | | | | | | | | | | | | |
| a.Vehicle Rollover Review | | | | | | | | | | | | | | | | | | |
| b.Study on Vehicle Dynamics Modeling | | | | | | | | | | | | | | | | | | |
| c.Study on Active Roll Control Strategies | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | |
| **2.Development of Vehicle Model** | | | | | | | | | | | | | | | | | | |
| a.Development of Mathematical Model for Vehicle Handling | | | | | | | | | | | | | | | | | | |
| b.Development of Simulink Model for Vehicle Handling | | | | | | | | | | | | | | | | | | |
| **3. Verification of Model** | | | | | | | | | | | | | | | | | | |
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| **6. Active Roll Control Performance Evaluation** | | | | | | ■ | ■ | ■ | ■ | | | | | | | | | |
| **7.Project 1/2 Report Writing** | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

**Figure 1.3** Project gantt chart

## 1.6 Organization of the Thesis

This thesis consists of five chapters. A brief outline of contents of the thesis is as follows:

**Chapter 1** presents the introduction to research which includes the background, problem statement, objectives, scope, and brief research methodology. The research procedure flowchart and gantt chart are also included in this chapter.

**Chapter 2** focuses on literature study on vehicle rollover. Firstly, previous work and passive and active rollover avoidance systems were discussed. This was followed by the discussion on the vehicle rollover detection methods and performance criteria.

The vehicle handling tests were also addressed in this chapter. Literature study on the type of control scheme implemented in active roll control strategies was included.

**Chapter 3** is devoted to comprehensive vehicle modelling and proposed control strategy description. Firstly, the assumptions made in developing the vehicle model are stated**.** This is followed by mathematical modelling of the full vehicle including non linear tire models. The vehicle dynamics tests used to evaluate vehicle rollover propensity are described in this chapter. Last but not least, the proposed rollover control strategies using active suspension and active front steering were described.

**Chapter 4** focuses on the evaluation of the active roll control strategies using active suspension and active front steering. Firstly, the validation of the vehicle model with CarSim software for double lane change and fishhook tests. Then, the performance evaluation was done on the for active roll control using active suspension and active steering.

**Chapter 5** provides summary of the research works which includes conclusion and suggestions for future research works.

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