JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING

MODELING AND SIMULATION OF ANTI-LOCK BRAKE SYSTEM ON SUPER URBAN VEHICLE

A Thesis Submitted to Jimma Institute of Technology, School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for Degree of Masters of Science in Mechanical Engineering (Design of Mechanical Systems)

By: Adugna Fikadu

September, 2021

Jimma University, Ethiopia

JIMMA UNIVERSITY

SCHOOL GRADUATE STUDIES

FACULTY OF MECHANICAL ENGINEERING

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DECLARATION

I declare that to the best of my knowledge the work presented in this thesis, entitled as "Modeling and Simulation of Anti-lock Brake System on Super Urban Vehicle" is my original work except as acknowledged in text and has not been presented by any other person for an award of degree in this or any other University.

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APPROVAL

As a member of the examining board of open defense, we have checked and evaluated the Master's Thesis prepared and presented by Adugna Fikadu entitled "*Modeling and Simulation of Anti-lock Brake System on Super Urban Vehicle*". Hereby we certify this work fulfilled the requirement of the Degree of Master of Science in Mechanical Engineering (Design of Mechanical System).

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ABSTRACT

The anti-Lock brake system (ABS) is a safety tool for vehicles to monitor wheel lock-up and modulate brake pressure to provide controlled braking under most situations. The system is subjected to unknown uncertainties caused by changing the vehicle model dynamics and road conditions which requires to development of strong control system. This paper focuses on the development and simulation of the ABS model for the SUV (Super urban vehicle) in the MATLAB/Simulink with Fuzzy logic controller and CarSim software so optimum brake performance will be obtained and progressively increasing car accidents due to sudden braking will be reduced in the country. First, the mathematical modeling of the system has been developed depending on the vehicle speed, and the slip ratio between the tire and the road conditions. Then, the Fuzzy logic control algorithm was designed and subsequently simulated with a quarter vehicle dynamic model using MATLAB/Simulink software on different road conditions, including wet, and dry, and different speeds. Finally, the simulation carried out in CarSim software interlinked with the MATLAB/Simulink and the performance of the developed controller were compared and concluded that the braking distance and vehicle stability were improved under the simulation process.

Keywords: **ABS, MATLAB/Simulink, CarSim, Dynamic Model, Simulation, Super Urban Vehicle**

ACKNOWLEDGMENT

I am grateful to my Advisor **Prof. Hirpa G. Lemu**, for continuous support, advice & contacts from the early stages of conceptual inception & through ongoing advice & encouragement to this day.

It is also my great pleasure to be grateful to my co-advisor **Mr. Iyasu Tafesse** for his much-needed encouragement, valuable comment, and suggestions.

Also, I would like to thank Jimma University, faculty of mechanical engineering, head of the department, and system of mechanical design chair for their cooperation, and facility offer on this research.

I wish to thank my parents for their continuous supporting advice and interest who inspired me and encouraged me to get here.

Last but not least I want to thank my friends, those who have been appreciating and motivating me to my work.

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LIST OF ACRONYMS

4WD	Four-wheel drive
ABS	Antilock brake system
BAI	Bishoftu automotive industry
BPD	Big pressure decrease
CarSim	Car simulator
DLL	Dynamically linked library
DOF	Degree of freedom
EBD	Electronic brake force distribution
ECU	Electronic controller unit
FLC	Fuzzy logic controller
FOSMC	Fractional-order sliding mode controller
HCU	Hydro controller unit
HPI	High pressure increase
MATLAB	MATrix LABoratory
MF	Membership function
MPD	Medium pressure decrease
MPI	Medium pressure increase
NB	Negative big
NM	Negative medium
NS	Negative small
ODEs	ordinary differential equations
PB	Positive big
PD	Proportional-derivative
PH	Pressure hold
PID	Proportional-integral-derivative gain
PM	Positive medium
PS	Positive small
SMC	Sliding-mode control
SPD	Small pressure decrease
SPI	Small pressure increase

SUV	Super urban vehicle
VS	Vehicle Sim
ZE	Zero

LIST OF SYMBOLS

A	Wheel cylinder area
A_f	Frontal area of the vehicle
c	Center Gaussian MF and
C1	Maximum value of friction curve
C2	Friction curve shape
C3	Friction curve difference between the maximum value and the value at $\lambda = 1$
C_d	Aerodynamic drag coefficient
E	Effectiveness factor
F_a	Aerodynamic force
F_r	Resistance force
F_b	Brake force
F_x	Traction force between the road and the wheel
F_z	Road reaction force acting normally on the wheel
h_{cg}	Height of center of gravity
I	Wheel's moment of inertia
m	Quarter mass of the vehicle consisting of body and wheel
P	Applied brake pressure
R	Radius of the wheel
r_e	Effective disc radius
T_b	Braking torque of the wheel
v	Longitudinal velocity of the vehicle
λ	Longitudinal Wheel Slip
μ	Friction coefficient between tire and road
ω	Angular velocity of the wheel
ρ	Air density
σ	Width of the Gaussian MF

CHAPTER ONE

INTRODUCTION

1.1. Background

The safe and reliable use of a road vehicle necessitates the continual adjustment of its speed and distance in response to change in traffic conditions. This is achieved through the design of a system that makes as efficient use as possible of the finite amount of traction available between the tire and the road over the entire range of operating conditions that are likely to be encountered by the vehicle during normal operation. Clearly the brakes, together with the steering components and tires represent the most important accident-avoidance systems present on a motor vehicle which must reliably operate under various conditions. Hence, effectiveness of any braking system is, however, limited by the amount of traction available at the tire–road interface.

There are four main stages involved in the design of a brake system. The first, and perhaps most fundamental stage, is the choice of brake force distribution between the axles of the vehicle. This is primarily a function of the vehicle dimensions and its weight distribution. Next is the design of the transmission system and this activity embraces the sizing of the master cylinder together with the front and rear wheel cylinders. Additional components, such as special valves that modulate the hydraulic pressure applied to each wheel are physically accounted for at this stage. The foundation brakes form the focus of the third stage of the process. As well as being able to react the applied loads and torques, the foundation brakes must be endowed with adequate thermal performance, wear and noise characteristics. The last phase in the process results in the incorporation of the pedal assembly and vacuum boost system into the brake system.

Nowadays, most research in automotive technology are focused on enhancing vehicle handling and stability, traveling comfort, and safety of passenger vehicles [1]. As a result, many active safety devices have been developed to assist the driver to improve the vehicle safety during dangerous conditions. Among those, Anti-Lock Braking System (ABS) is a common well-known active safety technology to control of automotive braking system.

Although, research on the antilock braking systems for a vehicle model has increased significantly because drivers are now more concerned about comfort and safety issues since, the ABS is advanced brake alert system which is important to avoid/reduce the accidents by percentage by giving the advanced light indications prior to fatal accidents.

With the rapid development of automobile industry in Ethiopia, the vehicle has become the most important means of transportation in today's society. Even though several automotive industries available in our country, Bishoftu automotive industry is a company that plays an important role in the further development of automotive technology. It is a developing industry that starts manufacturing of engine, transmission system, and manufacturing of sheet metal parts followed by the final assembly, painting, and testing [2]. The company has been playing a very important role in assuring the transformation plan in the industry sector and still there are a lot of its production consequences that need to be improved. In addition, some of the spare parts are also being imported from abroad and assembled at this company and the most important issue is to know how to improve the safety and reliability of their products with the environmental parameters.

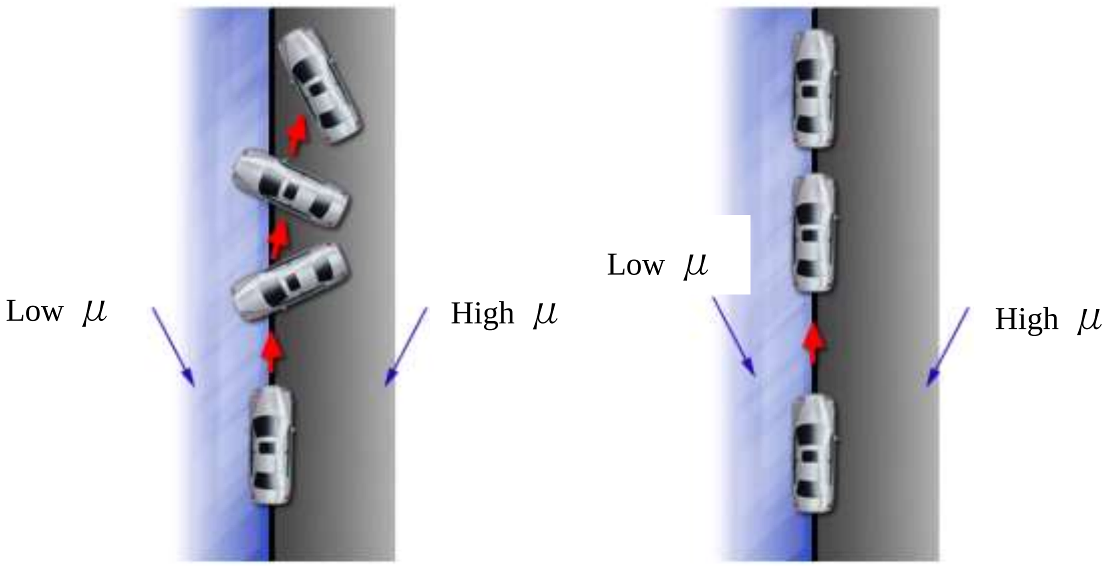
Generally, there is no action being taken in our country by the researchers or automotive companies concerning passenger safety in terms of the prevention of accidents that occur by sudden locking of the wheel while applying the emergency brake of a vehicle in motion at high speed, and reducing to the accidents happening daily.

Under braking, if one or more of a vehicle’s wheels lock (begins to skid) then few consequences occur like braking distance increases, steering control is lost (skidding takes place) and tire wear will be abnormal.

A skidding wheel (where the tire contact patch is sliding relative to the road) has less traction than a non-skidding wheel. Mainly, the front wheel locking will cause loss of vehicle steering force while the rear wheels locking will make the vehicle slide sideways and tail-flick. So, wheel lockup is undesirable since it prolongs the stopping distance and causes the loss of direction control.

Therefore, preventing wheel locking-up during the emergent braking process is extremely important and ABS becoming standard equipment to prevent injuries and damages, that automotive designers should pay attention to improve vehicles braking system. It provides vehicle stability until it stops (as illustrated in Figure 1(a)). The braking action with and without ABS is shown in Figure 1. In Figure 1, while taking a curve, the car without ABS goes off course while the one with ABS stays on course. When a part of the vehicle without ABS is on a slippery surface and the brake is applied, the vehicle spins while the vehicle with ABS stays on course.

The conventional friction (as illustrated in Figure 1) braking system must be retained and works together with the ABS since it can effectively enhance the driving stability, reduce the braking distance, and to some extent, prevent the accident from happening. If the vehicle on the different conditions of surface brakes, the wheels on the slippery surface easily lock up and the vehicle begins to spin. In such conditions ABS provides vehicle stability until it stops (as shown in Figure 1. Some advantages of ABS are: It allows the driver to maintain directional stability and control over steering during braking, safe and effective; automatically changes the brake fluid pressure at each wheel to maintain optimum brake performance, and it absorbs the unwanted turbulence shock waves and modulates the pulses thus permitting the wheel to continue turning under maximum braking pressure. While it also has some dis-advantages like it is very costly and maintenance cost of a car equipped with ABS is more.



a) Without ABS *b) With ABS*

Figure 1: Braking on straight and slippery road; without ABS and with ABS [3]

To overcome the wheel-lock up problem, this paper will conduct a detailed study of control strategies of ABS for automotive vehicles and propose an effective controller, that can make the simulation results more accurate. Simulation of any physical system plays an important role in analyzing the behavior of the system under certain applied conditions. Simulation is the imitation of the operation of a real-world process or system over time [4]. It is used to model, analyze, and simulate dynamic systems using block diagrams. This paper focuses on the development and simulation of the ABS model in the MATLAB/Simulink and CarSim softwares and comparison of the results obtained from both the software's. The proposed algorithm allows an easier and more direct selection of the wheel-slip cycling range and, consequently, to reduce the braking distance.

And also, it focuses on the analysis of whether ABS is effective in reducing accidents in Ethiopia, and some simulations will be conducted to examine the performance of the proposed control system for tracking the reference wheel slip in the presence of uncertainties in different maneuvers.

In this work, the SUV (super urban vehicle) which is being manufactured in Bishoftu automotive company's dynamic modeling and parameterization has been carried out. Then, the detailed explanation of the ABS with fuzzy logic controller as well as the control method description has been presented. Then, the control results for dry and wet road adhesion have simulated. Finally, the performance of the designed controller has been validated with CarSim and also compared with the related paper results to determine the performance of the designed controller.

1.2. The Problem of Statement

Overall, the accident due to the car crash is getting worse from time to time, approaching a crisis level, and requiring urgent and multi-pronged actions. Though, most of research and development in automotive technologies are focusing on enhancing vehicle handling and stability, traveling comfort, and safety of passenger vehicles. In contrary, in developing country like Ethiopia, more action is needed to address the problem through further research concerning the accidents that occur due to wheel lock during the sudden braking.

When the amount of braking force applied to the wheel exceeds, the static friction generated between the tire and the surface which causes wheel locking. The wheel locking causes loss of vehicle steering force and instability of the vehicle which increases the braking distance of the vehicle and finally may cause accidents. And, Wheel slip is avoided by releasing braking pressure just before wheels are lock up and then re-applying same which needs pressure modulation. The sudden locking of the wheel while applying the emergency brake of a moving vehicle is the critical issue that needs to be investigated. So far, many automotive industries are very conservatives in adopting modern technology performing all the assembly and production of automotive parts and proportionate action is not being taken to address the wheel locking problem. Also, due to high non linearity in the model it is not possible to use the classical controls on the car braking problem. ABS technology is the most recent development in enhancing passenger safety and effective in reducing accident which is happening daily and ABS with fuzzy logic controller can achieve the required goal. For this reason, this study focuses on SUV which is being assembled/manufactured in Bishoftu automotive industry that makes it important as well as challenging work. Based on the relation between the slipping ratio and the road coefficient of friction fuzzy logic control is used to achieve the main aims in steerability, stability, and the shortest stopping distance by keeping the friction between the tire and the road as maximum as possible during different operation and road conditions.

1.3. Objective

1.3.1. General objective

The objective of this study is to model and simulate the dynamic model of super urban vehicle (SUV) with effective antilock brake system.

1.3.2. Specific objective

The specific objectives of this study are the following: -

i. To conduct a detailed study of control strategies of ABS for automotive vehicles
ii. To develop a suitable and robust control strategy, using fuzzy logic control strategy.
iii. To analyse the effectiveness of the developed ABS controller using CarSim software

1.4. Material and Methods

This study uses a case study of the super urban vehicle (SUV) which is actively being manufactured/assembled in Bishoftu Automotive Industry. Both primary and secondary data collection mechanisms are used in this work (attached in Appendix A). Firstly, study of literatures about controller designs and theoretical backgrounds about antilock braking system were undertaken. After a good understanding of the system and controllers from the literatures, various controller performances were compared and then an appropriate technique is selected to improve the shortcomings of the system.

Since, MATLAB/Simulink and CarSim simulation are widely used simulation software for analyzing the performance of the different components, the simulation is carried out for Anti-lock braking system by above two mentioned softwares (i.e., MATLAB/Simulink and CarSim).

Proper modelled dynamic equation of a vehicle has a vital role in controlling of a system, and the modeling has two phases in this study. The first phase is, the mathematical dynamic models of the vehicle which was developed by using Newton's second law of motion. The necessary steps involved in modeling are writing the equations with each variable, sorting these equations, and implementing them in a solver. The developed mathematical background of the ABS and fuzzy logic control were applied and MATLAB/Simulink model is developed for the same and corresponding results are obtained. Further the CarSim simulation model for the complete vehicle ABS is developed for hatchback Super Urban Vehicle (SUV) and model is simulated by applying certain conditions. Finally. the results are compared with the Matlab/Simulink model which is developed for single wheel of the vehicle.

1.5. Significance of the study

During braking a vehicle on move, one or more of a vehicle's wheels lockup and begins to skid which is undesirable because of it prolongs the stopping distance and causes the loss of direction control. This is the main issue of progressively increasing car accidents throughout the country. in order to overcome this problem, this work will conduct a detailed study of control strategies of ABS for Super urban vehicle.

1.6. Organization of the thesis

Following this introduction section, the thesis is organized into five chapters. First, a brief overview of backgrounds of antilock brake system found in commercial vehicles and control methodologies are presented in Chapter 2 followed by review of literature on application of control system on vehicle brake system modelling such as classical PID control and intelligent control systems using fuzzy logic are presented in Chapter 3.

Chapter 4 describes the mathematical model for the vehicle dynamics and controlling mechanism. Furthermore, a detailed explanation of the assumptions involved along with the methodology adopted has been presented. This chapter is also dedicated to the design of the control system (i.e., fuzzy logic controller). Then the results obtained from the modeling are discussed in Chapter 5 and finally key conclusions of the study and recommendations are given in Chapter 6.

CHAPTER TWO

OVERVIEW OF ABS AND DESIGN METHODOLOGIES

2.1. Introduction to brake system

Braking has a crucial role in the vehicle, in which kinetic energy is converted into heat energy to slow down a vehicle in motion [1]. In braking system, the three separate functions must be fulfilled at all times; (1) it must decelerate a vehicle in a controlled and repeatable fashion and when appropriate cause the vehicle to stop, (2) it should permit the vehicle to maintain a constant speed when travelling downhill and (3) it must hold the vehicle stationary when on the flat or on a gradient.

In Conventional, brake system uses friction, to convert kinetic energy into heat and suffers from problems in terms of time taken for building up of pressure, thermal failure of the braking system during contract movement, limitation of braking performance at high speed, noise and brake pad wear which can be alleviated by the use of electromagnetic damping to replace pneumatic damping.

The brake systems can be categorized as mechanical, electric, hydraulic and power brake system based on the actuation methods.

Mechanical brakes use mechanical elements like levers or linkages to transmit force from one point to another, while electric brakes are actuator devices that use an electrical current or magnetic actuating force to slow or stop the motion of a rotating vehicle.

The hydraulic brake is an arrangement of braking mechanism which uses brake fluid. specially ethylene glycol to transfer pressure from the controlling unit to the actual brake mechanism of the vehicle. Hydraulic brake systems are used in passenger cars, while commercial vehicles such as buses are equipped with air brake systems [5]. The hydraulic brake system works based on the pascal’s law which states that the pressure at a point in the fluid is equal in all directions i.e., equal braking action on all wheels.

The other type of brake system is power brake system in which power of engine or battery is used to enhance the braking effort. The brake system that uses the engine power are like vacuum brake system and air brake system.

The operation of air brakes is similar to hydraulic brake except that compressed air is used to apply brakes instead of hydraulic pressure. Air brakes are commonly used on heavy vehicles like trucks, buses etc. A typical air -brake system basically consists of brake valves, a pressure control valve (PCV), and wheel cylinders. Nowadays, hydraulic and air brake systems are common among the four wheel and above vehicles.

2.2. Brake system components and configurations

The principal components that together comprise a conventional braking system are outlined below together with possible brake system layouts, as illustrated on Figure 2. The discussion of the components begins with the pedal assembly and moves through the brake system finishing with the foundation or wheel brakes.

2.2.1. Pedal assembly

A brake pedal consists of an arm, pad and pivot attachments. The majority of passenger cars make use of hanging pedals. A linkage is connected to the pedal and this transmits both force and movement to the master cylinder.

2.2.2. Brake booster

The brake booster serves to amplify the foot pressure generated when the brake pedal is depressed. This has the effect of reducing the manual effort required for actuation. Boosters are invariably combined with the master cylinder assembly. A vacuum booster employs the negative pressure generated in the intake manifold of a spark ignition engine whereas a hydraulic booster relies upon the existence of a hydraulic energy source and typically finds application in vehicles powered by diesel engines that generate only a minimal amount of intake vacuum.

2.2.3. Master cylinder

The master cylinder essentially initiates and controls the process of braking. The governing regulations demand that passenger vehicles be equipped with two separate braking circuits and this is satisfied by the so-called tandem master cylinder. A tandem master cylinder has two pistons housed within a single bore. Each section of the unit acts as a single cylinder and the piston closest to the brake pedal is called the primary piston whilst the other is called the secondary piston. Thus, if a leak develops within the primary circuit, the primary piston moves forward until it bottoms against the secondary piston. The push rod force is transmitted directly to the secondary piston through piston to piston contact thus allowing the secondary piston to pressurize the secondary circuit. Conversely, if the secondary circuit develops a leak, then the secondary piston moves forward until it stops against the end of the master cylinder bore. This then allows trapped fluid between the two pistons to become pressurized and so the primary circuit remains operative.

2.2.4. Regulating valves

The dynamics of the braking process gives rise to the need for some means of reducing the magnitude of the brake force generated at the rear of a vehicle under the action of increasing rates of deceleration. This need arises from the load transfer that takes place from rear to front during any braking event. This function is realized through the incorporation of some form of brake pressure regulating valve into the rear brake circuit. The exact nature of the valve depends upon the detail design but they fall into three generic types:

Load sensitive pressure regulating valve: Valves of this type are fitted to vehicles that experience large in-service changes in axle load. The valve is anchored to the vehicle body and is also connected to the rear suspension through a mechanical linkage. This permits the valve to sense the relative displacement between the body and suspension and adjust the valve performance to effect control over the rear line pressure and so enable the rear brakes to compensate for the change in axle load;

Pressure sensitive pressure regulating valve: Otherwise known as a pressure limiter, this type of valve isolates the rear brake circuit when the line pressure exceeds a predetermined value. They find application on vehicles that are characterized by a low center of gravity and a limited cargo volume;

Deceleration sensitive pressure regulating valve: This class of valve finds wide application. The actuation point is determined by the rate of deceleration of the vehicle and this is typically, of the order of 0.3g. A benefit of this type of valve is that it does provide for a degree of load sensitive operation as the overall deceleration of the vehicle is a function of the vehicle weight and the line pressure.

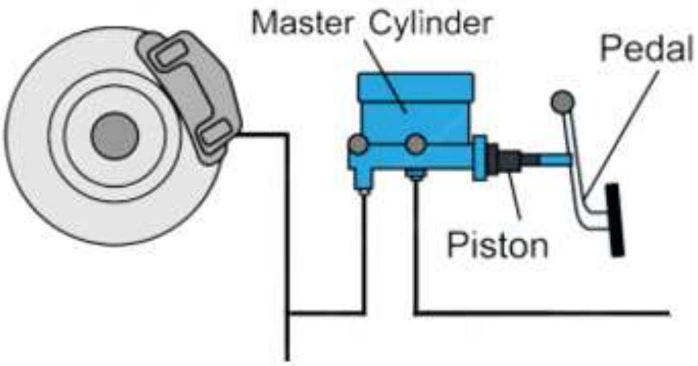


Figure 2: Layout of hydraulic brake system on single wheel [6]

They are also sensitive to braking on a slope. Mathematical models of this class of valve are developed later in the text and their influence on the performance of a brake system is demonstrated.

2.3. Brake system layouts

Among the five possible configurations of the brake system layouts, two have become standard and these are known as the II and X variants shown in Figure 3. The II design is characterized by separate circuits for both the front and rear axles whilst in the X configuration, each circuit actuates one wheel at the front and the diagonally opposed rear wheel. The II design is often found on vehicles that are rear heavy and the X layout has application on vehicles that are front heavy.

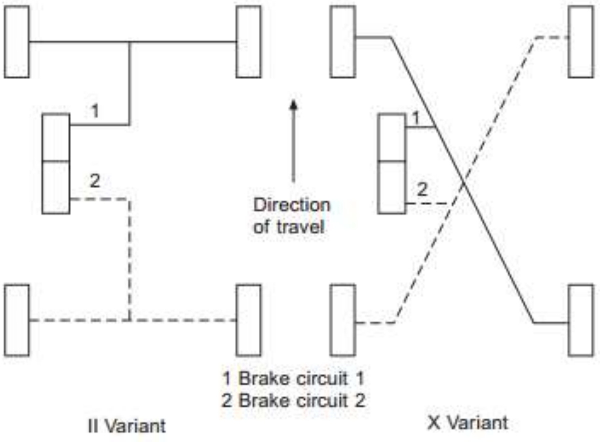


Figure 3: Common brake layouts

2.4. Antilock Brake System

It is obvious that efficient design of braking systems is to reduce accidents. Vehicle experts have developed this field through the invention of the first mechanical antilock-braking system (ABS) system which have been designed and produced in aerospace industry. Antilock brake system (ABS) is a device that regulates the wheel slip ratio to maximize the braking force and to maintain the directional stability. ABS only activate when wheels are about to lock up and does not necessarily shorten the stopping distance, but it does helps to keep the vehicle under control during hard braking. Nowadays, antilock brake systems are employed in many passenger cars, while a limited number of commercial vehicles are equipped with such systems. However, since commercial inter-state buses take a large number of people on board, more attention should be paid to their safety.

2.4.1. Wheel locking

From 0% to approximately 20% (equivalently 0.2) longitudinal slip, the magnitude of the brake force coefficient increases in a roughly linear fashion to its maximum value, μ_p . Due to increase in applied brake torque, the wheel decelerate rapidly to a condition of full lock and the brake force coefficient takes a value of μs at 100% longitudinal slip, i.e. the wheel torque produced by the adhesive force is not enough to overcome the brake torque generated by the brake system [7]. The ratio of peak to full lock brake force coefficient (i.e., μ_p/μ_s) depends upon the nature of the road surfaces whether it is dry, wet or icy. When the lock of the wheel is total (λ=1), vehicle steering control and stability diminishes, and the braking distance normally increases. In order to overcome this situation, braking control system is used to maintain the slip ratio within the values which obtain the maximum adherence coefficient.

If the wheel velocity is zero, the wheel slip will be the maximum. It means that the wheel is locked. However, if the wheel velocity is increased, the wheel slip will equal zero and the tire starts to roll freely (as illustrated in introduction section, Figure 1). In order to preserve this, various ABS control mechanisms have been advanced since the 1950’s [8].

In order to prevent the rear wheel locking due to the car side slip or even drift phenomenon, usually using electronic brake force distribution (EBD) control method is used in addition to ABS [9]. EBD uses electronic technology to replace the traditional proportional valve to control the vehicle hydraulic braking system before and after the bridge braking force distribution.

ABS was introduced in aircraft technology to reduce the stopping distance of an aircraft and it was too expensive for road vehicles. But nowadays, it is being commonly installed feature in road vehicle to improve their ability to steer while braking heavily and of reducing stopping distances on some surfaces. It is amongst the first of the high-technology in-car devices that have been or are being developed to assist drivers.

This report [8] also stated that development of safety systems has become a main concern in the automotive industry as a result of the increase in vehicle accidents and the system do not only secure the driver, but they also protect pedestrians. In their report they have also emphasized that front tire locking causes an oversteer phenomenon, whereas rear tire locking introduces understeer which might spin the car around and as only ABS enables the driver to steer the vehicle when the brake is abruptly applied, therefore keeping the vehicle safe and stable.

Anti-lock brake system technology is now given high priority for the ground vehicle design is because of its capability to help drivers to stop their vehicles in a shorter distance safely [10]. Stopping distance is the function of vehicle mass, its initial velocity and the braking force. Stopping distance can be minimize by increasing in braking force (keeping all other factors constant) [11]. In all types of road surface there is always exists a peak in friction coefficient. An antilock system can attain maximum fictional force and results minimum stopping distance.

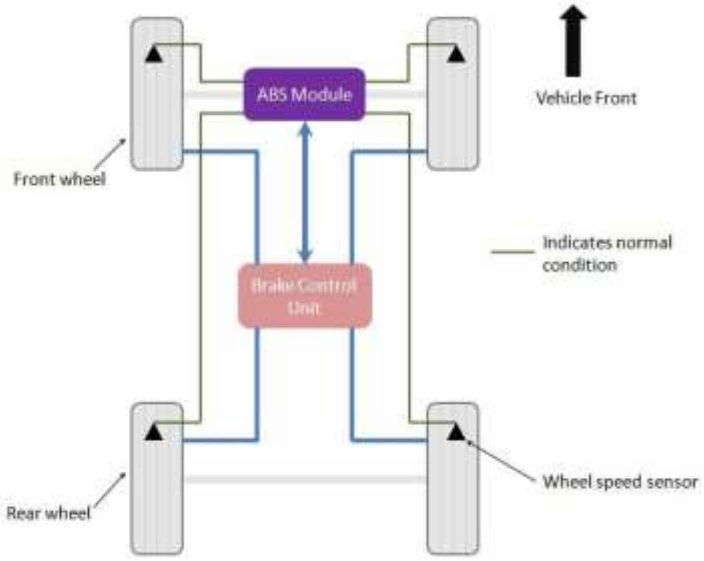


Figure 4: Schematic diagram of Antilock brake system[12]

The two major cases involved in the design of a practical braking control algorithm are [13]: Primarily, ABS control is a highly a nonlinear control problem due to the complicated relationship between friction and slip as the result of time varying parameters and Uncertainties.

The second issue is that the performance depends highly on the knowledge of the tire-road surface conditions. Consideration of the various conditions under which the brakes must operate leads to a better control of their role.

2.4.2. Components of Antilock brake system

Anti-lock braking systems consist of speed sensors, an electronic control unit and pressure control valves. The braking pressure in each brake cylinder is reduced or held constant as necessary. The speed sensor determines the wheel's rotation speed, which the electronic control unit converts into vehicle speed (reference speed). Microprocessors in the control unit use the speed and reference speed to calculate the slip on each individual wheel.

To monitor or calculate state variables need in the process, the typical vehicle ABS system includes the following hardware components:

Controller - This is one of the vehicle’s microcomputers. It is programmed with the algorithm that reads the current state variables, and determines the required pressure at each wheel and sends the appropriate signals to the brake pressure modulator receiving signal from the speed sensors and controls the valves.

Wheel Speed Sensors - A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. In case of brake system, anti-lock braking system needs some way of knowing when a wheel is about to lock up. The speed sensors, which are located at each wheel, or in some cases in the differential provide this information.

Electronic Control Unit (ECU) - The work of ECU is to receive, amplifies and filter the sensor signals for calculating the speed rotation and acceleration of the vehicle. ECU also uses the speeds of two diagonally opposite wheels to calculate an estimate for the speed of the vehicle. The slip of each wheel is obtained by comparing the reference speed with the individual wheel.

Brake Pressure Modulator - This component (or components, depending on the system) controls the wheel brake pressure according to the control conditions specified by the ECU.

Brake Master Cylinder - This component provides the fluid/air pressure source.

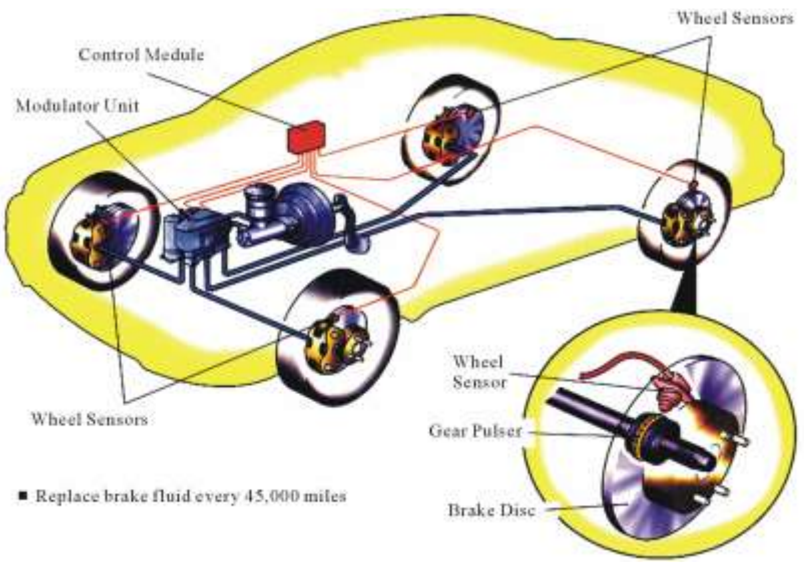


Figure 5: Layout and components of ABS [14]

Brake Wheel Caliper/Cylinder/Chambers - These components apply the braking force at each wheel according to the wheel brake pressure. The basic hardware requirements are generally the same for all vehicle types, ranging from passenger cars to on-highway trucks.

2.4.3. How ABS Works?

The ABS starts working after driver pushes the brakes due to which the hydraulic system is pressurized so as to squeeze the brake pads against the disc causing the car to stop and ABS detects the application of the brakes on all four wheels through the sensors. If the ABS detects some fluctuation among wheels during brakes then it subsequently reduce or increase the pressure by opening the pressure release valve to overcome the slippage [15]. The speed sensor senses when that wheel is going to lock up and the outputs of the wheel cylinder pressure is controlled with the help of anti-lock brake control module (ECU) by closing the normally open solenoid valves for that wheel. The ECU collects the signals from all the wheel sensors & compute the acceleration or retardation of an individual wheel. From this information, the brake pressure to one or more of the wheels is controlled i.e., the brake pressure can be reduced, held constant or allowed to be increased. Once the locked wheel comes back up to the speed, then the control module returns the solenoid valve to normal condition.

2.4.4. Types of ABS

Based on the numbers of sensors used, the antilock brake system can be categorized as; single, two, three or four channels.

Single channel

This system is found on pickup trucks which use rear-wheel ABS. It has one valve and one sensor for both of the rear wheels and control its pressure. This system is not very effective because as there is a possibility that one of the rear wheels will lock, reducing the effectiveness of brakes.

Two channels

This system works with four sensors and two valves. It uses speed sensors at each wheel, with one control valve for both of the front wheels and the other one for the rear wheels.

Three channels

Three-channel comes with two combinations, one is three-channel with four sensors and the other one with three-channel and three sensors. In three-channel and four sensor schemes, along with the four sensors on each wheel, there is a separate valve for each of the front wheels and a common valve for the rear wheels.

This type of sensor schemes is mostly employed in pickup trucks with only one sensor for the rear axle. There are individual sensors and valves for both the front wheels with a common valve and sensor for both of the rear wheel. This type is generally used for FR (Front engine Rear driving) car which has H-brake lines.

Four channels

This type is generally used for FF (Front engine Front driving) car which has X-brake lines. Front wheels are independently controlled and rear wheel control usually follows a select-low logic for vehicle stability while ABS operation. Which means, wheel speed sensors and valves monitor each wheel speed. With this setup, the controller also monitors each wheel individually to make sure it is achieving maximum braking force. Most modern cars like Ferrari & Lamborghini uses four channel system. This gives the best result as all the four wheels can be controlled individually which ensures the maximum braking force. As the currently available ABS models are developed by applying different control methods, it has certain disadvantages like the model developed is only for the single wheel.

2.5. Typical ABS Control Strategies

Several approaches and constant improvements are still being released in newer versions of ABSs. The various control algorithms existing in the literature can be categorized as threshold control, PID control [2], adaptive control [16, 21], feedback control [18] sliding-mode control (SMC) [19] and intelligent control such as fuzzy logic [4,8], genetic algorithms and neural networks [20] have been reported in the literature to optimize the ABS performance.

2.5.1. Threshold Control

It is a simple control method that has been widely applied in the early ABS versions. It usually uses wheel acceleration and/or wheel slip as controlled variables and defines threshold values, above/below which the pressure should be increased, held or decreased [19]. This parameter provides a minimum system pressure threshold for ABS actuation. ABS is bypassed when the system pressure is below this value.

2.5.2. PID Control

A controller with three terms in which the output is the sum of a proportional term, an integrating term, and a differentiating term, with an adjustable gain for each term. Due to its simplicity makes it simplicity to understand, design/tune, implement, and is easy to maintain it has been used for many years to in designing ABS. The longitudinal slip of ABS is verified based on three types of controllers such as P, PI and PD controllers.

In ABS development, P controller produces maximum overshoot with a long settling time and steady state error occurs. Meanwhile, I controller can reduce the steady state error of the wheel slip due to slow response behavior but, this can increase the maximum overshoot of longitudinal slip.

When both controllers merged, PI controller is obtained whereby the settling time of system is similar with no steady state error but higher overshoot. In order to reduce the maximum overshoot, PD controller is used due to its fast response action. Again, this may increase the settling time and steady state error. Hence, combination of three of them, PID controller achieve this goal and proposed as ABS controller. The parameters of PID controller can be tuned by using trial and error method. The PID controller is simple in design but there is a clear limitation of its performance. It does not perform enough robustness for practical implementation.

2.5.3. Sliding Mode Control (SMC)

Slide mode control (SMC) is the robust controlling approach among the ABS controlling mechanism and it requires only the bounds of uncertainties [20]. Its design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. Sliding-mode controller regulates the wheel slip, depending on the vehicle forward velocity. Th typical SMC design consists of two stages: sliding phase design and reaching phase design [17]. Usually, a hyperplane, namely, sliding surface, is fist designed to provide the desired behavior for the closed-loop system during sliding mode. Th sliding surface is also considered to be the switching condition during the reaching phase design that employs a discontinuous control law to force all the trajectories to reach the sliding surface and remain on it.

2.5.4. Intelligent Control

The intelligent control are such as fuzzy logic [7], genetic algorithms and neural networks. The fuzzy control is a controlling mechanism in which mathematical model of the system does not needed. In this method, the actual target pressure value is output to the braking system. And then the target vehicle braking torque is obtained through the hydraulic pressure system and brake operation. At the same time, the actual slip rate of the car is calculated by the detection device, which is the input to the fuzzy controller. Then actual slip rate is set in the desired slip rate error through the fuzzy logic controller to calculate the pressure and there is feedback to the braking system in order to get a good braking effect and handling stability. In these works, fuzzy logic controller was introduced. The major features in the proposed fuzzy control system are: its robustness to modeling errors and disturbance rejection capabilities, it provides optimal brake torque for both front and rear wheels; and also, it provides required amount of slip and torque references properties for different kinds of roads.

Above all, controlling mechanisms is to reduce stopping distances, to improve stability, and to improve steerability during braking. It also, needs to maintain controller real-time performance and reduce system cost, a simple but robust algorism is developed.

The braking distance highly depends on the mass of the vehicle, the initial velocity, and the braking force. By maximizing the braking force, the stopping distance can be minimized keeping all other parameters are constant. Since, on all types of surfaces, there exists a peak in friction coefficient by keeping all of the wheels of a vehicle near the peak, an antilock brake system can attain maximum frictional force and, therefore, minimizes stopping distance.

If more braking force is obtained on one side of the vehicle than on the other side this leads or maximum braking force on both side of the wheel can be formed and leads the vehicle to yaw moment which pulls vehicle to sideways due to high friction and this contributes for vehicle instability. This can be managed through antilock braking system by maintaining the slip of both rear wheels at the level where the lower of the both friction coefficients peaks, and lateral forces will be reduced.

Peak frictional force control is necessary in order to achieve satisfactory lateral forces, stability of the vehicle and also steerability. Steerability while braking is important for the possible of steering around an obstacle and tire characteristics play an important role in the braking and steering response of a vehicle. Tire traction forces and side forces formed when a difference exists between the speed of the wheel and the speed of the vehicle relative to the road surface.

2.6. CarSim Model

CarSim is a commercial software package that predicts the performance of vehicles in response to driver controls (steering, throttle, brakes, clutch, and shifting) in a given environment (road geometry, coefficients of friction, wind). The models simulate physical tests to allow engineers to view results that are similar to test results, but which can be obtained repeatably, safely, and much quicker than is possible with physical testing. The simulation models are often used to evaluate vehicle designs that have not yet been built. Results are visualized via animation, plotted for analysis, or exported to other software for analysis using the same methods that are applied to physical test data.

CarSim input data is stored in a number of simple text files that are intended to be user-friendly and reasonably intelligible without consulting a software manual. The top-level text file is called the simfile, and it contains the information necessary for the VehicleSim (VS) Solver to simulate the requested event(s). The VS Solver is a dynamically linked library (DLL) file that uses numerical integration techniques to solve the numerous coupled ordinary differential equations (ODEs). Depending on the type of event being simulated, CarSim can also interact with an external Simulink model.

CHAPTER THREE

REVIEWED LITERATURES

To avoid wheel locking, many ABS controller design methods have been proposed by researchers since 90s and the antilock braking technology is constantly improving and upgrading. Most previous studies have been essentially univariate, comparing the number of accident-involvements of paired groups of cars, one group being ABS-equipped, and the other not. And also, mostly they deal with quarter car models due to the complexity and much time-consuming. In general, a considerable amount of works has been carried out to solve the problem of the vehicle braking system.

Consequently, ABS devices have become essential equipment of automobiles [7] intending to maximize tire-road braking forces and prevent each wheel from being locked-up during braking of a vehicle. Several papers described the methodology for the ABS simulation and many researchers have contributed to the development of ABS so that it can reduce the accident with different hypotheses. The objective of ABS is to manipulate the wheel slip so that a maximum friction is obtained and the steering stability (also known as the lateral stability) is maintained.

The combination of hydraulic, mechanical, and electrical and electronic components, a wide range of controllable braking systems have been developed [1]. This system consists of a set of components (as shown in Figure 3) that work together to reduce a vehicle’s speed until it stops [8].The mechanical components are a pedal, master cylinder, disc, pads and tires. The electronic parts are sensors, actuators and a controller.

The antilock braking system is suitable for dangerous braking conditions such as braking on icy or wet asphalt road or for panic braking situations [15]. The friction coefficient between the tire and the road can vary in a very wide range, depending on factors like road surface conditions (dry or wet), tire side-slip angle, tire brand (summer tire, winter tire), vehicle speed, and the slip ratio between the tire and the road [21]. The controller recognizes the road surface to maintain energy-efficient and safe braking performance for a specific road.

Among recent researchers, [22] is one who has contributed ABS that has been fitted to four-wheel drive to prevent the lockup of vehicle wheels during hard braking, has been demonstrated effectively in numerous track tests. Another researcher [23] also investigated that antilock brakes appear to affect crash experience on dry as well as slippery road surfaces.

Dry road crash experience cannot be a guarantee as an exposure measure for evaluating antilock effectiveness. It should be evaluated on both dry and slippery roads since the effect of antilock on slippery and dry surfaces-antilock appear to increase fatal crashes in both cases. The study in [24] indicates that ABS can reduce stopping distances, especially on low adhesion surfaces; improve lateral stability and ability to keep within lane during braking on curves; and improve steering, stability and average braking decelerations in lane-change and braking maneuvers on slippery roads. In recent years ABS based on the slip ratio control algorithm has much attention because of its better control performance. The main objective of the slip control is to regulate wheel slip at its optimum value for ensuring that the vehicle braking system has a maximum tire-road friction.

3.1. ABS Control mechanism

This slip ratio control algorithm is programmed with the algorithm and became ABS controller in order to read the current state variables, and determines the required pressure at each wheel and sends the appropriate signals to the brake pressure modulator receiving signal from the speed sensors and controls the valves. So, controller is the crucial part among the components of ABS which needs more investigation so that the desirable goal is achieved.

Many theoretical studies have been conducted on slip ratio control algorithms, and these control algorithms have improved the response time and received the better slip ratio tracking performance, and still, there are some limitations in these algorithms which needs further research. Among the several approaches and constant improvements that are being released as a newer version of ABSs, some of them are summarized as follows:

3.1.1. Classical control based on PID control

PID control are classical control methods, inexpensive and has been widely applied in recent versions of ABS.

The report of [20] proposed another controller so-called a multiple surface sliding controller for an anti-lock braking system to maintain the slip ratio at the desired level. The uncertainty estimation technique called the inertial delay control for various types of uncertainties coming from unknown road surface conditions, the variations in normal force, and the mass of the vehicle. As a result, the slip ratio was maintained at the desired level under various scenarios without having to make any change in the control parameters. Since road conditions are timevariant during the braking process, or different at the bilateral wheels, braking stability performance is likely to be reduced, and [25] developed a practical identifier of road variations to enhance the braking performance collaborating with ABS controller.

Also, [26] states in the report that in cars fitted with ABS, firm brake pedal pressure activates the ABS, which in turn prevents skids by mechanical regulation of brake pressure. This means that ABS reduces brake pressure each time a wheel lockup is imminent, and it does it many times per second to avoid wheel lockup [27]. It is an electronically controlled braking system (as illustrated in Figure 3) that maintains control over the directional stability of the vehicle during emergency braking or braking on slippery roads by preventing wheel lock-up [15].

In [16] research it has been indicated that, when a braking torque is applied to the tire, it produces a tension at the tire tread within the contact patch which makes the tire travels more distance than it would during pure rolling.

The PID controller is simple in design but there is a clear limitation of its performance. It does not have enough robustness for practical implementation.

3.1.2. *Robust Control based on sliding mode control*

Sliding mode control is an important robust control approach and their characteristics are shown in [28], [29]. Design of fractional-order sliding mode controller (FOSMC) is proposed [30] for ABS to regulate the slip to the desired value. The proposed controller anticipates the upcoming values of wheel slip and takes the necessary action to keep the wheel slip at the desired value. But still, there exist some unsolved problems in the work reported in this paper because vehicle model dynamics are highly nonlinear; model parameters vary over a wide range due to variations of road and vehicle conditions such as road surface, mass, and center of gravity of the vehicle.

In design of sliding mode control, as the work of [31], system control law requires switching at an infinite frequency because, the actuators have time delays and other imperfections, the action can lead to chattering. Chattering is undesirable, since it involves extremely high control activity, and furthermore may excite high-frequency dynamics neglected in the course of modeling [32]. Chattering must be reduced (eliminated) for the controller to perform properly.

3.1.3. Intelligent Control based on fuzzy logic control

Fuzzy logic controller effective methods, In other works of [4, 6] it is reported that, the genetic Algorithm adjusted Fuzzy Controller causes chattering and does not seem suitable to control wheel slip since the stability of the vehicle system with a fuzzy controller is unclear under uncertainty conditions. In some researches it has been proposed that fuzzy logic control design methods can be done based on other controllers like, sliding-mode control (SMC), PID, and genetic algorithm scheme as well. For instance, in the work of [10], it was investigated that a neuro-fuzzy adaptive control approach for nonlinear systems with model uncertainties, in antilock braking systems. The control scheme consists of a PD controller and an inverse reference model of the response of the controlled system. In this work, the brake pressure is kept just below the point of causing a wheel to lock, ensures that maximum braking power is used to stop the vehicle which in turn gives rise to shorter stopping distances on the slippery road. Its output is used as an error signal by an online algorithm to update the parameters of a neuro-fuzzy feedback controller.

After the study of several published papers on anti-lock braking system, with a different control method, this study will propose an option of using the fuzzy logic control strategy can make the simulation results more accurate. The major features in the proposed control system are that it provides optimal brake torque for both front and rear wheels; and provides required amount of slip and torque reference properties for different kinds of roads. The proposed algorithm allows an easier and more direct selection of the wheel-slip cycling range and, consequently, to reduce the braking distance. The simulations illustrated on super urban vehicle (SUV) and simulation results show more reliable and better performance compared with other approaches and CarSim simulation results. Moreover, fuzzy control is advantageous in reducing design complexity and, also, anti-chattering and robustness properties of the controlled system.

3.2. Research Gap

Many different control methods for ABS systems have been developed as described in literatures. These methods differ in their theoretical basis and performance under the changes of road conditions and operational speed. The performance of ABS depends highly on the knowledge of friction coefficient between the tire and the road, vehicle speed, slip ratio between the tire and the road, and the vehicle brake system non-linearity due to the complicated relationship between friction and slip. Researchers have employed various control approaches to solve this problem.

Among several control methods developed for ABS, most of these approaches require system models, and some of them cannot achieve satisfactory performance under the changes of various road conditions. Intelligent control systems like fuzzy control can fill this gap in ABS control to match the qualitative aspects of human knowledge with several advantages such as robustness, universal approximation theorem and rule-based algorithms. And also, the simulation of ABS with full vehicle dynamics is complex and nonlinear, in which the CarSim software interlinked with MATLAB/Simulink can achieve this and also validates the Fuzzy logic controller performance.

CHAPTER FOUR

MODELING OF THE VEHICLE DYNAMICS SYSTEM

4.1. Introduction

Modelling is the first and milestone process in creating a control calculation for the ABS. In order to simulate the dynamics of a vehicle in longitudinal directions, and a quarter vehicle model with 3DOF is considered in this study. Detailed modeling of each of its components requires development of sophisticated models and to simplify the model, a quarter model of the vehicle has been taken and also, some assumptions executed for the model to be made, like straight-line emergency braking until stop is considered, the braking is performed on a dry, and wet and maximum brake torque was manipulated input in overall model.

It is also, assumed the exerted weight is distributed equally among all four wheels of vehicle and all wheels bears equal amount of vehicle braking force.

4.2. Mathematical Modeling of Vehicle Dynamics System

4.2.1. Longitudinal Vehicle Dynamics Model

It is obvious that, the vehicle dynamic model is too complex and so difficult to drive from the principle physical model, so the quarter-model of the vehicle dynamic and mathematical model are assumed. The partial differential equations that govern the brakes behaviors are differentiated accordingly. The longitudinal dynamics modeling of the vehicle consists of a single sprung mass (car body) connected to the unsprung mass (wheel) and the vertical dynamics effect of the vehicle on the traction has modeled as shown in Figure 6. The suspensions between the sprung mass and unsprung mass are modeled as linear viscous damper and spring elements, while the tire is modeled as linear spring and damping elements, as shown in Figure 6.

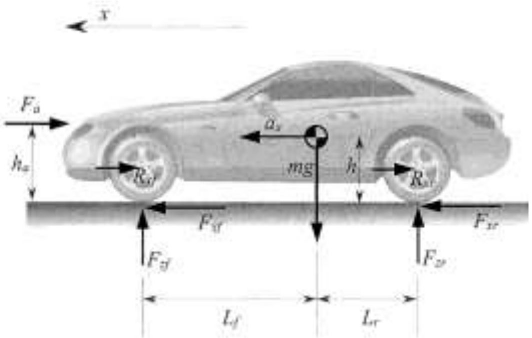


Figure 6: Vehicle longitudinal dynamics schematic diagram

The resultant force of a moving vehicle is provided by Newton's second law as follows:

$$\sum F = m_v * a \implies F_x - F_a - F_r \; = m_v * a \qquad (1)$$

Since, the derivative of the speed is the acceleration of the vehicle it can be rewritten as

$$m_v * \dot{v} \; = F_x - F_a - F_r \implies \dot{v} \; = \frac{F_x - F_a + F_r}{m_v} \qquad (2)$$

Where, m_v is the summation of the quarter sprung mass, m_s and unsprung (wheel) mass i.e.,

$$m_v = m_w + \frac{1}{4} m_s \qquad (3)$$

Aerodynamic resistance force (F_a) and rolling resistance force (F_r) are force components acting parallel and opposite to velocity of the vehicle and act as drag force.

Where, the aerodynamic force (F_a) is expressed as:

$$F_a = \frac{1}{2}(\rho * C_d * A_f * V^2) \qquad (4)$$

According to [17], the frontal area A_f the following relationship between vehicle mass and frontal area can be used for passenger cars with mass in the range of 800-2000 kg:

$$A_f = \; 1.6 + 0.00056(m - 765)$$

The rolling resistance force (F_r) is the energy that vehicle needs to send to tires to maintain movement at a consistent speed over a surface, which is expressed as:

$$F_r = C_r * m_v * g \qquad (5)$$

Where, m is the quarter mass of the vehicle

m_w is the mass of the wheel

m_s is the sprung mass of the vehicle

m_v is the total mass of the vehicle,

a is the acceleration of the vehicle

C_r is rolling resistance coefficient

A is frontal area of the vehicle

C_d is aerodynamic drag coefficient

ρ is density of air

The net force or total Vehicle longitudinal force (F_x) , therefore can be calculated as follows:

$$\begin{aligned} F_x &= m_v * a \; - F_a - F_r \\ &= m_v * a - \frac{1}{2}\left(\rho * C_d * A_f * V^2\right) - \frac{1}{4} * C_r * m_v * g \end{aligned}$$

4.2.2. Tire Dynamics Model

When braking torqne is applied at a wheel, braking forces are generated at the interface between the tire and the road surface [13]. With further increase in brake torque, this slippage between the tire and road surface increases until locking-up and skidding of the wheel occurs. The longitudinal force generated at each tire is known to depend on the longitudinal slip ratio, the tire-road friction coefficient, and the normal force applied at the tire.

The traction force of the tire (F_x) is given by:

$$F_x = \mu(\lambda) * F_z \tag{6}$$

Where, the normal force on the wheel (the reaction force from the ground to the tire) is the load due to the quarter vehicle weight and longitudinal weight transfer and which is given by:

$$F_z = m * \frac{g}{4} + F_l \tag{7}$$

The longitudinal weight transfer load due to braking, F_l is expressed by:

$$F_l = \frac{1}{2L}(m_v * h_{cg} * \dot{v}) \tag{8}$$

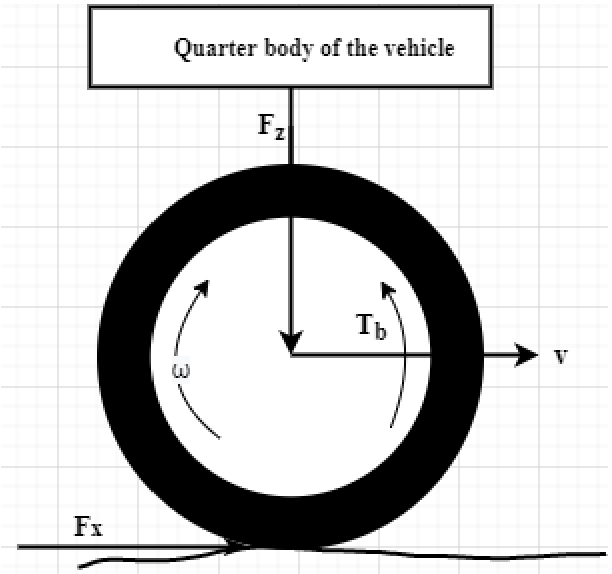


Figure 7: Free body diagram of single wheel

Where, h_{cg} is center of gravity height and,

L is wheel base (the distance between the front and rare wheel)

The angular acceleration of a body, decelerating vehicle at the amount α due to brake torque T_b applied to the wheel radius, R and moment of inertia I, causes the direct decrease in the wheel angular velocity ω. This, the rotational dynamics of the wheel can be represented by the following equation:

$$\sum T_y = I * a = I * \dot{\omega}$$

$$I * \dot{\omega} = F_{net} * R - T_b \qquad \Rightarrow \dot{\omega} = \frac{1}{I}(F_{net}) * R - T_b \tag{9}$$

Where, $F_{net} = F_x - F_a - F_r$

From the dynamic angular motion equation of the wheel, the angular acceleration of the wheel α is the ratio of net torque (i.e., $T_t - T_b$) and wheel moment of inertia, I_w.

$$T_t = I_w * \alpha \tag{10}$$

Where the wheel moment of inertia I_w, is calculated from the mass of the wheel m_w, and radius of the wheel r_w, as follows:

$$I = \frac{1}{2} m_w * r_w^2 \tag{11}$$

The brake force, F_b, which acts at the interface between a single wheel and the road is related to the brake torque, T_b, as

$$T_b = F_b * r \tag{12}$$

Where, r is the wheel cylinder radius

The force applied to the rotor by the pads is a function of hydraulic pressure in the brake system and of the area of the wheel cylinder (or cylinders, as the design dictates).

The maximum brake torque can be calculated using the following equation:

$$T_{b,max} = P * A * r_e \tag{13}$$

r_e is the effective radius (torque radius) of a brake disc from the center of the brake pads, which is the mean of the outside diameter and inside diameter of the disc. The radius of the wheel cylinder is taken as $0.034\ m$ and the torque due to pressure on the wheel cylinder is about 1.

4.2.3. Tire-road friction coefficient characteristics and estimation

This section deals with an empirical model of the complex friction dynamics between the tire and the various road conditions. Several different approaches have been proposed in literature for the real time estimation of tire-road friction coefficient. When a vehicle is braking or accelerating, the tractive forces produced by the tire are proportional to the normal forces of the road acting on the tire [6]. The coefficient of this proportion, denoted, μ is called road coefficient of adhesion (or friction coefficient) and varies depending on the road surface.

Since, the objective of an ABS is to manipulate the torque applied to the driven wheels in order to limit the slip between the road surface and the tire, it only operates within the stable region of the $\mu - \lambda$ characteristic which is shown in Figure 8.

Slip ratio is the point obtained during emergency braking scenarios, at which the tangential velocity of the tire surface (wheel speed) and the longitudinal speed of vehicle are not the same. It is computed to keep the slip ratio of the vehicle at a certain target value which requires measurements of vehicle speed and wheel speed. However, it is difficult to measure the vehicle speed accurately, and directly from sensors, while the wheel angular velocity can be directly measured with wheel-speed sensors placed on disc notches at some distances made along its circumference. So, the wheel longitudinal slip ratio λ (from Figure 8) is defined by the normalized difference between the vehicle speed v and the speed of the wheel perimeter $(R.\omega)$.

$$\lambda = \frac{v-\omega * R}{v} \quad \equiv 1 - \frac{\omega * R}{v} \tag{14}$$

Differentiating the equation above with respect to time (t), get:

$$\dot{\lambda} = \frac{\dot{v}(1-\lambda) - R * \dot{\omega}}{v} \tag{15}$$

Rewrite the equation above by substituting the equations (2) and (8), in equation (14) the final form will be:

$$\dot{\lambda} = -\frac{1}{v}\left(\frac{\mu * F_z}{M}(1-\lambda) - \left[\frac{\mu * R * F_z - T_b}{I}\right] R\right) \quad = -\frac{\mu .*}{v}\left[\frac{(1-\lambda)}{M} + \frac{R^2}{I}\right] + \frac{R}{I * v} * T_b \tag{16}$$

The understanding of relationship between the slipping ratio and the coefficient of friction between tire and road is too important to understand the main control requirement, and the friction coefficient as a function of slip ratio is known as magic formula which has derived from experimental data is given by the following function.

$$\mu(\lambda) = \left[C_1\left(1 - e^{C_2 * \lambda}\right) - C_3 * \lambda\right] \tag{17}$$

Due to the large number of parameters involved in the Magic Formula, it cannot be directly used conveniently for tire-road friction coefficient identification. In place of the Magic Formula, look up table is used in MATLAB/Simulink, for purposes of tire-road friction coefficient identification.

Table 1: Surface friction parameters of different road conditions [18]

Surface conditions	C_1	C_2	C_3
Dry asphalt	1.2801	23.9900	0.5200
Wet asphalt	0.8570	33.800	0.3470
Ice	0.1946	94.1290	0.0646

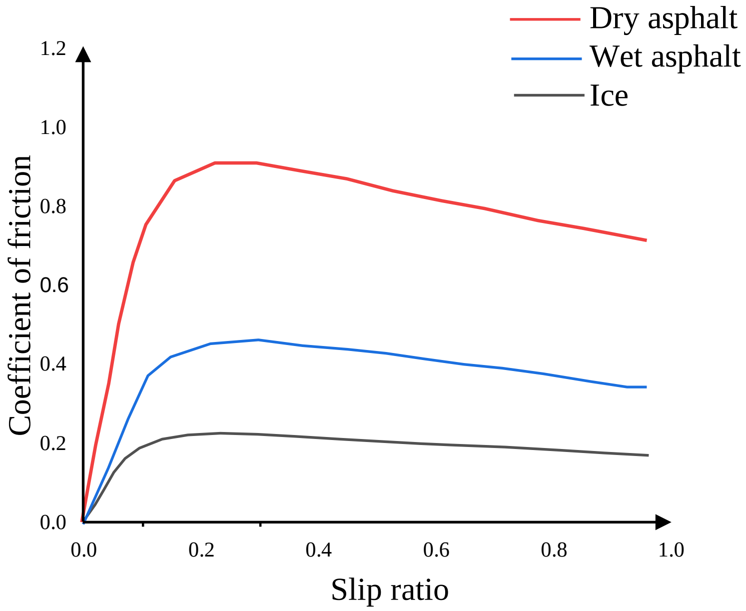


Figure 8: Friction coefficient versus slip ratio of different road conditions

As shown in Figure 8, the road coefficient of friction is a nonlinear function of wheel slip (λ) and the coefficient of friction reduces from the dry to ice road conditions. This shows how the friction coefficient $\mu(\lambda)$ increases with slip λ up to a value λ_0, where it attains its maximum value μ_0. For higher slip values, the friction coefficient will decrease until the wheel is locked. As the plots indicates, increasing slip can increase the tractive force between the tire and road surface by virtue of an increase in μ. However, once the peak of the characteristic μ_{peaks} encountered, any further increase in slip will reduce traction and consequently induce an unstable acceleration of the wheel until the drive torque is reduced.

So, the objective of an ABS is to manipulate the torque applied to the driven wheels in order to limit the slip between the road surface and the tire, and consequently, only operate within the stable region of the μ-λ characteristics [33]. The ABS command the brake operation system by controlling the input torque created by the actuator hydraulic system and the main parameters must be controlled and manipulated is the stopping distance, vehicle linear velocity, and the slip ratio.

The friction coupling that gives rise to the brake force characteristic reflects the combination of tire and road surface materials together with the condition of the surface. The best conditions occur on dry, clean road surfaces on which the brake force coefficient, defined as the ratio of brake force to vertical load, µb, can reach values between 0.8 and unity. Conversely, icy surfaces reflect the poorest conditions and on ice the brake force coefficient can lie between 0.05 and 0.1. On wet surfaces or on roads contaminated by dirt, the brake force coefficient typically spans the range 0.2 to 0.65 which is summarized in Table 2 [34].

The slip value of $\lambda = 0$, characterizes the free motion of the wheel where no friction force F_x is exerted. If the slip reaches the value λ = 1, then the wheel is locked ($\omega = 0$). The tire–road friction coefficient $\mu(\lambda)$ can span over a very wide range.

The tire–road friction coefficient can be determined as:

$$\mu(\lambda) = \frac{F_x}{F_z} \tag{18}$$

Table 2: Maximum values of the coefficient of friction for different road conditions

Road conditions	Maximum friction coefficient	Optimum slip (λ_0)
Dry asphalt	0.85	
Wet asphalt	0.45	0.2
Icy road	0.2	

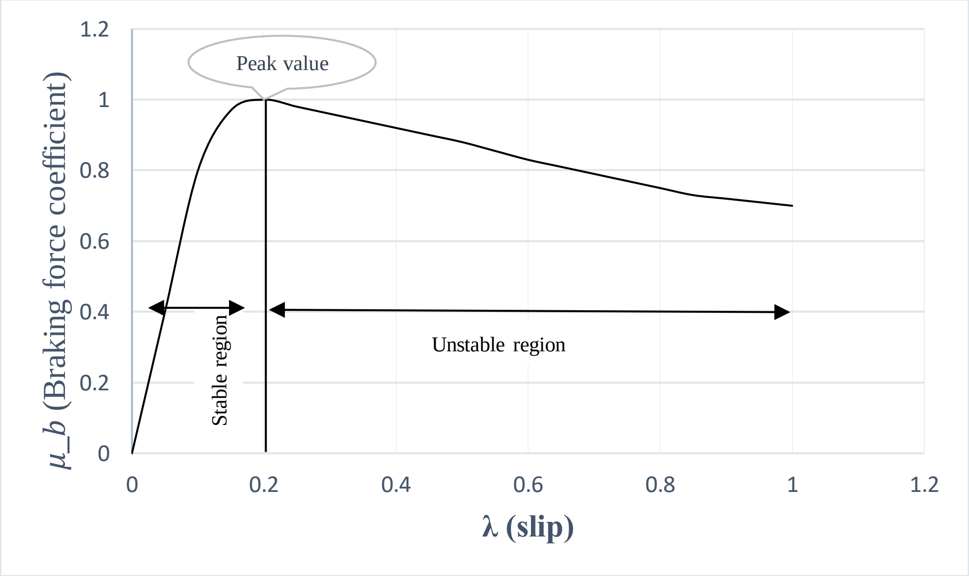


Figure 9: Characteristics function of tire-road friction

To understand the influence of longitudinal slip ratio on braking forces, consider the tire force characteristics shown in Figure 9. It shows the magnitude of the tire longitudinal force typically increases linearly with slip ratio for until it reaches a maximum (peak) value. Beyond this value, the magnitude of tire force decreases and levels out to a constant value. So, the entire wheel slip range is divided into two regions according to the road surface adhesion coefficient curve: the stable region and the unstable region [35]. If the wheel slip is located in the unstable region due to the brake torque, which is bigger than the ground brake torque, then the wheel speed decreases, the slip ratio increases, and the ground brake force decreases continuously, until the vehicle wheel was locked. Consequently, the purpose of the proposed control scheme based on look up table is to constrain wheel slip ratio in the stable region throughout the vehicle braking process.

4.3. MATLAB/Simulink Model of brake system

The vehicle dynamics model has been developed in the MATLAB/Simulink based on the mathematical equations involved in the quarter vehicle model. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming environment. Furthermore, MATLAB is a modern programming language environment: it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming.

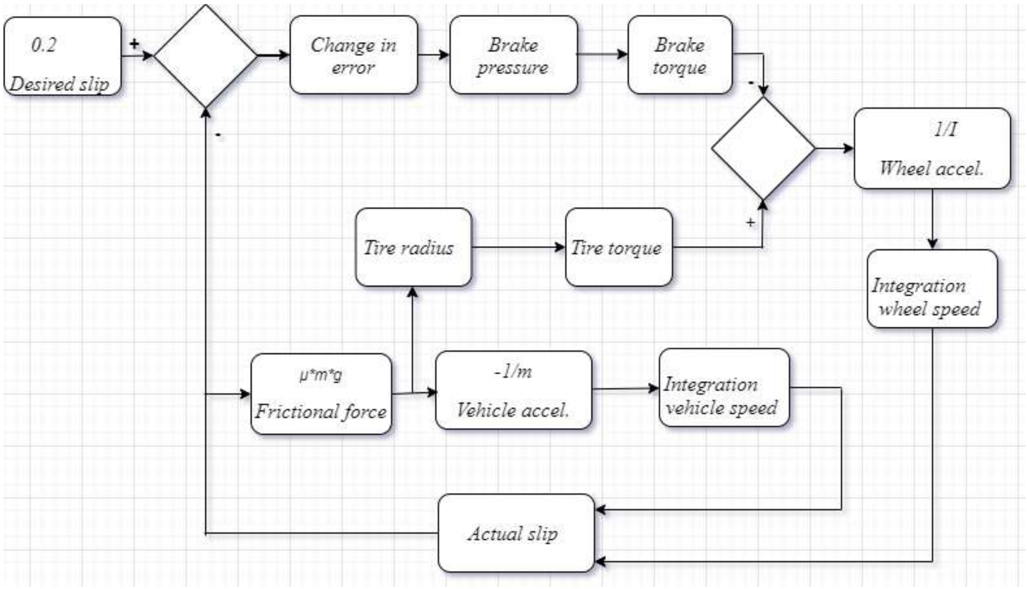


Figure 10: Diagrammatic modeling of Antilock brake system without controller

These factors make MATLAB an excellent tool for teaching and research. Simulink is a visual programming interface designed to make modelling systems intuitive. It offers a way to solve equations numerically using a graphical user interface, rather than requiring code. This modeling has been done for dynamic performance analysis in longitudinal direction; the lateral dynamics of the wheel is not considered.

In this modeling the reference slip was 0.2, as shown on Figure 10, under the tire-road friction coefficient model section and brake torque was given as step input during brake pedal. The friction coefficient, μ, was multiplied by the weight on the wheel, F_z to yield the longitudinal frictional force, F_x acting on the circumference of the tire. F_x is divided by the vehicle mass to produce the vehicle deceleration, which the model integrates to obtain vehicle velocity.

4.4. Fuzzy Logic Controller Design

Antilock brake system is needed in the vehicle to maintain wheel slip ratio as close as possible to the optimal target value to minimize stopping distance meanwhile ensuring side stability within acceptable range[34]. To this requirement, it need to monitors the wheel speed, the wheel deceleration/acceleration, and the vehicle speed. The dynamic model of ABS utilizing the MATLAB/Simulation program is designed and simulated. Based on the derived model, fuzzy logic controller algorithm is proposed to control the operation of the ABS system. The control commands (to hold, decrease or increase the brake torque) depend on the actual values of the monitored parameters and, whether or not certain threshold levels have been exceeded.

The foremost control methods existing in the literature can be categorized in four different areas: Threshold control, PID control, Sliding-mode control (SMC) and Intelligent control. Threshold control and PID control is a simple control method that has been widely applied in the early ABS versions. It usually uses wheel acceleration and/or wheel slip as controlled variables and defines threshold values, above/below which the pressure should be increased, held or decreased [19]. The intelligent control are such as fuzzy logic [7], genetic algorithms and neural networks. The fuzzy control is a controlling mechanism which performs well in nonlinear, complex and doesn’t need mathematical model of the system. It is the best and robust mechanism used in the designing of the antilock brake system in order to determine the position of change in pressure, whether the it should be increased, hold on or decreased. The other convincing advantage is that, each controlling algorithm have a nonlinear characteristic surface and fuzzy logic has the ability to modify and tune certain parts of this characteristic surface easily and carefully [36].

The fuzzy techniques are applied in complicated and imprecise processes for which either no mathematical model exists or the mathematical model is severely nonlinear [36]. Fuzzy logic controllers are represents the knowledge relatively easily in the form of linguistic rules and encompassing a great complexity with few rules [38].

The fuzzy logic controller (FLC) consists of 4 main processes;

1. **Fuzzification**- in which the crisp (real number) input into fuzzy sets is converted and it also determines an input's % membership in overlapping sets.
2. **Inference mechanism** - which turns the fuzzy input into a fuzzy output,
3. **Rules**- which determine outputs based on inputs and rules with the Mamdani's method.
4. **Defuzzification** is required to convert the fuzzy output to a numerical value as shown with diagram in Figure 11. It combines all fuzzy actions into a single fuzzy action and transform the single fuzzy action into a crisp, executable system output.

In this work, i.e., in designing process of the fuzzy logic controller, MATLAB, Fuzzy Logic Toolbox™, Mamdani's method was used.

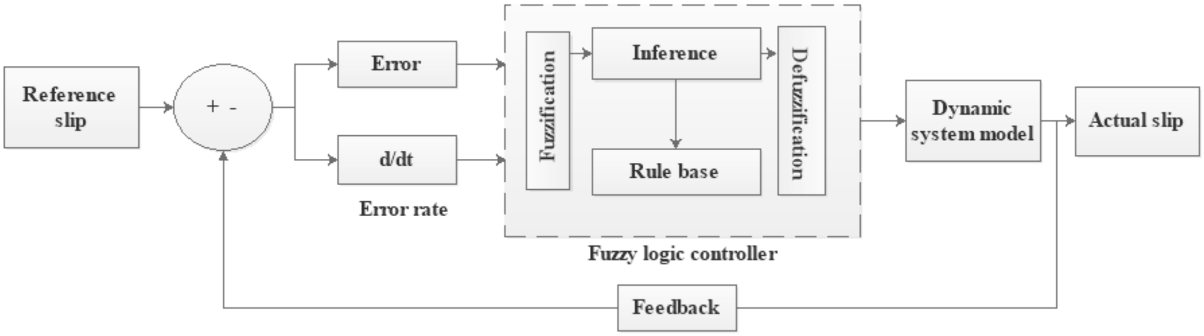


Figure 11: Fuzzy logic controller block diagram in the system

As shown in Figure 11, the inputs of the fuzzy controller i.e., slip error and slip error rate are defied during the initialization stage and all fuzzy membership functions are defined in order to form the complete rules.

4.4.1. Fuzzy membership functions

The membership function editor is applied to define the shape of membership functions (MFs) that are related to input and output variables. The controller selected is Mamdani FLC having two inputs and single output in order to determine the brake pressure.

Input variable

The inputs for the FLC are; the error between the reference slip and the actual slip ratio i.e., e_{error}, and its variation in time $d\lambda_{error}/dt$ which is the deceleration of the vehicle. It was expressed by seven fuzzy member-ship languages which are defined as: negative big (NB), negative medium, negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB).

Output variable

The output of the FLC is the brake torque or change in pressure and the fuzzy sets for the input fuzzy variables are defied as; big pressure decrease (BPD), medium pressure decrease (MPD), small pressure decrease (SPD), pressure hold (PH), small pressure increase (SPI), medium pressure increase (MPI), and big pressure increase (BPI).

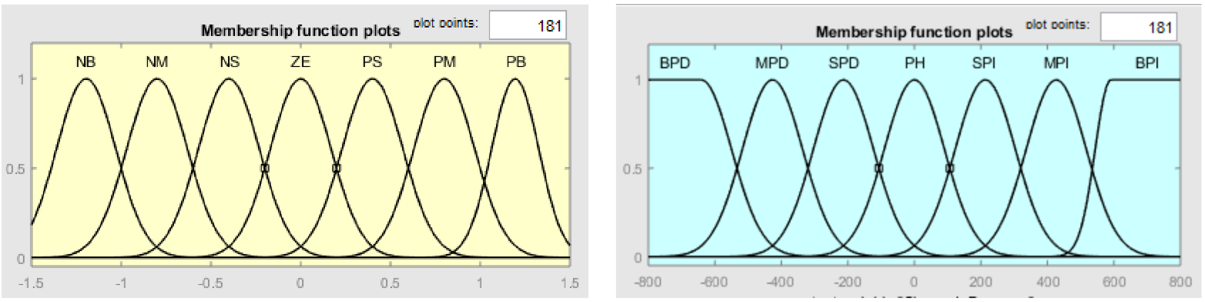
As a result of two fuzzy variables, each of them having seven labels, 49 (i.e., 7 × 7) different logic configurations are possible and formulated basically using a combination approach of membership functions so called ‘If and Then’ logic. Since, the large amount of the fuzzy rules makes the analysis complex 19 rules, as shown in Table 3, are selected through trial and error.

Piecewise linear MFs may not always be suitable for all applications. Therefore, nonlinear smooth functions are also in widespread use in fuzzy systems and control.

Gaussian MF

Gaussian, bell-shaped, z-shaped, s-shaped and sigmoidal functions are very common among them. Gaussian MFs are also popular among fuzzy systems due to the fact that it can be specified by only two parameters $\{c, \sigma\}$ and defined by

$$\mu(x) = exp\left[-\frac{\frac{1}{2}(x-c)^2}{\sigma}\right] \tag{19}$$



a) Input variables structure

b) Output variable structure

Figure 12: Gaussian membership functions of seven levels

Were,

c is the center Gaussian MF and

σ is the width of the Gaussian MF

Gaussian MF is smooth, symmetric and non-zero at all points as illustrated in Figure 12. Gaussian MF are two sided and there are two Gaussian functions. The first function $f_1(x)$, described by the parameters (σ; m_1) determines the shape of the left-side curve. The second function $f_2(x)$ described by the parameters (σ; m_2), determines the shape of the right-side curve.

$$f_1(x)=\begin{cases} exp\left[\frac{-\frac{1}{2}(x-m_1)^2}{\sigma_1}\right], & x \leq m_1 \\ 1 & otherwise \end{cases} \tag{20}$$

$$f_2(x)=\begin{cases} exp\left[\frac{-\frac{1}{2}(x-m_2)^2}{\sigma_2}\right], & x \leq m_2 \\ 1 & otherwise \end{cases} \tag{21}$$

Then, the two-sided Gaussian membership function is defined by:

$$\mu(x) = f_1(x) * f_2(x) \tag{22}$$

4.4.2. Fuzzy logic rules

Table 3: Fuzzy logic base rule

No.	Error	Error rate	ΔP
1	ZE	NB	BPI
2	NB	ZE	BPI
3	NB	PS	MPI
4	PS	NB	MPI
5	ZE	NM	MPI
6	NM	ZE	MPI
7	ZE	NS	SPI
8	NS	ZE	SPI
9	PS	NS	PH
10	NS	PS	PH
11	PB	NS	MPD
12	NS	PB	MPD
13	ZE	ZE	PH
14	PS	ZE	SPD
15	ZE	PS	SPD
16	PM	ZE	MPD
17	ZE	PM	MPD
18	PB	ZE	HPD
19	ZE	PB	HPD

Both the inputs and output are crucial in Fuzzy logic control approach. For the inputs and outputs, Gaussian membership functions (MFs) are used. Gaussian MFs are chosen as the best choice in obtaining adequate parameter values for a more robust control system.

The MF range for the input and output is [-1, 1]. The controller's output is brake pressure, which regulates vehicle slippage and maintains safety.

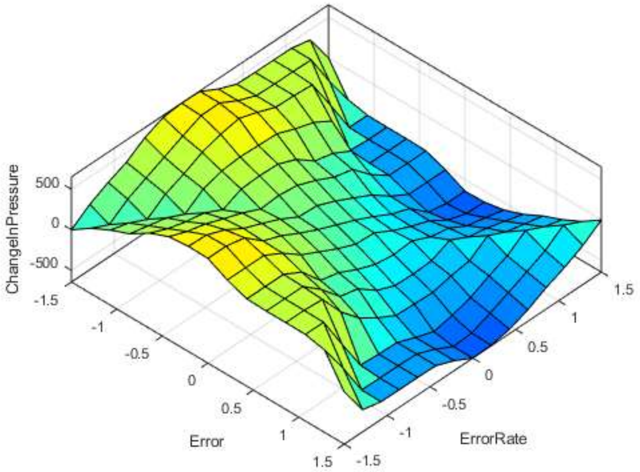


Figure 13: Fuzzy logic controller surface characteristics

This surface viwer shows output surface for any system output versus any one (or two) inputs. The control surface of a two-input and single-output system is shown in Figure 13, where error and error rate represent inputs and change in pressure represents the controller output.

4.5. MATLAB/Simulink Model with FLC

Implementing ABS in a simulation model is significantly easier than designing, manufacturing and installing ABS on a vehicle. The brake system and control system were mathematically modelled, the initial conditions were set and computer simulations carried out using MATLAB/Simulink for all the configurations and scenarios defined above. The MATLAB/Simulink simulation mode can be categorized as; the vehicle dynamics, wheel dynamics and tire-road interaction.

The performance of the controller that needs to be investigated in this study is designated by the parameters like, wheel slip, vehicle and wheel speed, and the stopping distance. Figure 14 shows the MATLAB/Simulink model of the system with the fuzzy logic controller. The error between the reference slip and the actual slip ratio, and its variation in time is the inputs for the controller, while the the braking torque or the change in pressue is the out put of the controller as illustrated in Figure 10. The modelling of a friction coefficient a data was based on look-up-table.

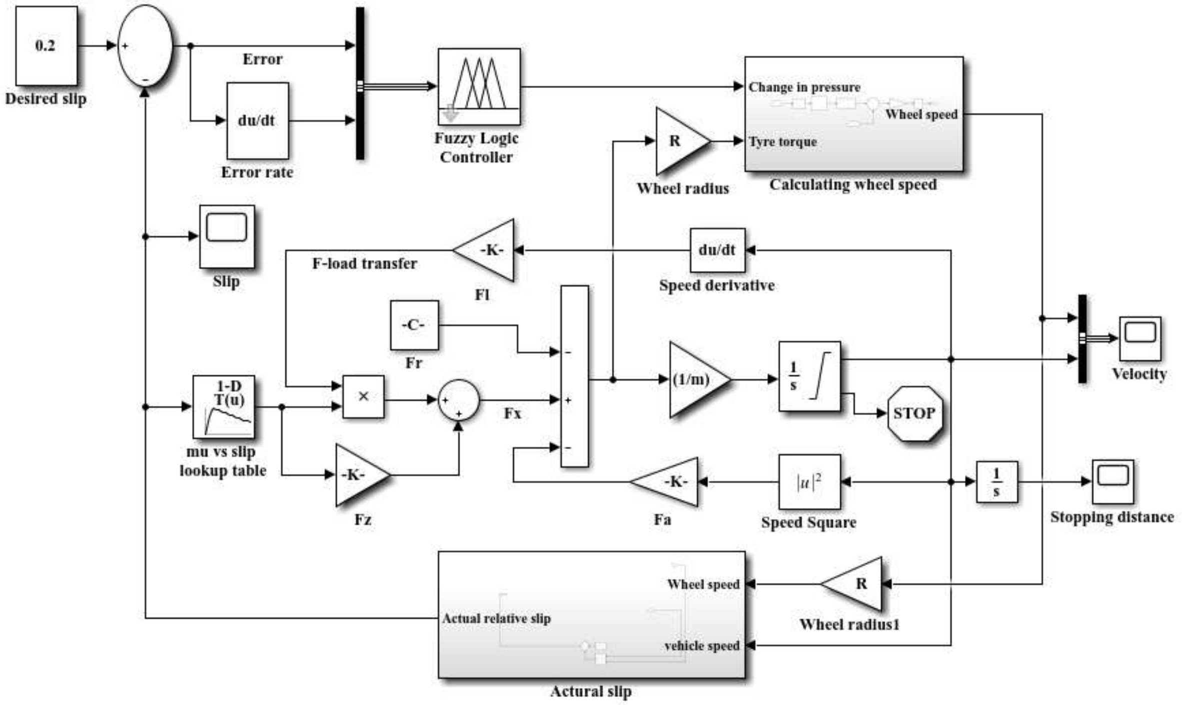


Figure 14: Quarter vehicle model with fuzzy logic controller

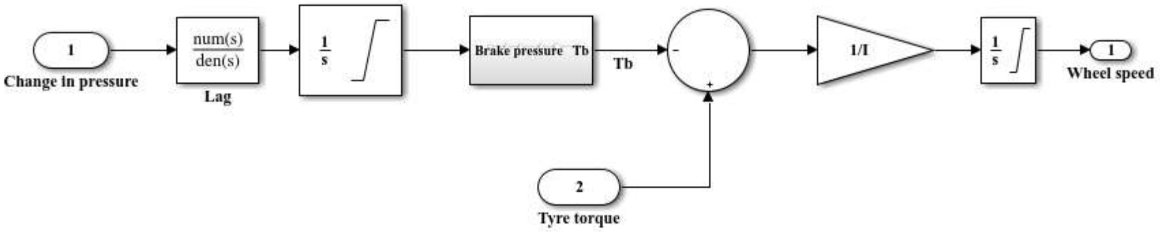


Figure 15: Wheel speed calculation subsystem

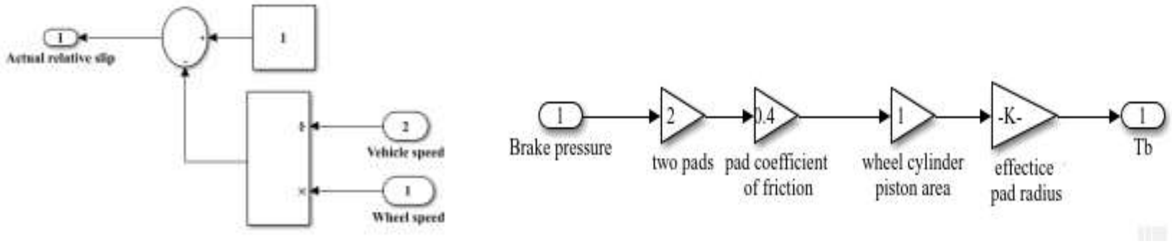


Figure 16: Actual slip and brake torque calculation subsystem

In this wheel speed calculation process (Figure 15), to control the rate of change of brake pressure, the model subtracts actual slip from the desired slip and feeds this signal into a fuzzy logic control (+1 or -1, depending on the sign of the error). The forward velocity and tire rolling speed are equal when the slip ratios of the vehicle approach to zero.

Zero slip ratio implies an absence of either engine torque or brake torque. A positive slip ratio implies the vehicle approaches a greater finite forward velocity with the tire having a positive finite rolling velocity. While a negative slip ratio implies the tire has a greater equivalent positive rolling velocity meanwhile the vehicle has a finite forward velocity. The conditions are: the wheel is 'spinning' with the vehicle at zero speed or the wheel is locked at zero speed.

The lag represents the delay associated with the compressed liquid lines of the brake system. It is the time required for the brakes to work after the brake pedal is pushed. If there is lag, there will be lag compensator in which a transfer function, characterized by a pole on the negative real axis close to the origin and a zero close and to the left of the pole, that is used for the purpose of improving the steady-state error of a closed-loop system.

Tests were done on the vehicle longitudinal model using MATLAB/Simulink under certain condition. Most of the simulation parameters of the quarter vehicle model (i.e., constants values) that are used in developing the above ABS model are taken from Bishoftu Automotive Industry and summarized in Table 4. In this work a new way to interface the concept of fuzzy logic was proposed and used in ABS system simulation tests on super urban vehicle with antilock-braking system.

Table 4: Vehicle model parameters

Symbol	Numerical Value	Unit	Description
m_v	627.5	kg	Mass of quarter vehicle
L	2.73	m	Wheel base
R	0.31	m	Radius of the wheel
I_w	1.9	$kg.m^2$	Moment of inertia of the wheel
m_w	40	kg	Mass of the wheel
v	16.66	m/s	Longitudinal initial velocity
λ_r	0.2	-	Reference slip ratio
g	9.8	m/s^2	Acceleration due to gravity
h_{cg}	0.5	m	Height of vehicle CG
A_f	1.746	m^2	Effective frontal cross-sectional area
C_d	0.5	-	Coefficient of drag
ρ	1.225	$Kg.m^3$	Density of air
r_e	0.115	m	Effective pad radius.

4.6. CarSim Model interlinked with MATLAB/Simulink

As the ABS models are developed in MATLAB/Simulink by applying fuzzy logic control, they may have certain disadvantages, like the model developed is only for the single wheel and simulation results are obtained for the single wheel data. Hence, it is necessary to obtain the complete vehicle simulation of ABS in a way such that the complete four-wheel simulation data can be obtained and accurate control over the ABS can be achieved.

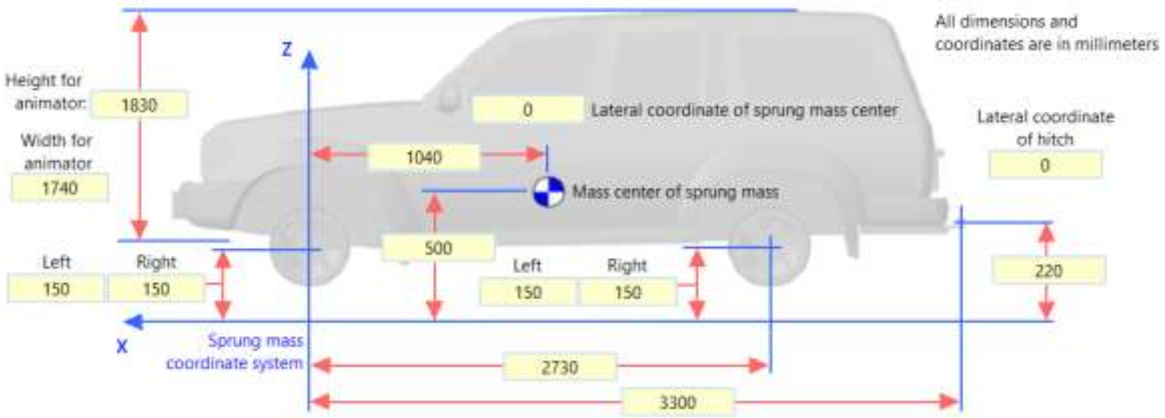


Figure 17: Vehicle parameters in CarSim

In order to preserve this, the complete four-wheel simulation model of the ABS model was developed for the hatchback segment vehicle in CarSim, which is integrated with MATLAB and the results of the model developed are compared with MATLAB/Simulink.

The simulation parameters for CarSim are set here (Figure 17). The full vehicle simulation of the ABS model is used in the CarSim software, which is interlinked with MATLAB. Some additional parameters' behavior can be used as compared to the MATLAB/Simulink ABS model. Then, the Simulink model given in Figure 18 shows that the output simulation model of CarSim is sent to MATLAB/Simulink for further simulations like pressure, velocity of the vehicle, and wheel and controller modes.

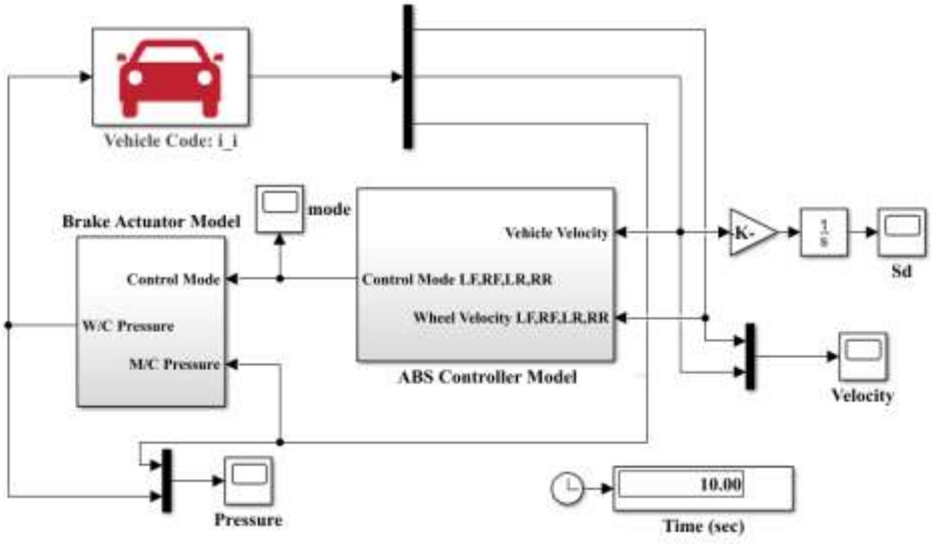


Figure 18: Car Sim model integrated with Simulink

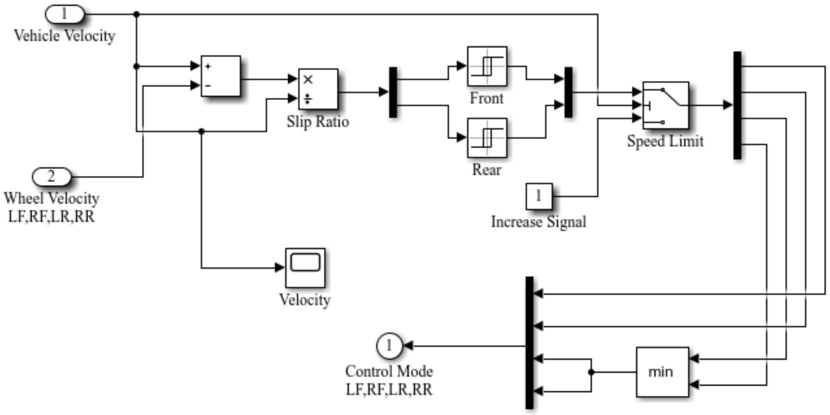


Figure 19: ABS controller subsystem

The simulation time is set at 10 seconds in total. The input parameters like vehicle velocity, wheel velocity, and master cylinder pressure are imported from the CarSim environment and are given the simple ABS controller model. The master cylinder pressure is set at 0.3 MPa for the hatchback SUV.

In the ABS controller model (Figure 19), the slip ratios of each wheel are calculated. The wheel speed is subtracted from the vehicle speed by using a sum block. The result of this subtraction is given to the divide block where this value is divided by vehicle speed to obtain the slip ratio. This mathematical calculation is performed for each wheel and then these values of slip ratios are given to the brake actuator model. The brake actuator model is shown in Figure 20.

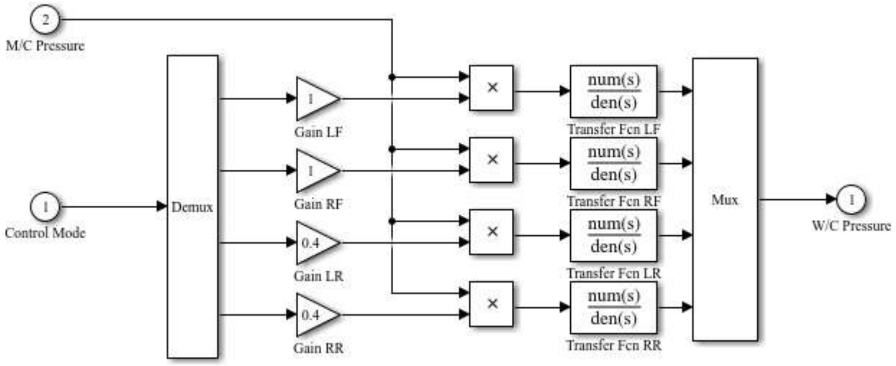


Figure 20: Brake actuator model subsystem

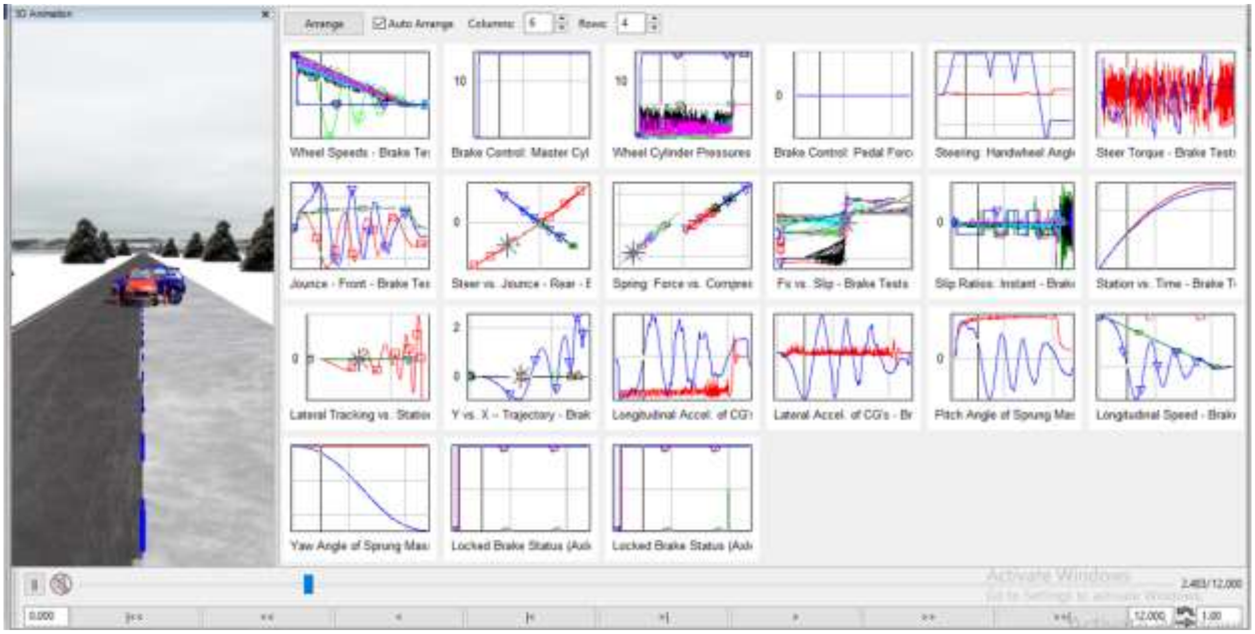


Figure 21: Viewing synchronized video and plot of CarSim vehicle response.

As shown in figure 21, the graphs and animations for each parameter of the brake system is given at the end of the simulation, indicating that the results from CARSIM are very close to the values obtained from field test.

CarSim includes VS Visualizer, a tool for providing high-quality animation of simulation results corresponding to engineering plots of hundreds of variables from the math model as shown in Figure 21. Time-synchronization of the plots and video facilitates the viewing of both qualitative and quantitative data, and the option to overlay multiple runs (like with ABS and without ABS in this case) allows for comparisons of various vehicle and control combinations.

CHAPTER FIVE

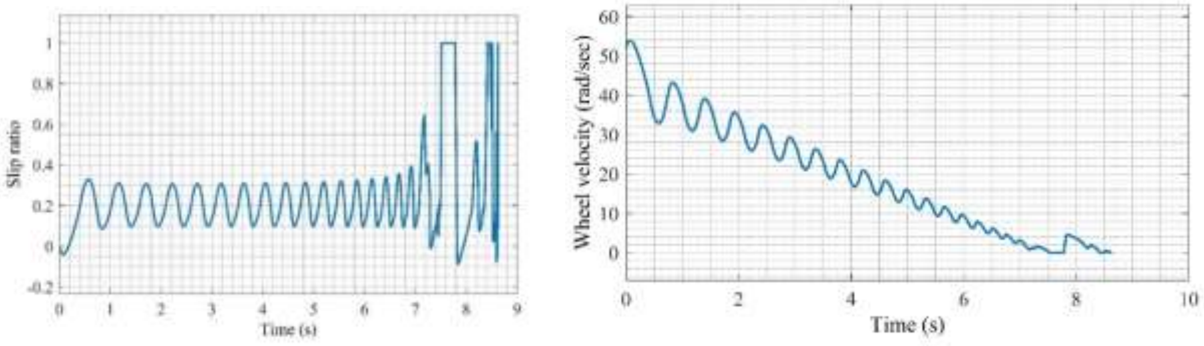
RESULT ANALYSIS AND DISCUSSION

5.1. MATLAB/ Simulink Simulation Result

In this simulation, the vehicle responses are taken under braking conditions on a straight, dry, flat road surface and analyzed with various parameters of braking. The simulation was carried out with an initial velocity of 60 km/hr and 100 km/hr. The nominal values of simulation parameters are as given in table 4.

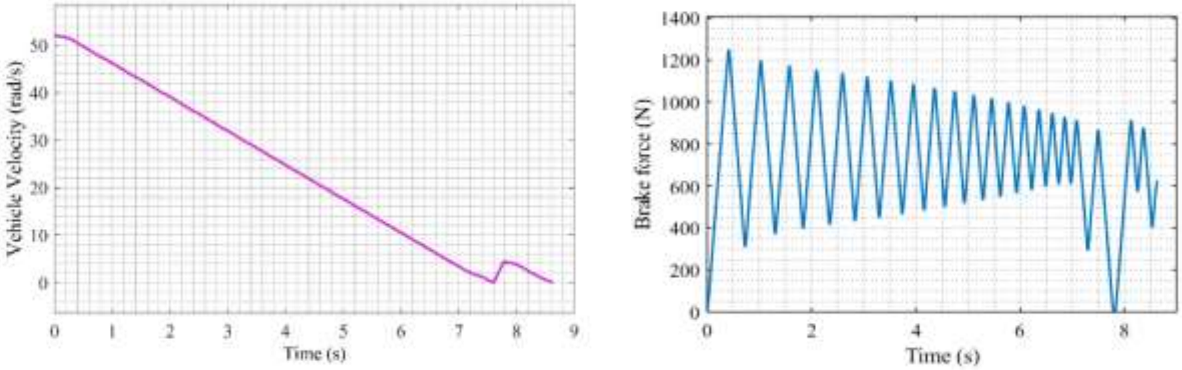
5.1.1. Simulation result without controller

The quarter vehicle dynamics were modeled on the MATLAB/Simulink without the controller with a reference slip of 0.2. Figures 22 (a-d) show the results of the simulation without a controller to estimate parameters like vehicle velocity, slip ratio, brake force and wheel speeds.



a) The slip of the vehicle dynamics model

b) Angular wheel speed of the vehicle



d) Vehicle velocity

e) Brake force

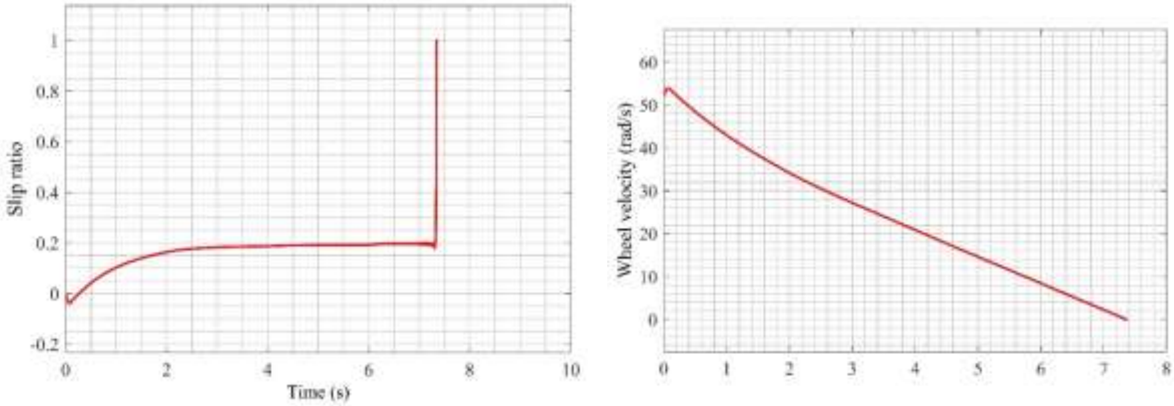
Figure 22: Simulation results of conventional brake system without controller

As seen from plot given in Figure 22 (a), the slip ratio of the vehicle reaches its value within 7 seconds if the brakes are applied without the ABS system and the wheel locking conditions occur. And also, the plots show that the vehicle has no stability at all and the vehicle spins around after the seventh second due to the wheel locking up or when it comes to about to stop.

The braking forces also fluctuate and nonconstant, which can be a good reason for the long stopping distance. The locking of the wheels reduces the braking forces generated by the tires and results in the vehicle taking a longer time to come to a stop.

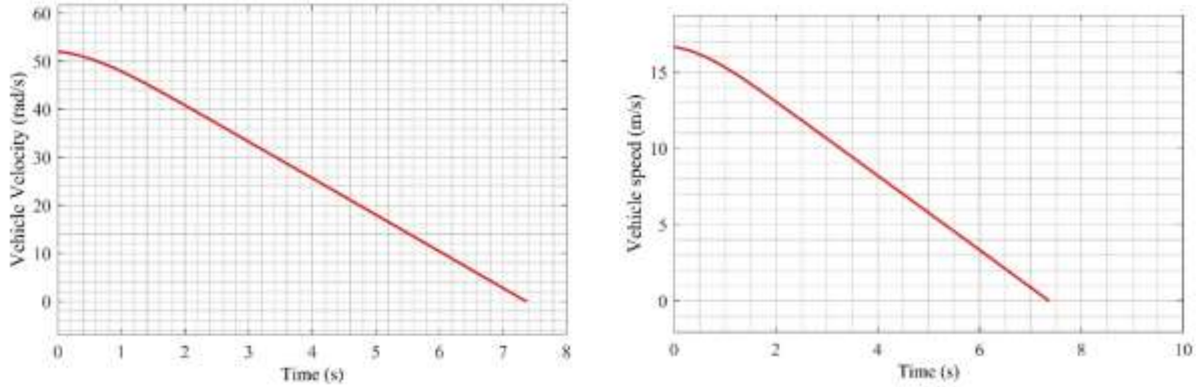
5.1.2. Simulation result with fuzzy logic controller

The simulation results were given for both dry and wet road conditions. As the result shows, braking time increases as the friction coefficient reduces due to the road condition and the same is true for speed. As the initial speed of the vehicle increases, the braking time and braking distance increase.



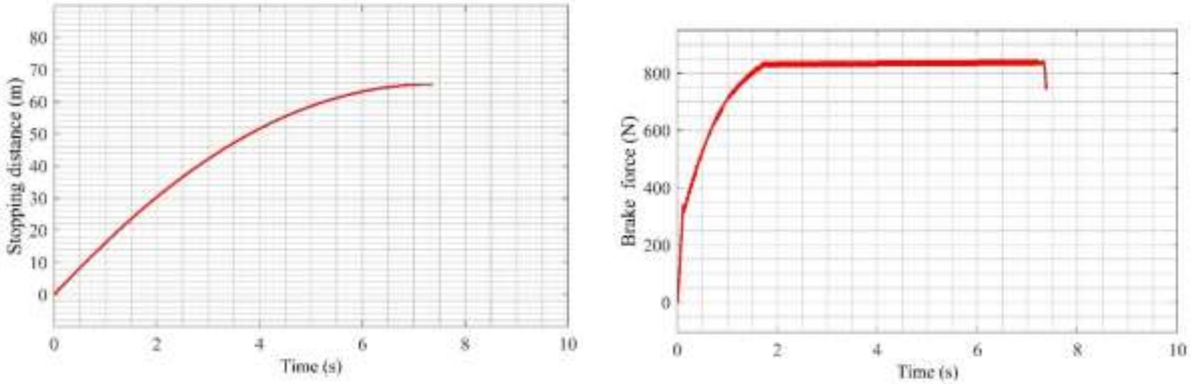
a) Slip ratio

b) Wheel Velocity

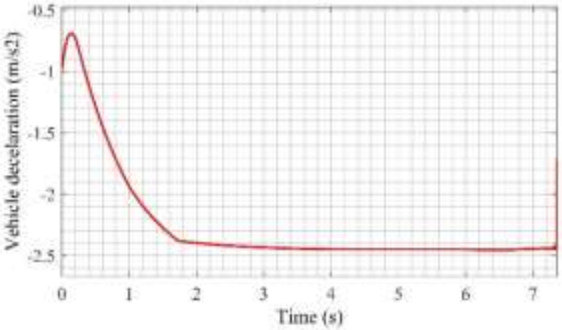


c) Angular vehicle speed

d) Vehicle linear velocity



e) Stopping distance f) Brake force



g) vehicle deceleration

Figure 23: Simulation results of ABS with fuzzy logic controller at 60 km/hr

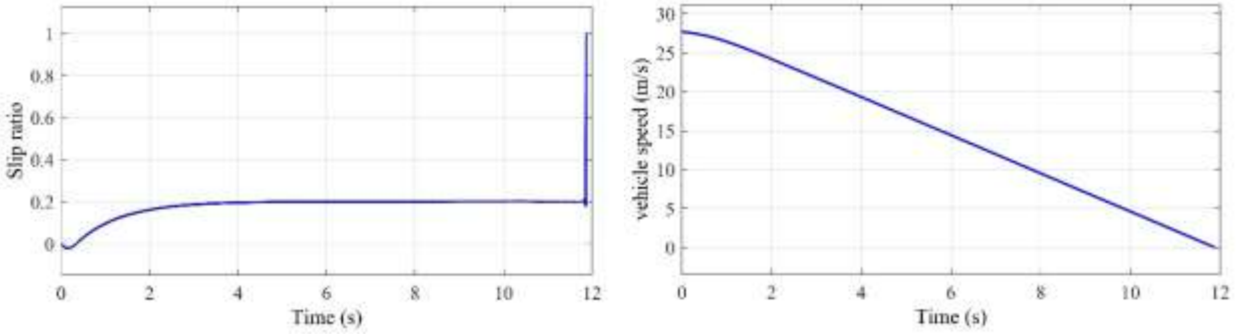
The purpose of the controller is to maintain the vehicle slip as close as possible to the value of 0.2 which was achieved in this work as shown in Figure 23 (a). Consequently, vehicle stability is maintained with the help of a developed fuzzy logic controller, by which the actual slip is maintained as close as possible to the desired value of slip.

From the simulation study, it has been seen that the stability of the vehicle is more stable as compared to the other models. Braking force (as shown in Figure 23 (f)), is the most important parameter of the brake system which is directly related to braking torque and braking distance since it is the amount of force needed to achieve assumed braking parameters for the mechanical vehicle.

The distance travelled by the vehicle at a speed of 60 km/hr., controlled by fuzzy logic control, is about 65 meters and the wheel speed suddenly comes to zero at a time of 7 seconds after braking. In order to obtain the maximum braking torque to stop the vehicle within a minimum distance, the location of the peak as the controller has been exhibited. In the case of conventional braking

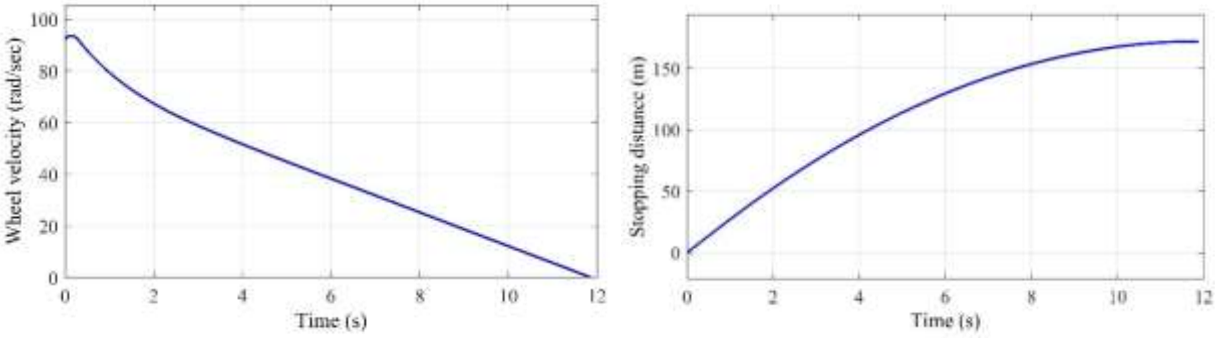
systems or other controlling mechanisms, after the brake is applied to the wheel, it takes 10 to 14 seconds to let it slow down and regain traction, which takes only about 7 seconds in this study.
A velocity graph for both wheels and vehicle has been obtained, and it shows that both the velocity curves converging at a point when the vehicle is stopped, which ensures the vehicle stops without skidding.

In general, the plot given in Figure 23 shows, developed fuzzy logic controller receives better tracking performance, smoother braking force, better stopping time and stopping distance with the help of the fuzzy logic controller.



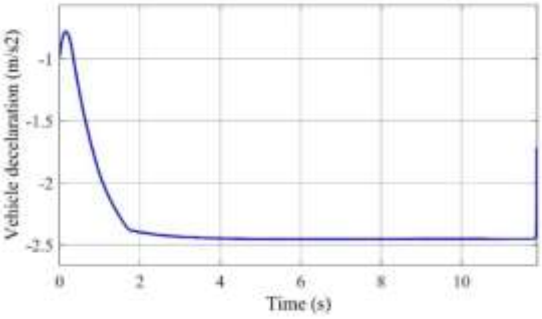
a) Slip ratio

b) vehicle speed



c)Wheel velocity

d) stopping distance



e) Vehicle deceleration

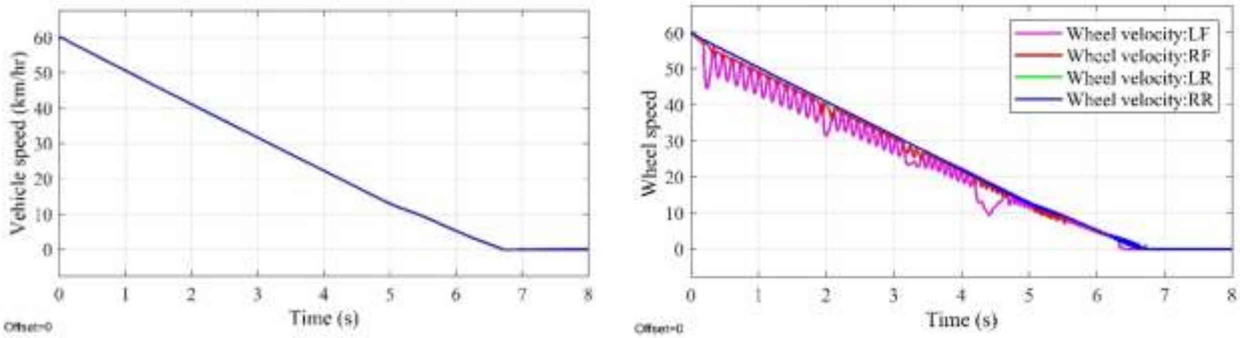
Figure 24: Simulation results of ABS with fuzzy logic controller at 100 km/hr.

In figure 24, the simulation result with fuzzy logic controller at initial speed of 100 km/hr is given, which ensures avoidance of wheel locking and maintain the stability of the vehicle, even if the braking time and distance increases as the initial speed of the vehicle increases.

5.2. CarSim Simulation Results

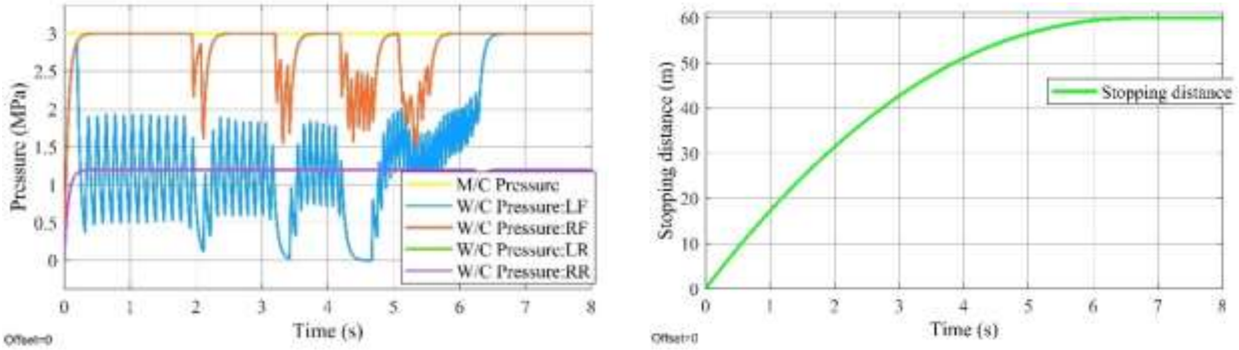
The second simulation is realized by CarSim simulation in order to confirm the performance of the proposed fuzzy logic controller. Since, ABS model of the CarSim software represents the full vehicle simulation, and can be taken as a vehicle test under given circumstances, it was interlinked with MATLAB/Simulink for further simulation and comparison.

At the beginning, the simulation of quarter vehicle dynamics was carried out with a fuzzy logic controller and compared with convectional braking. Then, MATLAB/Simulink was integrated with CarSim & the parameters used are the same, in which the achieved result is almost similar to that illustrated in Figure 25. The wheel cylinder pressure variation is one of the additional parameters used in the CarSim ABS model for hatchback SUV vehicles. The braking pressure applied to the brake pedal is about 3 MPa, which was kept constant.



a) Vehicle velocity

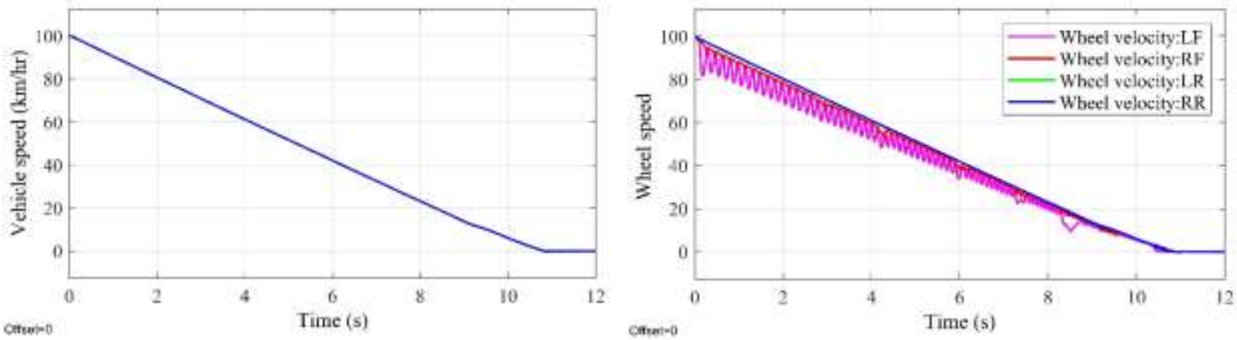
b) Wheel velocity



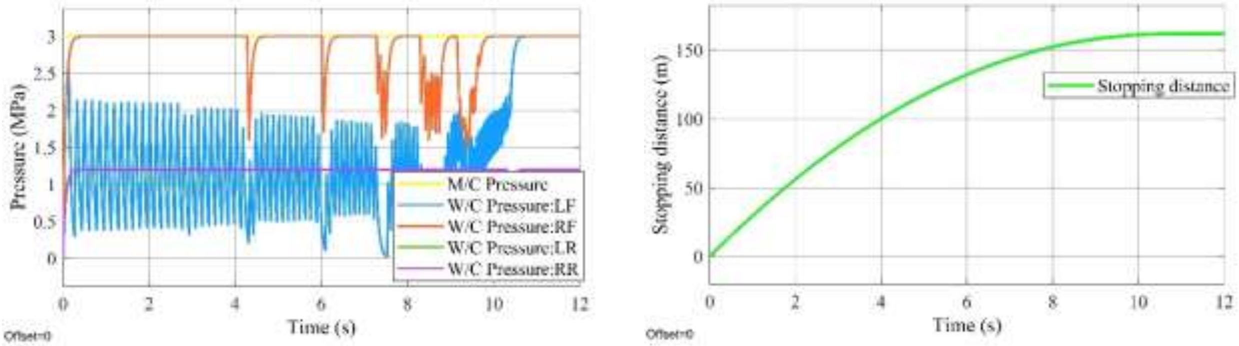
c) Wheel and master cylinder pressure

d) Stopping distance

Figure 25: Simulation results of ABS in CarSim at 60 km/hr



a) Vehicle velocity b) Wheel velocity



c) Wheel and master cylinder pressure d) Stopping distance

Figure 26: Simulation results of ABS in CarSim at 100 km/hr.

At the end of the simulation, it gives the required wheel cylinder pressure that is to be applied to each wheel of the vehicle and the wheel control pressure increases quickly back to system or master cylinder pressure as the vehicle velocity drops below the velocity threshold and comes to rest, as shown in Figure 25 (c). From the simulation results, the wheel cylinder pressure variation has been obtained for each wheel. The front and rear brake system pressure have their own proportion and the front brake pressure is more compared to the rear.

The MATLAB/Simulink result (Figure 23 & 24) shows that the stopping distance and stopping time are about 64 m and 7.2 s at an initial speed of 60 km/hr respectively. While the stopping distance is about 155 m and the time taken is 12 s with an initial speed of 100 km/hr under dry road conditions. When the CarSim result (Figure 25 & 26) shows that the stopping distance and stopping time are about 60 m and 6.7 s respectively at an initial speed of 60 km/hr, and the stopping distance is about 153 m and the time taken is 10.5 s at an initial speed of 100 km/hr.

When the results obtained from both the models are compared, it is seen that the model which is developed in the CarSim software gives more accurate, detailed and precise results than the model in the MATLAB software. This happens because the quarter model of a vehicle is considered to develop the MATLAB/Simulink model while a full-vehicle system model is used in CarSim. Hence, it is concluded that the developed controller for a quarter vehicle model has fast convergence and good performance.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1. Conclusion

Two simulations illustrating the effect of ABS on vehicle braking system handling were presented in this study; in MATLAB/Simulink and CarSim. The quarter vehicle is modeled and its brake performance is studied in MATLAB/Simulink using a fuzzy logic controller and interlinked with CarSim software. A comparison has also been made with a proposed ABS model in order to investigate the performance of the controller. The new proposed control strategy has been simulated for SUV and makes the vehicle act as smart equipment under complex driving conditions. The simulation results show that the proposed fuzzy logic controller ensures avoidance of wheel locking, even in different road conditions, even if the braking time and distance increase as the friction coefficient reduces. For both wheels and vehicle, the velocity curves converging at a point when the vehicle is stopped. Thus, the controller ensures the vehicle stops without skidding. It ensures that the anti-lock braking system definitely guarantees higher speeds with minimum risks by reducing the stopping distance and maintaining the stability of the vehicle.

The vehicle stability and braking performance have been improved by contributing additional braking with the help of a fuzzy logic controller strategy to the standard EBD and conventional braking systems. The proposed controller shows better performance to minimize the slip error as compared to the conventional controller, and hence, it maintains the stability of the vehicle and reduces the stopping distance of the vehicle.

The simulation was also carried out in CarSim software interlinked with the MATLAB/Simulink for validation purposes and in order to overcome some disadvantages of the ABS model, and the result shows that the wheel cylinder pressure is regulated appropriately and the braking stability is improved under the simulation process.

6.2. Recommendation

ABS is an enhancement to the braking system and it can be upgraded to more advanced features with shorter braking distances.

In this study, the quarter model of a vehicle is considered, which may have disadvantages like the model developed is only for the single wheel and simulation results are obtained for the single wheel agrees with car sim results in which the full dynamics of the vehicle is modeled and simulated. So, a half-vehicle o a full-vehicle system model in MATLAB/ Simulink and, incorporating the model of the ABS into a full vehicle model and comparing the simulation results with the vehicle test results will be future work.

The model behavior can also be further studied by considering different coefficients of friction under the circumstances of different road conditions and shapes.

And also, a reduction in stopping distance and stability of the vehicle is expected to be provided by ABS during straight-line braking, and this work can further be extended to braking along curved roads with lateral forces.

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APPENDIX A

SIMULATION DATA

The Specification, Technical Parameter, Configuration of the Products of Super Urban Vehicle (SUV) taken from Bishoftu Automotive Industry

Table 5:Super urban vehicle specifications

Speci-fication	**Description and value of SUV**
Perfor-mance	- Min. steering diameter (m)-------- 12 - Max. speed km/hr ------------------- 130 - Fuel tank capacity (L) --------------- 90 - AC capacity (kpa) -------------------0.55 - Parking brake grade angle (min) -----20^0 5min. not move - Idling speed (rpm) ------------------ 800 - Emission ------------------------------ Euro III -ON road speed performance------------------130 OFF road speed performance------------------90
Dimension	- Over all (l x w x h) mm -------- 4620 x 180 x 1830 - Frame (L x W) mm ---------------- 4470 x 1740 - Cabin (l x h x w) mm -------- - Wheel base (mm) ------2730 - Wheel track front/rear (mm) --------- 1480/1492 - Min ground clearance (mm) ---------- 220
Electrical system	- Type single line negative grounded - Generator -------------------------- 12v/100A - Battery ----------------------------- 12V/90A - Starter ------------------------------ 12V
Mass	- Curb weight of chassis (kg) ---------------910 - Axle load distribution front (kg) ---------- 1150 - Axle load distribution rear (kg) -----------1360 - G.V.W (kg) ---------------------------------- 1860 - Complete vehicle weight (kg) -------------2510 - Max load capacity (kg) ------------------- 2510
Engine	- Model ------------------------------- R425DOHC - 4 cylinder in line, 4 stroke, turbo charger, water cooled, inter cooler, electric control, common rail diesel engine -1 cylinder with 4 valves - Displacement----------2499cc -Max output power (kw/r/min) --------- 105/4000 - Max torque (Nm/r/min) ----------------340/2000 - Min fuel conception (g/kwh) ------------ 210 - Fuel conception (L/km) -----1L/12km
Clutch	- Single disc, dry type, friction clutch
Gear Box	- Mechanism ------------ 5 gear, reverse gear - Manual operated ------ 4 WD and 2 WD - Gear ratio ---I:4.016; II:2.318; III:1.401; IV:1.000; V:0.778; R:3.549
Steering mechanism	- Model ------- ZDZ7 - Circulating ball power steering, hydraulic assisted

Specification	**Discription and value of SUV**
Rack	- Front over suspension ------- Dual cross member independent, torsion bar - Rear cover suspension ------- torsion bar,5 bar coil spring
Wheel	- Rim --------- Aluminum type,17 inch - Tire ----------235/75R Spare tire
Cab	- Type ---------- all metal closed with AC - Seats ---------- 5 seats - electronic type AC and DVD entertainment system with Bluetooth - Door ---------- has indicator light has remote control - Seat cloth ---- leather laminated - Remote control of rearview mirror - Motor operated window glass - Electrical control of side indicator light under rear view mirror
Frame	- Mitsubishi tech.
Wheel Alignment	- Camber angle --------- $10'$-1^0 $10'$ - Caster angle ----------- 2^0 - 4^0 - Tow in (mm) ---------- - Tow out (mm) --------- * The gap should be in – out (3 – 5) (mm)
Others	- Car model ------------- DD6470C - Color ------------------- Silver/black - Safety energy absorbing steering column -Air bag -camera capacity on Reveres gear--------- -Media player-------------------DVD + Bluetooth + GPS
Braking	- Parking brake ------- Handle cable, central control, Drum type - Front brake ------ Disc type - Rear brake ------ Disc type -Brake type--------ABS+EBD

Modeling and simulation parameters

```
clear all
close all
clc
V0=17; % initial speed of the vehicle in m/s
m=450; % quarter mass of the vehicle in kg
g=9.81; % gravitational acceleration in m/s^2
J=0.65; % moment of inertia in kg*m^2
R=0.31; % radius of the wheel in m
Tb=1200; %maximum braking torque in Nm
```

Graph editing command tools

```
set(0,'ShowHiddenHandles','on')
set(gcf,'menubar','figure')
```

Coefficient of friction and slip data for wet and wet road conditions

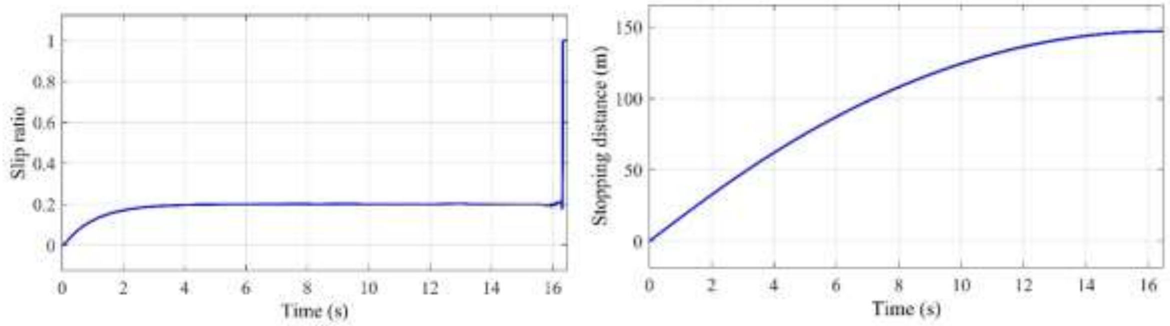
Table 6:Coefficient of friction and slip data

Coefficient of friction (μ)	Slip (λ)		
	Dry	Wet	Ice
0	0	0	0
0.05	0.25	0.14	0.06
0.1	0.5	0.28	0.12
0.15	0.7	0.4	0.17
0.2	0.9	0.45	0.2
0.25	0.899	0.448	0.198
0.3	0.88	0.44	0.195
0.35	0.86	0.43	0.194
0.4	0.84	0.42	0.192
0.45	0.83	0.41	0.19
0.5	0.82	0.4	0.188
0.55	0.81	0.39	0.186
0.6	0.8	0.38	0.185
0.65	0.79	0.37	0.183
0.7	0.78	0.36	0.18
0.75	0.77	0.35	0.178
0.8	0.75	0.34	0.175
0.85	0.73	0.33	0.173
0.9	0.72	0.32	0.17
0.95	0.71	0.31	0.165
1	0.7	0.3	0.162

APPENDIX B

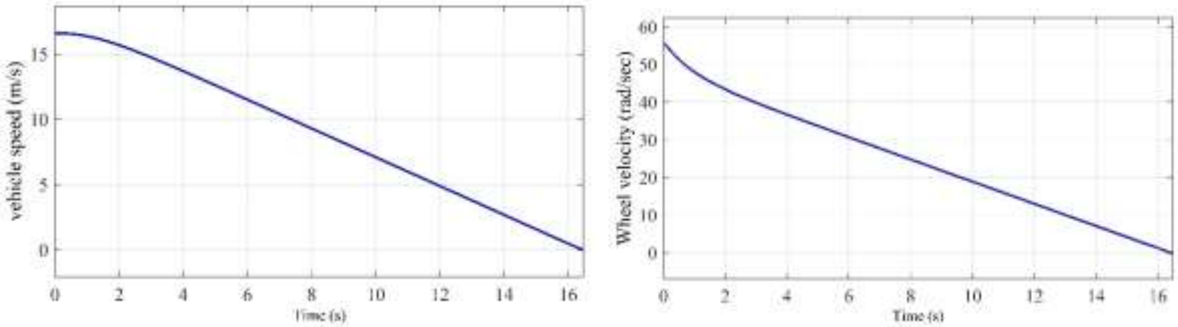
EXTRA SIMULATION PLOTS

Simulation results of ABS in MATLAB/Simulink at vehicle speed of 60 km/hr and wet road conditions.



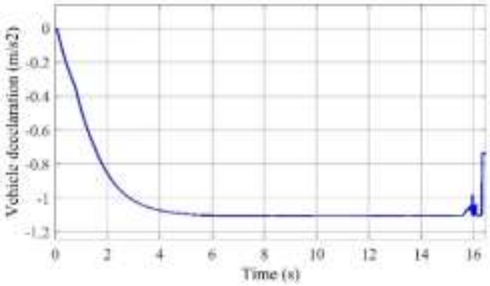
a) Slip ratio

b) stopping distance



c) vehicle speed

d) Wheel velocity



e) vehicle deceleration

Figure 27: Simulation results of ABS with fuzzy logic controller in wet road condition at 60 km/hr