APPLICATION OF FUZZY CONTROL: SAFE BRAKING IN AUTOMOBILE USING ABS CONTROL SYSTEM

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
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ELECTRONICS AND COMPUTER ENGINEERING
(With Specialization in Control and Guidance)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is presented in this dissertation report, titled **"Application of Fuzzy control: Safe braking in automobile using ABS control system"**, being submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **Control and Guidance**, in the Department of Electronics and Computer Engineering, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out from July 2009 to June 2010, under guidance and supervision of **Dr. R. MITRA**, Professor, Department of Electronics and Computer Engineering, Indian Institute of Technology, Roorkee.

The results embodied in this dissertation have not submitted for the award of any other Degree or Diploma.

Date : 30/6/2010
Place: **Roorkee**

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CERTIFICATE

This is to certify that the statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Antilock braking system (ABS) is a control system used in vehicle for avoiding wheel locking which may occur during panic braking or because of the low frictional road surface. ABS developed at starting stage was having four wheel sensors along with actuators and an Electronic Control Unit (ECU) which was nothing but the simple ON-OFF controller. Now a days ABS comes with a faster ECU which can handle more inputs from more sensors. Also modern controlling techniques are used to control wheel speed such as neural control technique, sliding mode control technique, fuzzy logic control technique etc.

The main objective of this work is to control the brake wheel pressure by considering the vertical load on rear wheels. Since the rear wheels are more responsible for stability of vehicle. Also another goal of this work is to reduce the stopping distance while cornering along with improved lateral stability.

The controlling technique used in this work is fuzzy logic with Mamdani's fuzzy inference method. There are three inputs for the fuzzy controller Yaw rate error, wheel slip and the vertical force on a wheel. The output of controller is brake pressure for rear wheels. Results for this controller with three different road conditions and two different steering inputs are compared with the traditional ABS. Three different road conditions used are high μ, low μ and split μ road surfaces whereas the steering inputs used are J-turn test steering signal and sinusoidal steering signal. The simulation environment is created with the help of CarSim8 software and controlling is done with MATLAB & SIMULINK.

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Chapter 1: Introduction

1.1. General

Vehicle model is highly nonlinear system with high Degree-Of-Freedom[1]. Antilock braking systems (ABS) are designed to stop vehicles as safely and quickly as possible. The application of ABS has been a great improvement in the automotive industry. Due to its high cost, the first ABS has been used in airplanes to reduce the braking distance. Now a days ABS is widely used in automotive industry.

Current ABS designs typically use wheel speed compared to the velocity of the vehicle to measure when wheels lock (i.e., when there is “slip” between the tire and the road) and use this information to adjust the duration of brake signal pulses (i.e., to “pump” the brakes).

At large slip angles, changing the steering angle produces very little change in the yaw rate of the vehicle. On dry roads, vehicle manoeuvrability is lost at vehicle slip angles greater than 10°, while on packed snow, this occurs at slip angles as low as 4°. Owing to this change in vehicle behaviour, a driver finds it difficult to drive at the limits of physical adhesion. First, the driver is often not able to recognize that the friction coefficient has changed, and has no idea of the vehicle’s stability margin. Second, if the limit of adhesion is reached and the vehicle skids, the driver is caught by surprise and very often reacts inappropriately, usually oversteering. Third, because of other traffic on the road, minimizing the dependence on correct action on the part of the driver is important. Lateral stability control systems address these issues to reduce the deviation of the vehicle from its normal dry-road behaviour by preventing the vehicle slip angle from becoming too large.

1.2. Challenges and Demand

As the wheel slip increases past a critical point where it is possible that lateral stability (and hence our ability to steer the vehicle) could be lost, the controller releases the brakes. Then, once wheel slip has decreased to a point where lateral stability is increased and braking effectiveness is decreased, the brakes are reapplied. Inherent process nonlinearities, limitations on our abilities to sense certain variables, and uncertainties associated with process and environment (e.g., road conditions changing from wet asphalt to ice) make the ABS control problem challenging.

In general, there are two kinds of ABS systems, one is based on the wheel deceleration, the other is based on the wheel slip ratio[2]. According to a survey study by Manning and Crolla, three methods are applied to control vehicle lateral handling: yaw rate control, slip angle (side-slip) control, and combined yaw and slip angle control. These control methods are performed by left–right differential braking, roll motion distribution (RMD) in the suspension system, or an active front or rear steer (AFS or ARS) system. However, RMD, AFS, or ARS systems require additional hardware and have limited effectiveness, depending on the driving conditions[3].

When braking force is applied to a rolling wheel, it begins to slip, i.e., the wheel circumferential velocity v_w will be less than the vehicle velocity v_v. Slip λ is defined as the difference between vehicle velocity and wheel circumferential velocity normalized to the vehicle velocity. If sufficient braking force is applied, wheel slip and wheel deceleration will increase, and the wheel will lock up. A locked wheel has no lateral stability. Most control strategies define their performance goal as maintaining slip near a value of 0.2 throughout the braking trajectory[4].

1.3. Problem description

Many successful proprietary algorithms exist for the control logic for ABS. In addition, several conventional nonlinear control approaches have been reported in the open literature. Various control techniques that maintain the wheel slip to a desired level have been developed. Some of the approaches that were proposed in the design of ABS controller consist of sliding mode, fuzzy, fuzzy-neural, fuzzysliding mode, and fuzzy-neural sliding mode. Some of these methods have not shown proper performance for different road conditions. Conventional/traditional ABS has high stopping distances and high oscillations especially on icy road.

In this work, a fuzzy controller, is proposed for ABS. The input variables to the controller are yaw rate error, wheel slip and the vertical force on a wheel. The objective function is defined to maintain the wheel slip to a desired level so that maximum wheel traction force and maximum vehicle deceleration are obtained. The performance of the proposed controller is simulated with the help of CarSim vehicle model considering the effect vertical force on individual rear wheel, with the hydraulic brake system, for different road conditions. Road conditions used here are low frictional surface, dry road surface and split μ road surface. Two tests are taken for results. In the J-turn test the steering angle is increased to 25 deg within 2 sec and in sinusoidal steering angle test a signal with 30 deg amplitude and 0.2 Hz frequency is used.

1.4. Organization of the work

This report has been organized into seven chapters. This chapter presents a general introduction, challenges and demand and problem description. Second chapter give an idea about vehicle dynamics in which forces acting on vehicle and steady state turning are discussed briefly. Third chapter contains principle and working of ABS. Fourth chapter tells about the brake hydraulic system their braking modes and functioning. Fifth chapter contains information about fuzzy logic which is used as the controlling techniques. Sixth chapter is about the simulation results obtained by MATLAB & SIMULINK and CarSim8 for different conditions. Seventh chapter presents the conclusion of the study and suggestions are given for further study of this subject.

Chapter 2: Vehicle dynamics

2.1. Introduction

It has often been said that the primary forces by which a high speed motor vehicle is controlled are developed in four patches-each the size of man's hand-where the tires contact the road. This is indeed the case. Knowledge of forces and moments generated by pneumatic (rubber) tires at the ground is essential to understanding highway vehicle dynamics. Vehicle dynamics in its broadest sense encompasses all forms of conveyance-ships, airplanes, railroad trains, track-laying vehicles as well as rubber tired vehicles[5].

Inasmuch as the performance of a vehicle-the motions accomplished in accelerating, braking, cornering and ride-is a response to forces imposed, much of the study of vehicle dynamics must involve the study of how and why the forces are produced. The dominant forces acting on a vehicle to control performance are developed by the tire against the road. Thus it becomes necessary to develop an intimate understanding of the behaviour of tires, characterized by the forces and moments generated over the broad range of conditions over which they operate.

2.2. Vehicle Coordinate Frame

The equations of motion in vehicle dynamics are usually expressed in a set of vehicle coordinate frame $B(Cxyz)$, attached to the vehicle at the mass centre C, as shown in Figure 1. The x-axis is a longitudinal axis passing through C and directed forward. The y-axis goes laterally to the left from the driver's viewpoint. The z-axis makes the coordinate system a righthand triad. When the car is parked on a flat horizontal road, the z-axis is perpendicular to the ground, opposite to the gravitational acceleration g[6].

Orientation is shown with three angles roll angle φ about the x-axis, pitch angle θ about the y-axis, and yaw angle ψ about the z-axis. We use special character to show *roll rate, pitch rate,* and *yaw rate.*

$$\dot{\varphi} = p \qquad \text{.... (2.1)}$$

$$\dot{\theta} = q \qquad \text{.... (2.2)}$$

$$\dot{\psi} = r \qquad \text{.... (2.3)}$$

The resultant of external forces and moments, that the vehicle receives from the ground and environment, makes the vehicle force system (F,M). This force system will be expressed in the body coordinate frame.

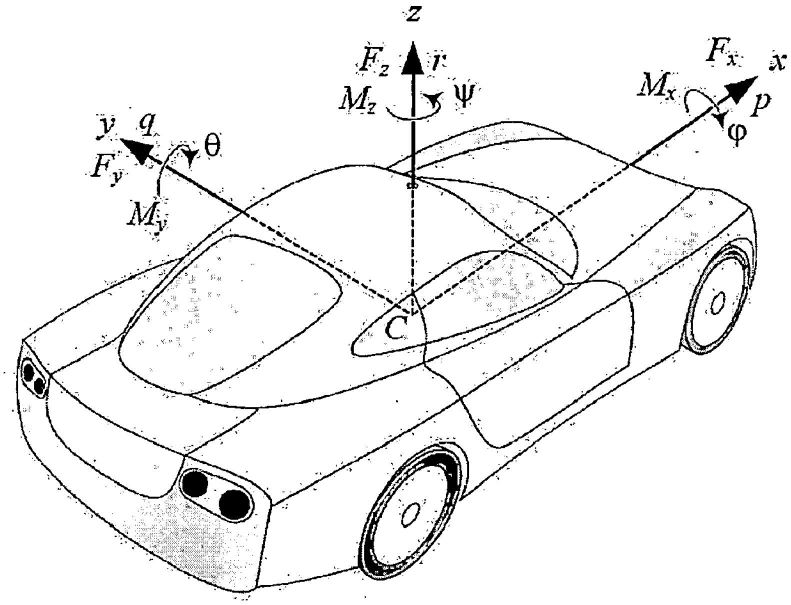


Fig 2.1 Vehicle body coordinate frame $B(Cxyz)$

$$B_F = F_x\hat{i} + F_y\hat{j} + F_z\hat{k} \qquad \text{.... (2.4)}$$

$$B_M = M_x\hat{i} + M_y\hat{j} + M_z\hat{k} \qquad \text{.... (2.5)}$$

The individual components of the 3D vehicle force system are shown in fig 2.2. These components have special names and importance.

1. *Longitudinal force* F_x. It is force acting along the x-axis. The resultant $F_x > 0$ if the vehicle is accelerating, and $F_x < 0$ if the vehicle is braking. Longitudinal force is also called forward force, or traction force.

2. *Lateral force* F_y. It is an orthogonal force to both F_x and F_z. The resultant $F_y > 0$ if it is leftward from the driver's viewpoint. Lateral force is usually a result of steering and is the main reason to generate a yaw moment and turn a vehicle.

3. *Normal force* F_z. It is a vertical force, normal to the ground plane. The resultant $F_z > 0$ if it is upward. Normal force is also called vertical force or vehicle load.

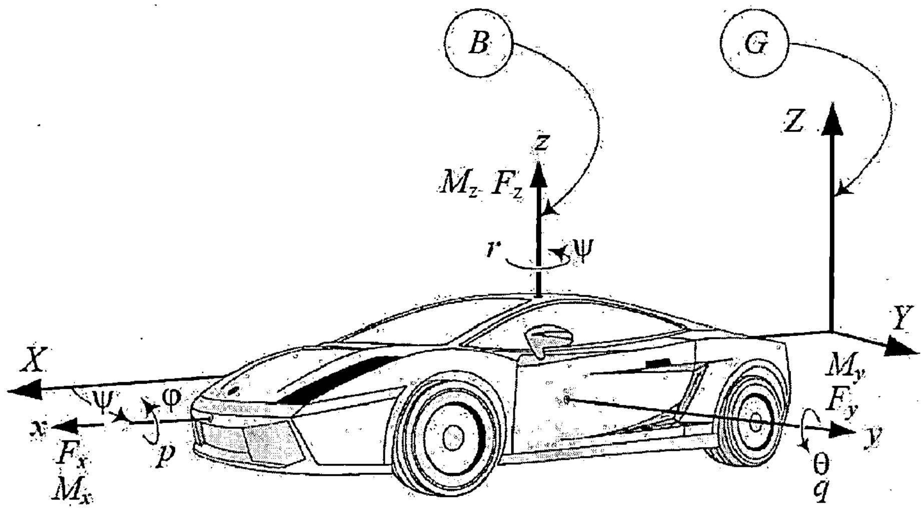


Fig 2.2 Illustration of a moving vehicle, indicated by its body coordinate frame *B* in a global coordinate frame *G*

4. *Roll moment* M_x. It is a longitudinal moment about the x-axis. The resultant $M_x > 0$ if the vehicle tends to turn about the *x*-axis. The roll moment is also called the bank moment, tilting torque, or overturning moment.

5. *Pitch moment* M_y. It is a lateral moment about the y-axis. The resultant $M_y > 0$ if the vehicle tends to turn about the y-axis and move the head down.

6. *Yaw moment* M_z. It is an upward moment about the z-axis. The resultant $M_z > 0$ if the tire tends to turn about the z-axis. The yaw moment is also called the aligning moment.

The position and orientation of the vehicle coordinate frame *B*(*Cxyz*) is measured with respect to a grounded fixed coordinate frame *G(OXY Z)*.

The vehicle coordinate frame is called the body frame or vehicle frame, and the grounded frame is called the global coordinate frame. Analysis of the vehicle motion is equivalent to expressing the position and orientation of *B(Cxyz)* in *G(OXY Z)*. fig 2.2 shows how a moving vehicle is indicated by a body frame *B* in a global frame *G*.

The angle between the x and X axes is the yaw angle ψ and is called the heading angle. The velocity vector v of the vehicle makes an angle β with the body x-axis which is called sideslip angle or attitude angle. The vehicle's velocity vector v makes an angle $\beta + \psi$ with the global X-axis that is called the cruise angle. These angles are shown in the top view of a moving vehicle in fig 2.3.

There are many situations in which we need to number the wheels of a vehicle. We start numbering from the front left wheel as number 1, and then the front right wheel would be number 2. Numbering increases sequentially on the right wheels going to the back of the vehicle up to the rear right wheel. Then, we go to the left of the vehicle and continue numbering the wheels from the rear left toward the front. Each wheel is indicated by a position vector r_i

$$B_{r_i} = x_i i + y_i j + z_i k \qquad \ldots. (2.6)$$

expressed in the body coordinate frame B. Numbering of a four wheel vehicle is shown in fig 2.3.

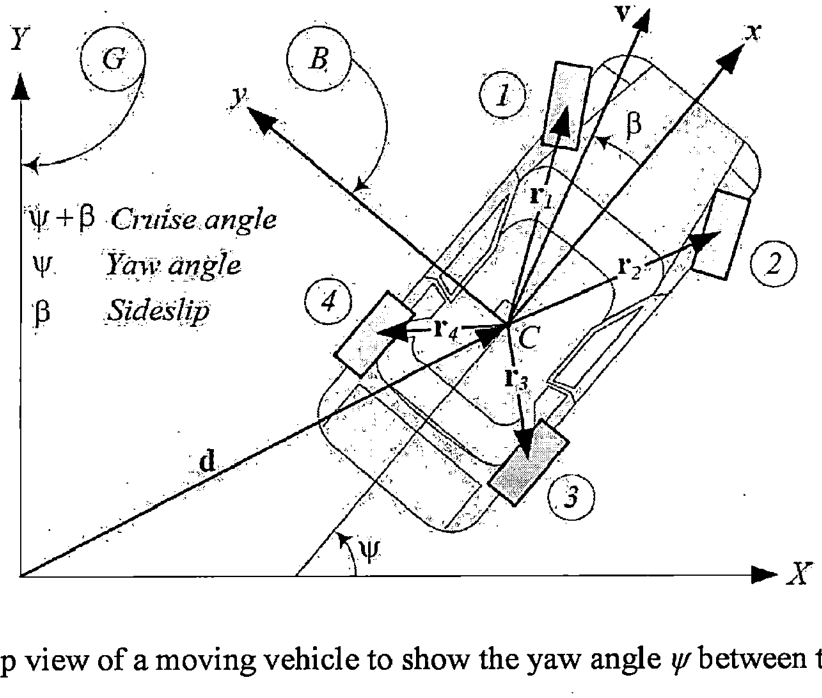


Fig 2.3 Top view of a moving vehicle to show the yaw angle ψ between the x and X axes, the sideslip angle β between the velocity vector v and the x-axis, and the Crouse angle $\beta + \psi$ between with the velocity vector v and the X-axis

2.3. Rigid Vehicle Newton-Euler Dynamics

A rigid vehicle is assumed to act similar to a flat box moving on a horizontal surface. A rigid vehicle has a planar motion with three degrees of freedom that are: translation in the x and y directions, and a rotation about the z-axis. The *Newton-Euler equations of motion* for a rigid vehicle in the body coordinate frame B, attached to the vehicle at its mass centre C are:

$$F_x = m\dot{v}_x - m\omega_z v_y \qquad \text{.... (2.7)}$$

$$F_y = m\dot{v}_y + m\omega_z v_x \qquad \text{.... (2.8)}$$

$$M_z = \dot{\omega}_z I_z \qquad \text{.... (2.9)}$$

2.4. Force System Acting on a Rigid Vehicle

To determine the force system on a rigid vehicle, first we define the force system at the tireprint of a wheel. The lateral force at the tireprint depends on the sideslip angle. Then, we transform and apply the tire force system on the body of the vehicle.

2.4.1 Tire Force and Body Force Systems

Fig 2.4 depicts wheel number 1 of a vehicle. The components of the force system in the xy-plane applied on a rigid vehicle, because of the generated forces at the tireprint of the wheel number i, are

$$F_{xi} = F_{x_{\omega i}} \cos\delta_i - F_{y_{\omega i}} \sin\delta_i \qquad \text{.... (2.10)}$$

$$F_{yi} = F_{y_{\omega i}} \cos\delta_i + F_{x_{\omega i}} \sin\delta_i \qquad \text{.... (2.11)}$$

$$M_{zi} = M_{z_{\omega i}} + x_i F_{yi} - y_i F_{xi} \qquad \text{.... (2.12)}$$

Therefore, the total planar force system on the rigid vehicle in the body coordinate frame is

$$\begin{aligned} B_{F_x} &= \sum_i F_{x_i} \\ &= \sum_i F_{x_\omega} \cos\delta_i - \sum_i F_{y_\omega} \sin\delta_i \qquad \text{.... (2.13)} \\ B_{F_y} &= \sum_i F_{yi} \end{aligned}$$

$$= \sum_i F_{y_w} \cos\delta_i + \sum_i F_{x_\omega} \sin\delta_i \qquad \ldots.\ (2.14)$$

$$B_{M_z} = \sum_i M_{zi} + \sum_i x_i F_{yi} - \sum_i y_i F_{xi} \qquad \ldots.\ (2.15)$$

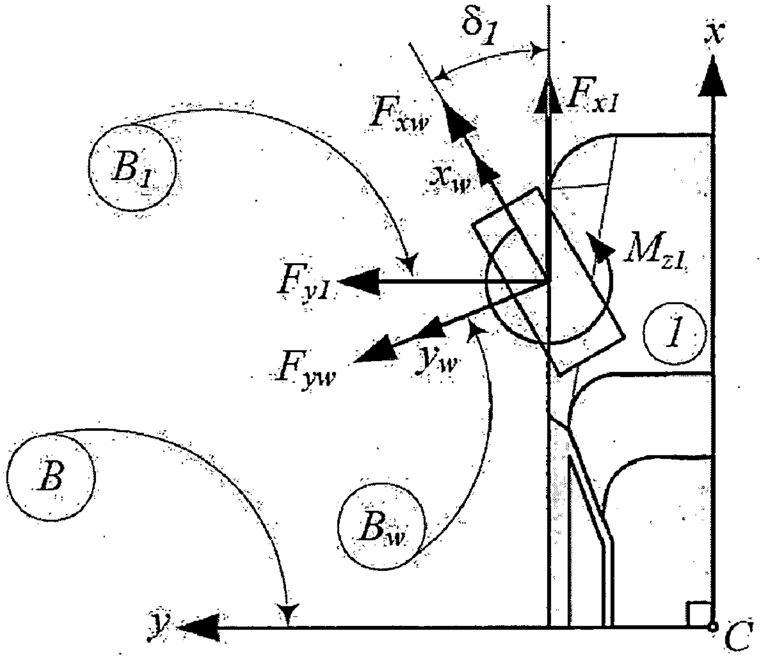


Fig 2.4 The force system at the tireprint of tire number 1

2.4.2 Tire Lateral Force

Fig 2.5 illustrates a tire, moving along the velocity vector v at a sideslip angle α. The tire is steered by the steer angle δ. If the angle between the velocity vector v and the vehicle x-axis is shown by β, then

$$\alpha = \beta - \delta \qquad \ldots.\ (2.16)$$

The lateral force, generated by a tire, is dependent on sideslip angle α that is proportional to the sideslip for small α.

$$F_y = -C_\alpha \alpha$$

$$= -C_\alpha(\beta - \delta) \qquad \ldots.\ (2.17)$$

2.4.3 Two-wheel Model and Body Force Components

Fig 2.6 illustrates the forces in the xy-plane acting at the tireprints of a front-wheel-steering four-wheel vehicle. When we ignore the roll motion of the vehicle, the xy-

plane remains parallel to the road's XY-plane, and we may use a two-wheel model for the vehicle. Fig 2.7 illustrates a two-wheel model for a vehicle with no roll motion. The two-wheel model is also called a bicycle model, although a two-wheel model does not act similar to a bicycle.

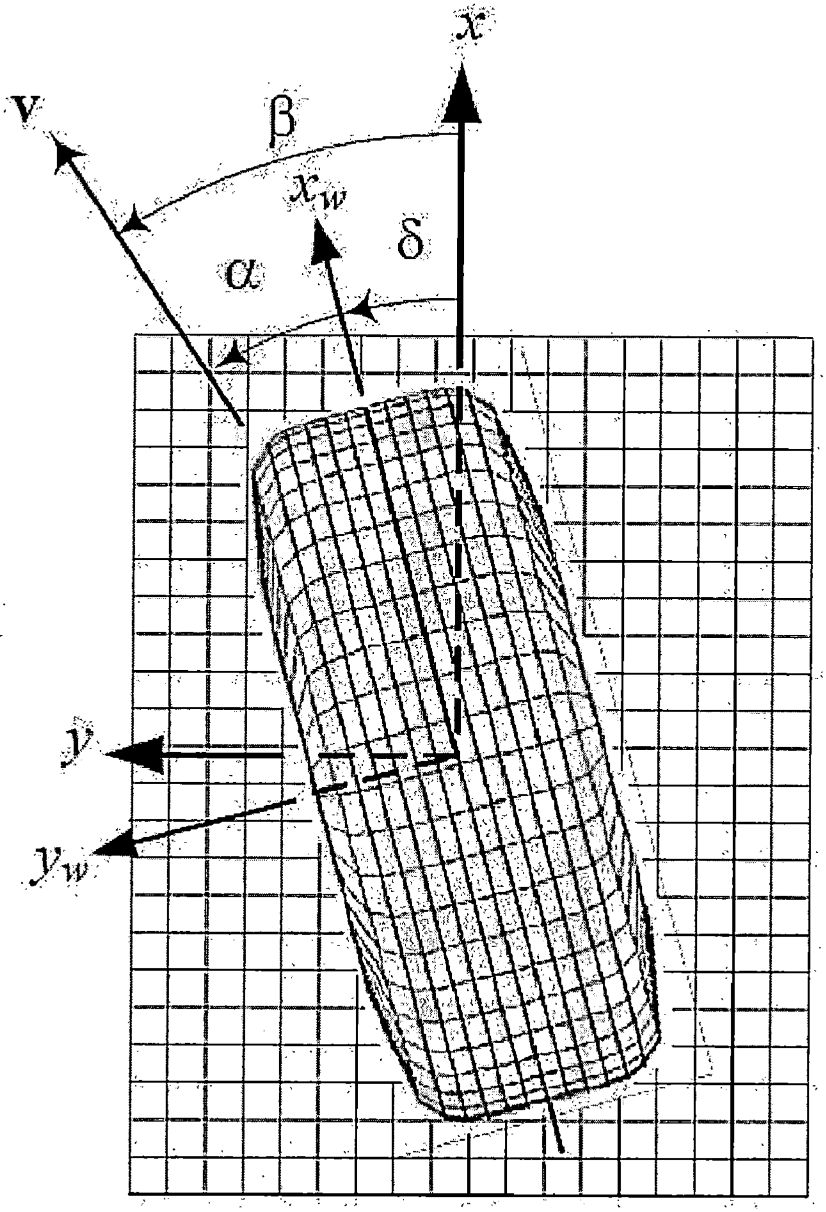


Fig 2.5 Angular orientation of a moving tire along the velocity vector v at a sideslip angle α and a steer angle δ

The force system applied on a two-wheel vehicle, in which only the front wheel is steerable, is

$$F_x = F_{x_f} \cos\delta + F_{x_r} - F_{y_f} \sin\delta \qquad \text{.... (2.18)}$$

$$F_y = F_{y_f} \cos\delta + F_{y_r} + F_{x_f} \sin\delta \qquad \text{.... (2.19)}$$

$$M_z = \alpha_1 F_{y_f} - \alpha_2 F_{y_r} \qquad \text{.... (2.20)}$$

where, (F_{x_f}, F_{x_r}) and (F_{y_f}, F_{y_r}) are the planar forces on the tireprint of the front and rear wheels. The force system may be approximated by the following equations, if the steer angle δ is assumed small:

$$F_x \approx F_{x_f} + F_{x_r} \qquad \text{.... (2.21)}$$

$$F_y \approx F_{y_f} + F_{y_r} \qquad \text{.... (2.22)}$$

$$M_z \approx a_1 F_{y_f} - a_2 F_{y_r} \qquad \text{.... (2.23)}$$

The vehicle lateral force F_y and moment M_z depend on only the front and rear wheels' lateral forces F_{y_f} and F_{y_r}, which are functions of the wheels sideslip angles α_f and α_r. They can be approximated by the following equations:

$$F_y \quad = \left(-\frac{a_1}{v_x} C_{\alpha f} + \frac{a_2}{v_x} C_{\alpha r} \right) r - (C_{\alpha f} + C_{\alpha r})\beta + C_{\alpha f}\delta \qquad \text{.... (2.24)}$$

$$M_z \quad = \left(-\frac{a_1^{\,2}}{v_x} C_{\alpha f} - \frac{a_2^{\,2}}{v_x} C_{\alpha r} \right) r - (a_1 C_{\alpha f} + a_2 C_{\alpha r})\beta + a_1 C_{\alpha f}\delta \qquad \text{.... (2.25)}$$

where $C_{\alpha f} = C_{\alpha f_L} + C_{\alpha f_R}$ and $C_{\alpha r} = C_{\alpha r_L} + C_{\alpha r_R}$ are equal to the sideslip coefficients of the left and right wheels in front and rear, respectively.

$$C_{\alpha f} = C_{\alpha f_L} + C_{\alpha f_R} \qquad \text{.... (2.26)}$$

$$C_{\alpha r} = C_{\alpha r_L} + C_{\alpha r_R} \qquad \text{.... (2.27)}$$

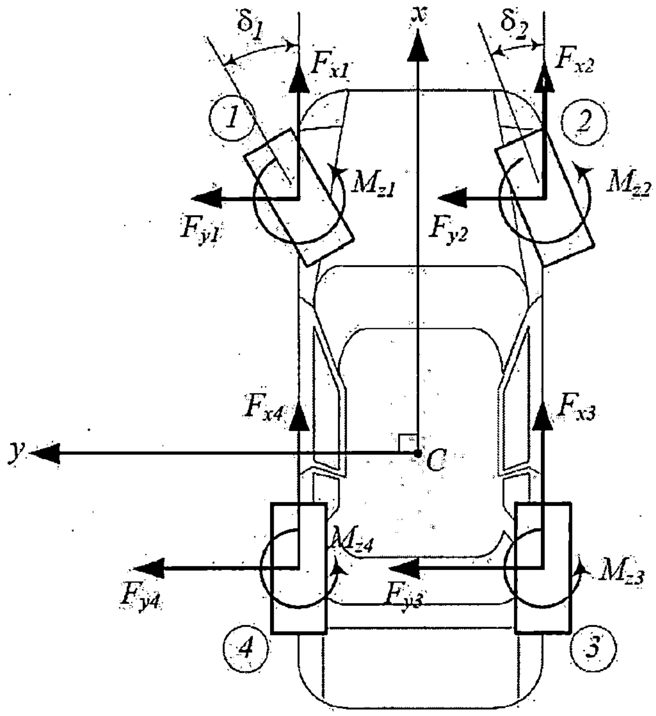


Fig 2.6 A front-wheel-steering four-wheel vehicle and the forces in the xy-plane acting at the trireprints

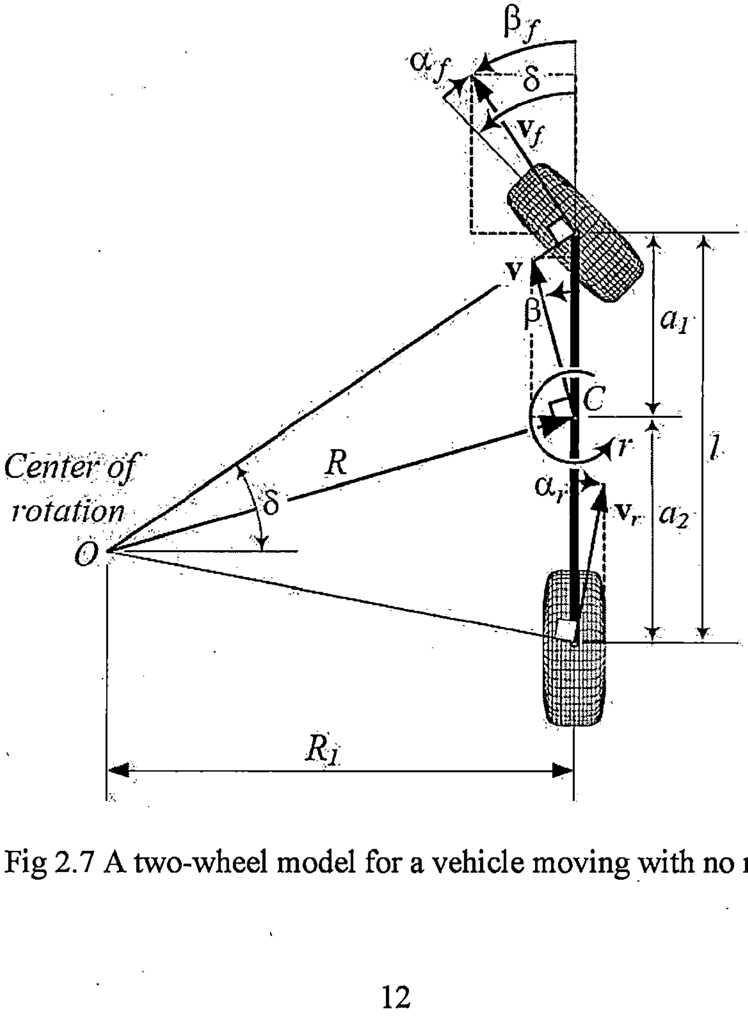


Fig 2.7 A two-wheel model for a vehicle moving with no roll

2.5. Two-wheel Rigid Vehicle Dynamics

We can approximate the planar equations of motion (2.7)-(2.9) along with (2.21)-(2.23) for a two-wheel rigid vehicle with no roll motion, and express its motion by the following set of equations:

$$\begin{aligned}\dot{v} &= \frac{1}{m}F_x + rv_y \\ &= \frac{1}{m}(F_{x_f} + F_{x_r}) + rv_y \end{aligned} \qquad \text{.... (2.28)}$$

$$\begin{aligned}\begin{bmatrix} \dot{v}_y \\ \dot{r} \end{bmatrix} &= \begin{bmatrix} \frac{C_\beta}{mv_x} & \frac{C_r}{m} - v_x \\ \frac{D_\beta}{I_z v_x} & \frac{D_r}{I_s} \end{bmatrix} \begin{bmatrix} v_y \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_\delta}{m} \\ \frac{D_\delta}{I_s} \end{bmatrix} \delta \\ &= \begin{bmatrix} -\frac{C_{\alpha f} + C_{\alpha r}}{mv_x} & \frac{-a_1 C_{\alpha f} + a_2 C_{\alpha r}}{mv_x} - v_x \\ -\frac{a_1 C_{\alpha f} - a_2 C_{\alpha r}}{I_z v_x} & -\frac{a_1^2 C_{\alpha f} + a_2^2 C_{\alpha r}}{I_z v_x} \end{bmatrix} \begin{bmatrix} v_y \\ r \end{bmatrix} \\ &\quad + \begin{bmatrix} \frac{C_{\alpha f}}{m} \\ \frac{a_1 C_{\alpha f}}{I_z} \end{bmatrix} \delta \end{aligned} \qquad \text{.... (2.29)}$$

These sets of equations are good enough to analyze a vehicle that is moving at a constant forward speed. Having $\dot{v}_x = 0$, the first equation (2.28) becomes independent, and the lateral velocity v_y and yaw rate r of the vehicle will change according to the two coupled equations (2.29).

Assuming the steer angle δ is the input command, the lateral velocity v_y and the yaw rate *r* may be assumed as the output. Hence, we may consider Equation (2.29) as a linear control system, and write them as

$$\dot{q} = [A]q + u \qquad \text{.... (2.30)}$$

in which $[A]$ is a coefficient matrix, q is the vector of control variables, and *u* is the vector of inputs.

$$[A] = \begin{bmatrix} -\frac{C_{\alpha f}+C_{\alpha r}}{mv_x} & \frac{-a_1C_{\alpha f}+a_2C_{\alpha r}}{mv_x}-v_x \\ -\frac{a_1C_{\alpha f}-a_2C_{\alpha r}}{I_z v_x} & -\frac{a_1^2C_{\alpha f}+a_2^2C_{\alpha r}}{I_z v_x} \end{bmatrix} \quad \text{.... (2.31)}$$

$$q = \begin{bmatrix} v_y \\ r \end{bmatrix} \quad \text{.... (2.32)}$$

$$u = \begin{bmatrix} \frac{C_{\alpha f}}{m} \\ \frac{a_1C_{\alpha f}}{I_z} \end{bmatrix}\delta \quad \text{.... (2.33)}$$

2.6. Steady-State Turning

The turning of a front-wheel-steering, two-wheel rigid vehicle at its steady-state condition is governed by the following equations:

$$F_x = -mrv_y \quad \text{.... (2.34)}$$

$$C_r r + C_\beta\beta + C_\delta\delta = mrv_x \quad \text{.... (2.35)}$$

$$D_r r + D_\beta\beta + D_\delta\delta = 0 \quad \text{.... (2.36)}$$

or equivalently, by the following equations:

$$F_x = -\frac{m}{R}v_x v_y \quad \text{.... (2.37)}$$

$$C_\beta\beta + (C_r v_x - mv_x^2)\frac{1}{R} = -C_\delta\delta \quad \text{.... (2.38)}$$

$$D_\beta\beta + D_r v_x\frac{1}{R} = -D_\delta\delta \quad \text{.... (2.39)}$$

The first equation determines the required forward force to keep v_x constant. The second and third equations show the steady-state values of the output variables, vehicle slip angle β, and path curvature κ.

$$\kappa = \frac{1}{R} \quad \text{.... (2.40)}$$

$$= \frac{r}{v_x} \quad \text{.... (2.41)}$$

for a constant steering input δ at a constant forward speed v_x. The outputinput relationships are defined by the following responses:

1– Curvature response, S_κ

$$\begin{aligned} S_\kappa &= \frac{\kappa}{\delta} \\ &= \frac{1}{R\delta} \\ &= \frac{C_\delta D_\beta - C_\beta D_\delta}{v_x(D_r C_\beta - C_r D_\beta + m v_x D_\beta)} \end{aligned} \qquad \text{.... (2.42)}$$

2– Sideslip response, S_β

$$\begin{aligned} S_\beta &= \frac{\beta}{\delta} \\ &= \frac{D_\delta(C_r - m v_x) - D_r C_\delta}{D_r C_\beta - C_r D_\beta + m v_x D_\beta} \end{aligned} \qquad \text{.... (2.43)}$$

3– Yaw rate response, S_r

$$\begin{aligned} S_r &= \frac{r}{\delta} \\ &= \frac{\kappa}{\delta} v_x \\ &= S_\kappa v_x \\ &= \frac{C_\delta D_\beta - C_\beta D_\delta}{D_r C_\beta - C_r D_\beta + m v_x D_\beta} \end{aligned} \qquad \text{.... (2.44)}$$

4– Lateral acceleration response, S_a

$$\begin{aligned} S_a &= \frac{v_x^2 / R}{\delta} \\ &= \frac{\kappa}{\delta} v_x^2 \\ &= S_\kappa v_x^2 \\ &= \frac{(C_\delta D_\beta - C_\beta D_\delta) v_x}{D_r C_\beta - C_r D_\beta + m v_x D_\beta} \end{aligned} \qquad \text{.... (2.45)}$$

Chapter 3: Anti-lock Braking System (ABS)

The ABS system aims at minimizing the braking distance while retaining steer-ability during braking. The shortest braking distance can be reached when the wheels operates at the slip of maximum adhesion co-efficient μ_L. The tire slip angle is disregarded here, approximating $\cos\alpha \approx 1$. The relation between wheel slip and adhesion coefficient is shown in fig 3.1.

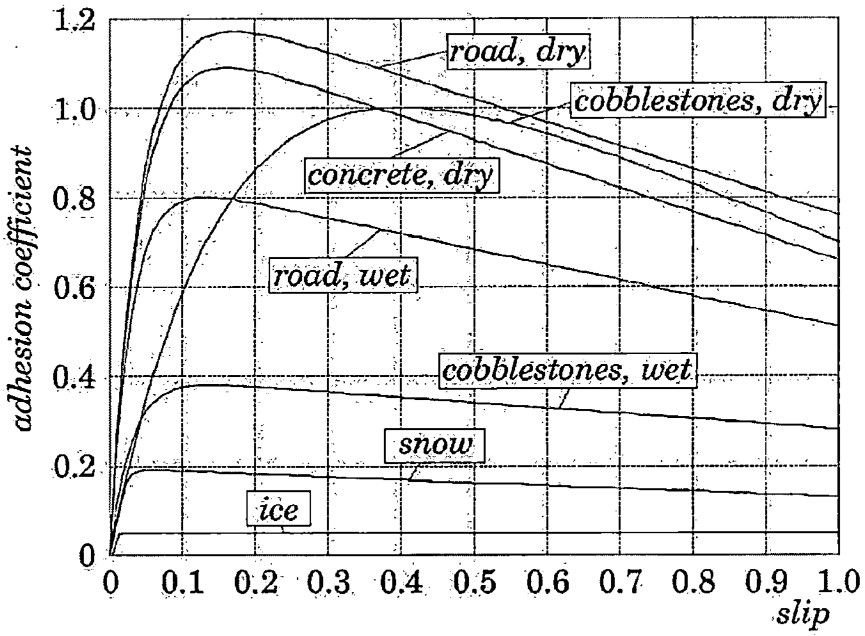


Fig 3.1 Typical cohesion coefficient characteristics

3.1. Torque balance at wheel-road contact

By modelling the torque balance at the wheel-road contact, a better understanding can be obtained of how ABS systems are able to operate around maximum friction without sophisticated estimation algorithm. Figure 3.2 shows the forces acting on the wheel[7].

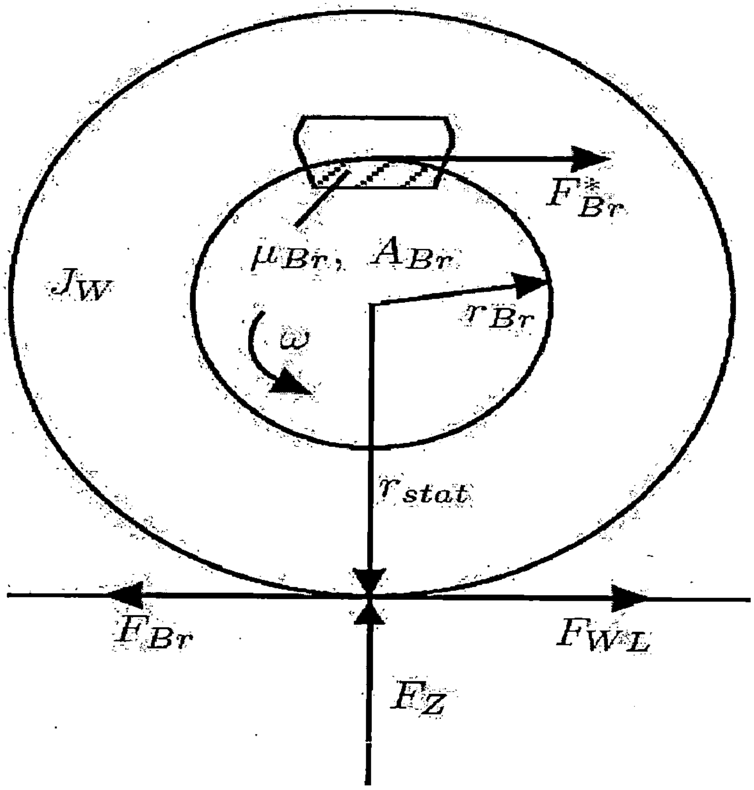


Fig 3.2 Torque balance at the wheel-road surface contact

Where $F^{\bullet}_{Br}$ braking force at brake disc

r_{Br} Effective braking radius

μ_{Br} Friction co-efficient of brakes

A_{Br} Brake area

P_{Br} Braking pressure

F_{Br} Brake force at wheel contact

T_{Br} Brake torque at wheel contact

ω Rotational wheel speed

J_W Wheel moment of inertia

F_Z Wheel ground contact force

F_{WL} Friction force

T_{WL} Friction torque

In hydraulic brakes, the brake torque at wheel base depends on the applied braking pressure p_{Br}:

$$T_{Br} = F_{Br}.r_{stat} = r_{stat}.k_{Br}.p_{Br} \qquad .... (3.1)$$

Disregarding the drive torque balance is

$$J_{W}\dot{\omega} = r_{stat}.\mu_L(s_L).F_Z - r_{stat}.k_{Br}.p_{Br} \qquad .... (3.2)$$

The respective block diagram is shown in fig 3.

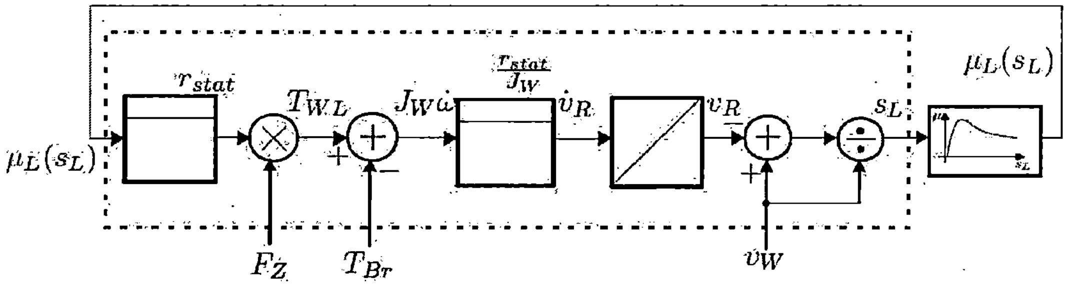


Fig 3.3 Block diagram of torque balance at wheel base

On applying the braking pressure p_{Br}, the brake torque T_{Br} increases. The difference between friction torque T_{WL} and brake torque T_{Br} is negative, resulting in a wheel deceleration. The wheel rotational equivalent velocity v_R starts to decrease and yields an increasing slip s_L. At first the friction co-efficient $\mu_L(s_L)$ increases as well, building up the friction torque T_{WL} which narrows the torque difference.

After passing the maximum friction co-efficient, the friction curve changes the sign of its gradient. Thus the loop becomes *unstable,* resulting, in the absence of control, in extremely high rotational wheel decelerations: blocking of wheel.

3.2. Principle

In a panic braking situation, the wheel speed sensors detect any sudden changes in wheel speed. The ABS ECU calculates the rotational speed of the wheels and the change in their speed, then calculates the vehicle speed. The ECU then judges the slip ratio of each wheel and instructs the actuator to provide the optimum braking pressure to each wheel. The hydraulic brake actuator operates on signals from the ABS ECU to **hold, reduce or increase** the brake fluid pressure as necessary, to maintain the optimum slip ratio of 10 to 30% and avoid wheel lockup[8]. It is also important to understand that ABS is not active during all stop.

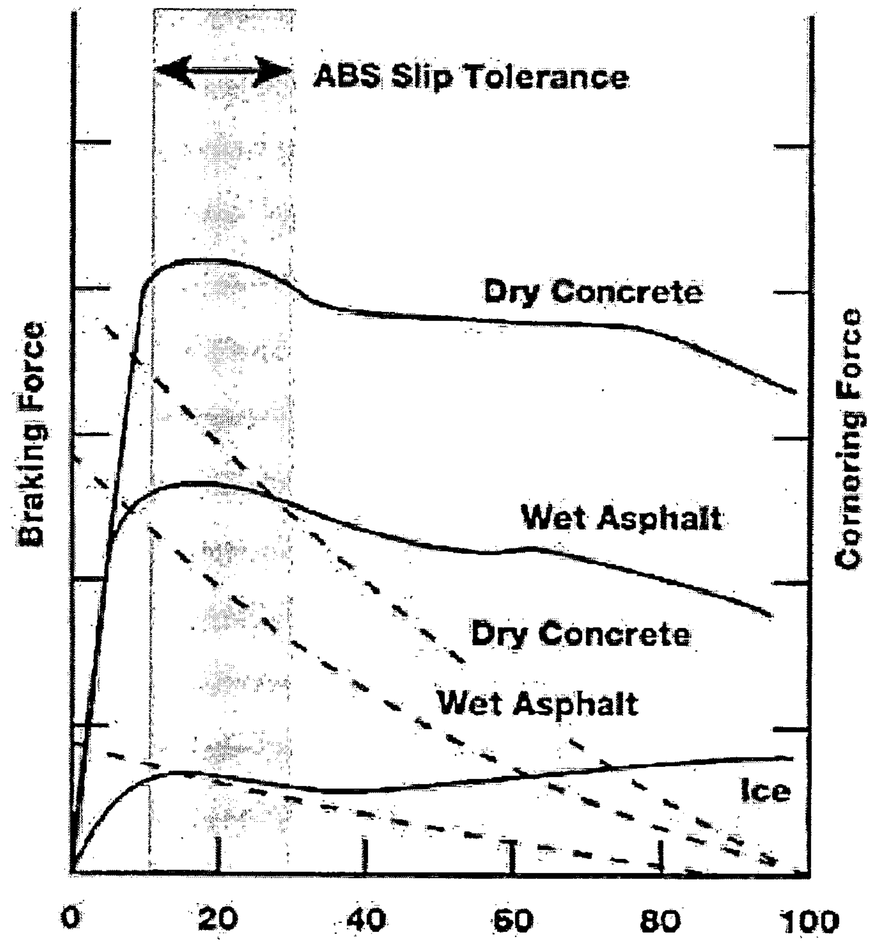


Fig 3.4 Braking force chart

From the above figure we can see that we will get maximum braking force if we keep slip ratio between 10 to 20%. In the figure solid line shows the longitudinal braking force where as dotted line represent lateral force. At 0% wheel is free wheel and at 100 % wheel is locked up.

3.3. Various layouts of ABS for passenger cars

The common layouts for passenger cars are of three types

a) four-channel and four-sensors configuration
b) three-channel and three-sensors configuration

c) three-channel and four-sensors configuration

A channel refers to the portion of the brake system that the control unit/modulator controls independently of the rest of the brake system e.g. hydraulic brake circuits[9].

3.4. Block diagram of Typical ABS control system

The ECU monitors the four wheel sensors processes the data and controls the actuator solenoids and pump motor through the ABS Relay[8]. Fig 3.5 shows the typical ABS control system block diagram.

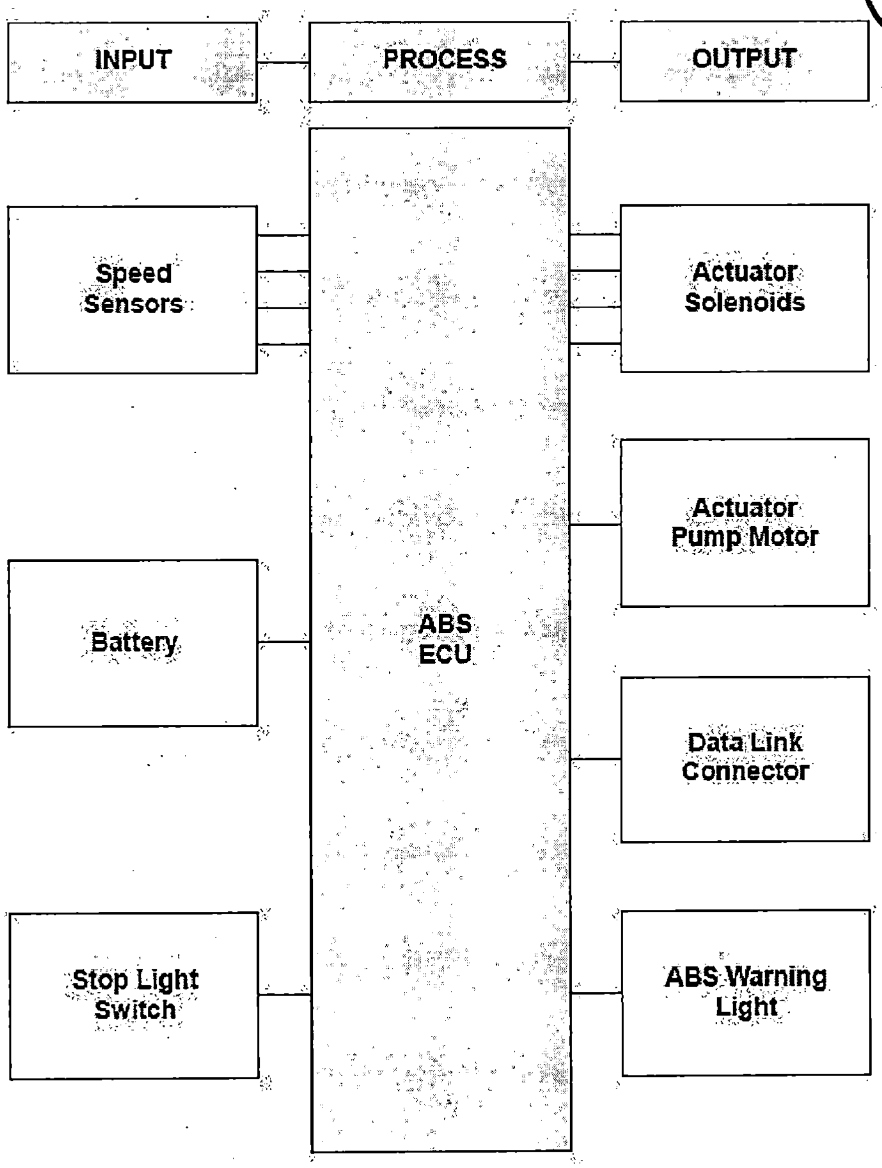


Fig 3.5 Typical ABS control system

3.5. Control cycle of ABS system

The ECU (Electronic Control Unit) continuously receives wheel speed signals from the speed sensors and deceleration sensors. By calculating the speed and deceleration of each wheel, the ECU estimates the vehicle speed. When the brake pedal is depressed, the hydraulic pressure in each disc brake cylinder begins to increase and wheel speed begins to decrease. If any of the wheels are near the lock up condition the ECU goes into a pressure hold mode to stop the increase of hydraulic pressure in the disc brake cylinder of that wheel[8].

SECTION A

The ECU sets the solenoid valves to the pressure reduction mode based on wheel speed, thus reducing the hydraulic pressure in the disc brake cylinder. After the pressure drops, the ECU switches the solenoid valve to the Holding mode and then monitors the change in the wheel speed. If the ECU judges that the hydraulic pressure needs to reduced further, it will return to reduction mode.

SECTION B

When the hydraulic pressure inside the disc brake cylinder decreases(SECTIONA), the hydraulic pressure applied to the wheel falls. This allows the wheel that was locking up to speeds up. However if the hydraulic pressure is held down, the braking force acting on the wheel will become too low. To prevent this, the ECU sets the solenoid valves to the pressure increase mode and holding mode alternately as the wheel which was locking up, recovers speed.

SECTION C

As the hydraulic pressure is gradually increased in the brake cylinder by the ECU actuator (section B), the wheel tends to lock up again. In response, the ECU again switches the solenoid valves to the pressure reduction mode to reduce hydraulic pressure inside the disc brake cylinder.

SECTION D

Since the hydraulic pressure in the brake cylinder is decreased again as in the section B. The cycle of Hold, Reduce and increase is repeated many times until the wheels are no longer outside the 30% slip ratio.

Fig 3.6 shows all the sections discussed above.

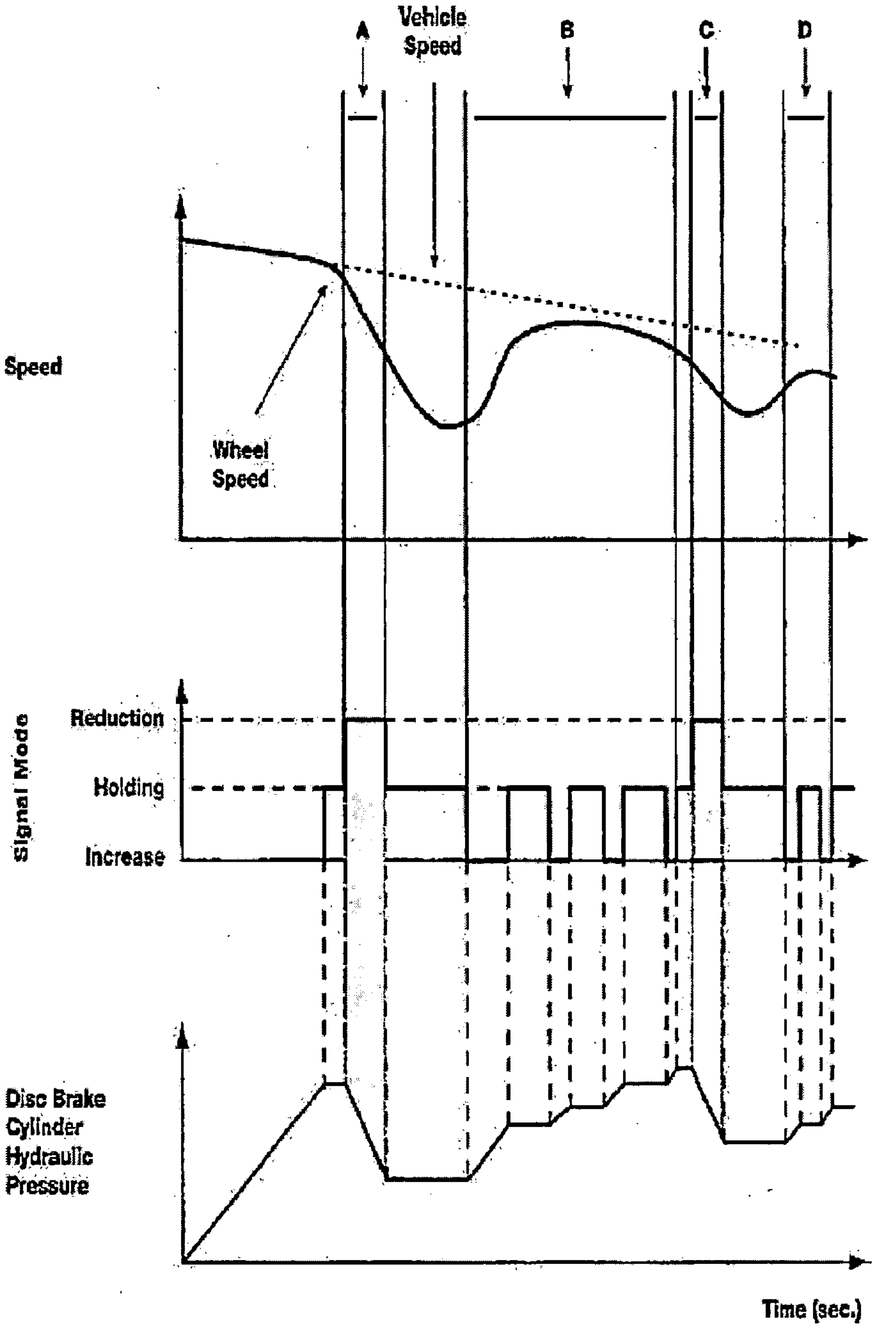


Fig 3.6 Wheel speed control chart

Chapter 4: Brake Hydraulic System

The operation performed in braking is the reverse of that carried out in acceleration. In the latter the heat energy of the fuel is converted into the kinetic energy of the car, where as in the former the kinetic energy of the car is converted into heat.

As the acceleration possible is limited by the adhesion available between driving wheels and the ground, so the deceleration possible is also limited. Even so, when braking from high speed to a halt, the rate of retardation is considerably greater than that of full throttle acceleration. Consequently the power dissipated by the brakes and therefore the heat generated, is correspondingly large[10].

4.1. Two functions of brakes

Two distinct demands are made upon the brakes of motor vehicles. First, in emergencies they must bring the vehicle to rest in the shortest possible distance, and secondly, they must enable the control of the vehicle to be retained when descending long hills[10].

4.2. Braking systems

A driving wheel can be braked in two ways: directly by means of brakes acting on a drum attached to it: or indirectly, through the transmission by a brake acting on a drum on a main shaft of the gearbox, or on the bevel pinion, or worm, shaft of final drive. A brake in either of the latter positions, being geared down to the road wheels, can exert a large braking torque on them than if it acted directly on them. If the final drive ratio is 4:1, then the braking torque exerted on each road wheel is twice the braking torque exerted on the brake drum by the brake, that is, the total braking torque is the four times the torque on the brake drum. Thus, brakes acting on the engine side of the final drive are much powerful than those acting on the wheels directly. A transmission brake, however, gives only a single drum to dissipate the heat generated, whereas when acting directly on the road wheels there are two or more drums. Also in many vehicles a transmission brake would be badly placed as regards heat dissipation, but in commercial vehicles it can sometimes be better in this respect than wheel brakes since the latter are generally situated inside the wheels and away from any flow of air. The transmission brake has the advantage that the braking is divided equally between the road wheels by the differential but the torques have to be transmitted through the universal joints and teeth of the final drive and these parts may have to be increased in size if they are not to be overloaded[10].

In present-day vehicles the wheel brakes are usually operated by a foot pedal and are the ones used on most occasions; they are sometimes referred to as the *service brakes.* The brakes on the rear wheels can be operated also by a hand lever and are used chiefly for holding the vehicle when it is parked and are consequently called *parking brakes* but as they can, of course, be used in emergencies they are sometimes called *emergency brakes*.

4.3. Types of brake

Brakes may be classified into three groups as follows-

(1) Friction brakes.
(2) Fluid brakes.
(3) Electric brakes.

The last two types are, in practice, confined to heavy vehicles and are not used in cars. The principle of the fluid brakes is that a chamber has an impeller inside it that is rotated by the motion of the road wheel so that if the chamber is filled with fluid, usually water, a churning action occurs and kinetic energy is converted into heat thereby providing a braking effect. To dissipate the heat the water may be circulated through a radiator[10].

The vast majority of brakes are friction brakes and these may be subdivided into: (1) drum brakes and (2) disc brakes, according to whether the braked member is a drum or a disc.

4.4. Hydraulic systems

The **hydraulic brake** is an arrangement of braking mechanism which uses brake fluid, typically containing ethylene glycol, to transfer pressure from the controlling unit, which is usually near the operator of the vehicle, to the actual brake mechanism, which is usually at or near the wheel of the vehicle[11].

The actuator controls hydraulic brake pressure to each disc brake calliper or wheel cylinder based on input from the system sensors, thereby controlling wheel speed. These solenoids provide three operating modes during ABS operation:

- **Pressure Holding.**
- **Pressure Reduction.**
- **Pressure Increase.**

The actuator consists of six or eight 2-position solenoid valves, a pump and reservoir. Each hydraulic circuit is controlled by a single set of solenoids:

- Pressure holding solenoid.
- Pressure reduction solenoid.

4.4.1. Pressure holding valve and pressure reduction valve

4.4.1.1. Pressure holding valve

The pressure holding valve controls(open and closes) the circuit between the brake master cylinder and the wheel cylinder. The valve is spring loaded to the open position (normally open). When current flows in the coil the valve closes. A spring loaded check valve provides an additional release passage when pressure from the master cylinder drops. Fig 1 shows the pressure holding valve[8].

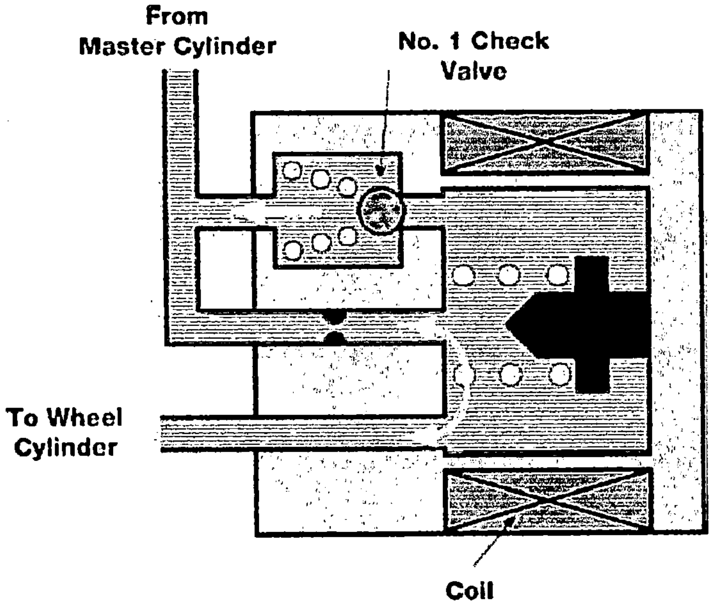


Fig 4.1 Pressure holding valve

4.4.1.2. Pressure reduction valve

The pressure reduction valve controls (opens and closes) the circuit between the wheel cylinder and the actuator reservoir. The valve is spring loaded in the closed position (normally closed). When current flows through the coil, the valve compresses the spring and opens the valve. Fig 2 shows the pressure reduction valve.

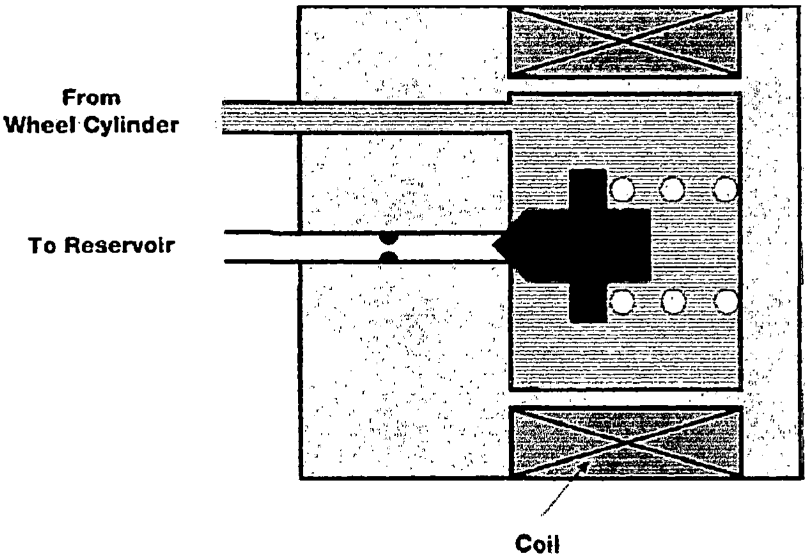


Fig 4.2 Pressure reduction valve

4.4.2. Braking modes

4.4.2.1. Normal braking mode

During normal braking the solenoids are not energized so the pressure holding valve remains open and the pressure reduction valve remains closed[8].

When the brake pedal is depressed, the master cylinder fluid passes through the pressure holding valve to the wheel cylinder. The pressure reduction valve prevents fluid pressure from going to the reservoir. As a result normal braking occurs. Fig 4.3 shows Normal braking mode.

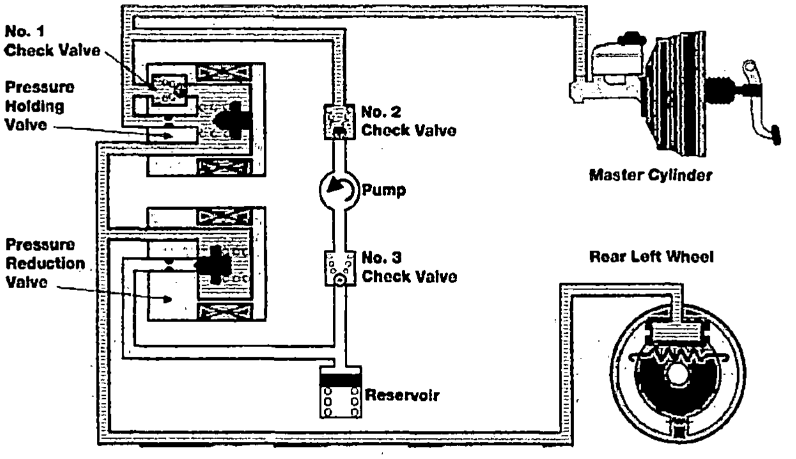


Fig 4.3 Normal braking mode

4.4.2.2. Pressure holding mode

When any wheel begins to lock, the ABS ECU initially goes to hold mode to prevent any additional increase in pressure. The ECU turns OFF the Pressure Reduction Valve and turns the Pressure Holding Valve ON. The pressure reduction valve closes, preventing hydraulic fluid from going to the reservoir. The pressure holding valve remains closed so no additional fluid pressure can reach the cylinder. Fig 4.4 shows Pressure holding mode.

4.4.2.3. Pressure reduction mode

After the initial hold mode operation, the ABS ECU energizes both the holding valve and the reduction valve. The pressure holding valve closes and blocks pressure from the master cylinder. The open reduction valve allows hydraulic pressure from the wheel cylinder circuit into the reservoir, reducing brake pressure. The pump is also energized to direct hydraulic fluid back to the master cylinder. This causes brake pedal feedback and alerts the driver to ABS operation. Fig 4.5 shows Pressure reduction mode.

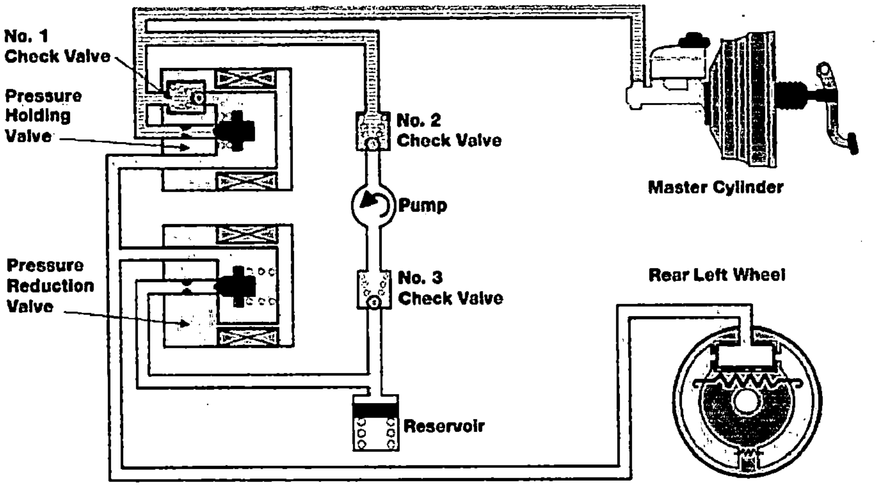


Fig 4.4 Pressure holding mode

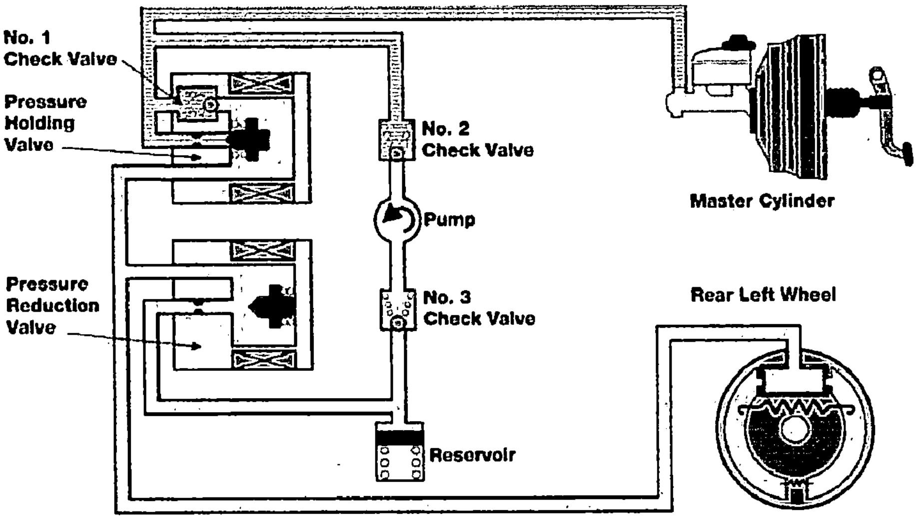


Fig 4.5 Pressure reduction mode

4.4.2.4. Pressure increase mode

As pressure inside the wheel cylinder is reduced and the speed sensor sends a signal indicating that the speed is above the target level, the ECU turns OFF the both the Pressure Reduction Valve and the Pressure Holding Valve. The pressure reduction valve closes preventing hydraulic fluid from going to the reservoir. The pressure holding valve opens so additional pressure enters the wheel cylinder if the driver maintains pedal pressure. The operation is the same as Normal Mode except the pump is ON. Fig 4.6 shows Pressure increase mode.

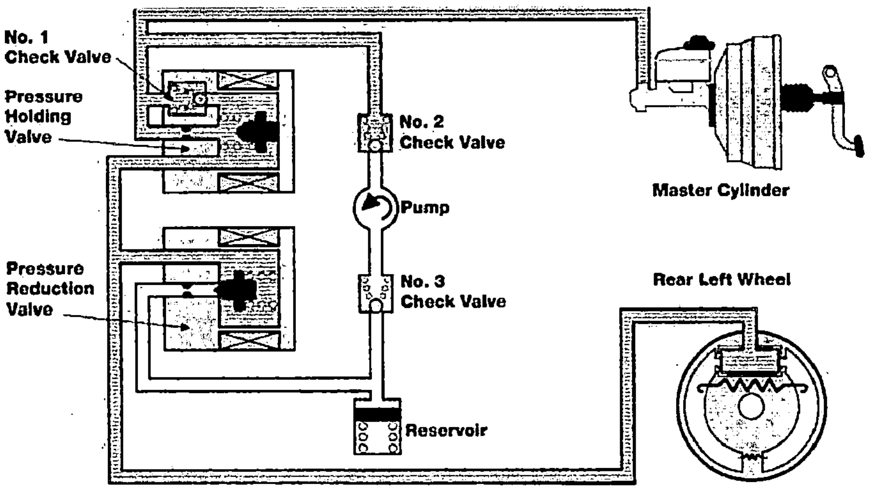


Fig 4.6 Pressure increase mode

4.4.3. Hydraulic system model

The hydraulic system has the standard structure shown in Fig 4.7. Hydraulic system dynamics for the *i*th wheel cylinder can be modelled as follows:

$$C_f \dot{P}_{bi} = A_1 C_{d_1 i} \sqrt{\frac{2}{\rho}(P_p - P_{bi})} - A_2 C_{d_2 i} \sqrt{\frac{2}{\rho}(P_{bi} - P_{low})} \quad \ldots.(1)$$

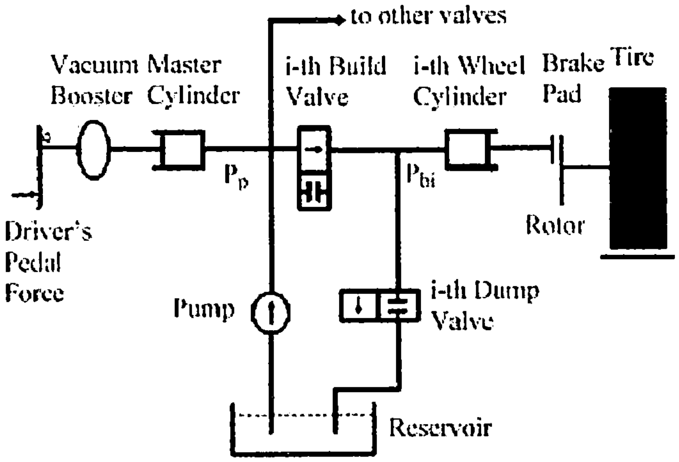


Fig 4.7 Hydraulic system

The coefficients $C_{d_1 i}$ and $C_{d_2 i}$ are the control inputs, which can take the values 0 or 1, depending on the corresponding valve being open or closed. C_f is the coefficient of the flow and the time derivative function of hydraulic pressure. Brake torque depends on different factors, such as brake friction coefficient, fluid pressure, vehicle speed, temperature, etc. It can be approximated by a first-order differential equation of the brake pressure. In this brake model, time delays are considered 3 ms for transferring hydraulic pressure from valves to the wheel cylinder and 12 ms for the wheel cylinder[4].

Chapter 5: Fuzzy Logic

5.1. Fuzzy Logic

Fuzzy Logic (FL), introduced by Zadeh, gives us the language with syntax and local semantics in which we can translate the qualitative knowledge about the problem to be solved the and provides us the benefit of enabling systems more easily to make human-like decisions. The basis for proposing fuzzy logic was that humans often rely on imprecise expressions like *big, expensive* or *far*. But the "comprehension" of a computer is limited to black-white, everything-or-nothing, or true-false modes of thinking. In this context, Zadeh[12] emphasizes that humans easily let themselves be dragged along by a desire to attain the highest possible precision without paying attention to the imprecise character of reality.

The theory of fuzzy sets, which is based on fuzzy logic, is a mathematical way to represent vagueness in linguistics and can be considered a generalization of classical set theory. The basic idea of fuzzy sets is quite easy to comprehend. In a classical set, collection of distinct objects dichotomizes the elements of the universe of discourse into two groups;

$\mu_A(u) = 1$, if u is an element of set A

$\mu_A(u) = 0$, if u is not the element of set A

In using this, an element either belongs to a given set or does not belong. On the other hand, fuzzy sets eliminate the sharp boundaries that divide members from nonmembers in a group. In this case, the transition between full membership and non-membership is gradual (a fuzzy membership function) and an object can belong to a set partially.

The degree of membership is defined through a generalized characterized function called the membership function:

$$\mu_A(u) : U \rightarrow [0,1] \qquad \text{.... (5.1)}$$

where U is called the universe and A is a fuzzy subset of U.

The values of the membership function are real numbers in the interval [0, 1], where 0 means that the object is not a member of the set and 1 means that it belongs entirely to the set. Each value of the function is called a membership degree. Fig 5.1 shows the principal difference between an ordinary, crisp set and a fuzzy set. Crisp sets are 'clear cut' while fuzzy sets are graded. In Fig 1, for instance, the membership degree to which the two values 14.999 and 15.001 belonging to the fuzzy set 'medium' are very close to each other, which represents their closeness in the universe, but because of the crisp border between the crisp set 'cool' and 'medium', the two values are associated with different crisp sets.

Among the pioneering contributors on fuzzy logic, the work of Tanaka[13] in stability analysis of control systems, Mamdani[14] in cement kiln control in fuzzy tools and techniques needs special mention.

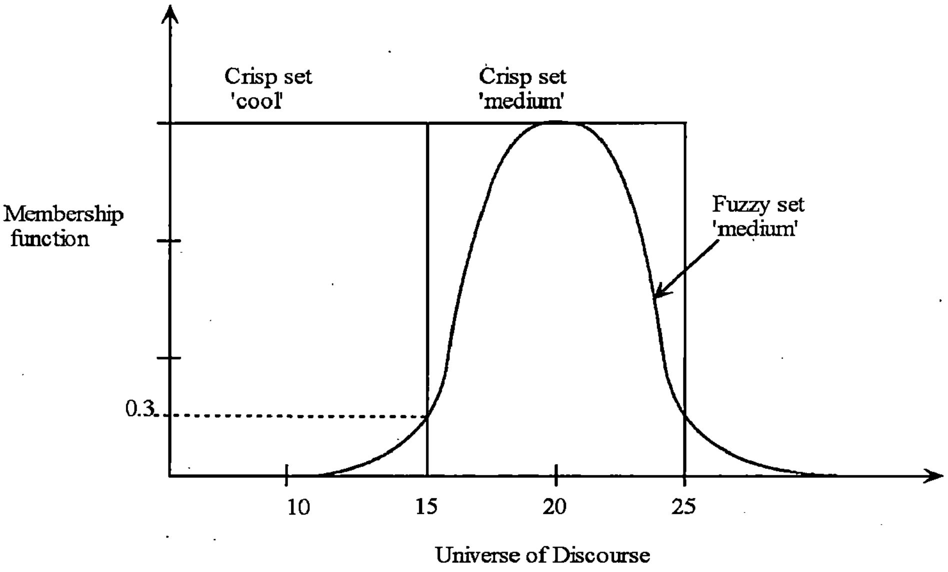


Fig 5.1 Representing crisp and fuzzy sets

The main advantage gained from this approach is the ability to express the amount of ambiguity in human thinking and subjectivity (including natural language) in a comparatively undistorted manner. In this sense, fuzzy logic is appropriate to be used in the following types of problems

- In problems which are concerned with continuous phenomena (e.g., one or more of the control variables are continuous) that are not easily broken into discrete segments;
- In problems where a mathematical model of the process does not exist, or exists but is too difficult to encode, or is too complex to be evaluated fast enough for real-time operation, or involves too much memory on the designated chip architecture;
- In problems in which high ambient noise levels must be dealt with or it is important to use inexpensive sensors and/or low-precision microcontrollers;
- In problems which involve human interactions and when there is a need to understand human descriptive or intuitive thinking;
- In problems in which an expert is available who can specify the rules underlying the system behavior as well as the fuzzy sets that represent the features of each variable.

5.2. Fuzzy Logic Controller

Fuzzy logic controllers (FLC) are the most important applications of fuzzy logic. They work rather different than conventional controllers with expert knowledge used instead of differential equations to describe a system and the knowledge can be expressed in a very natural way using linguistic variables, which are described by fuzzy sets. Fuzzy control is a control method based on fuzzy logic. Just as fuzzy logic can be described simply as 'computing with words rather than numbers', fuzzy control can be described simply as 'control with sentences rather than equations'. A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants.

Basically the conventional control schemes are designed with differential equations defining the system, where as the fuzzy control system comprises of two distinct levels i.e. heuristics and rules. There are symbolic *if-then* rules, qualitative fuzzy variables and values such as;

If fuzzy variable one is <*high*> and fuzzy variable two is <*low*> then the Output fuzzy variable is <*low*>.

5.3. Structure of Fuzzy logic controller

In the block diagram shown in Fig 5.2, the fuzzy controller is between a preprocessing block and a post processing block.

5.3.1. Preprocessing

Inputs are most often hard or crisp measurements from some measuring equipment, rather than linguistic. The preprocessor process the measurements before they enter the controller. Examples of preprocessing are:

- Quantization in connection with sampling or rounding to integers.
- Normalization or scaling onto a particular, standard range.
- Filtering in order to remove noise.
- Averaging to obtain long term or short term tendencies.
- A combination of several measurements to obtain key indicators.
- Differentiation and integration or their discrete equivalences.

5.3.1.1. Fuzzification

The first block inside the controller is fuzzification, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable.

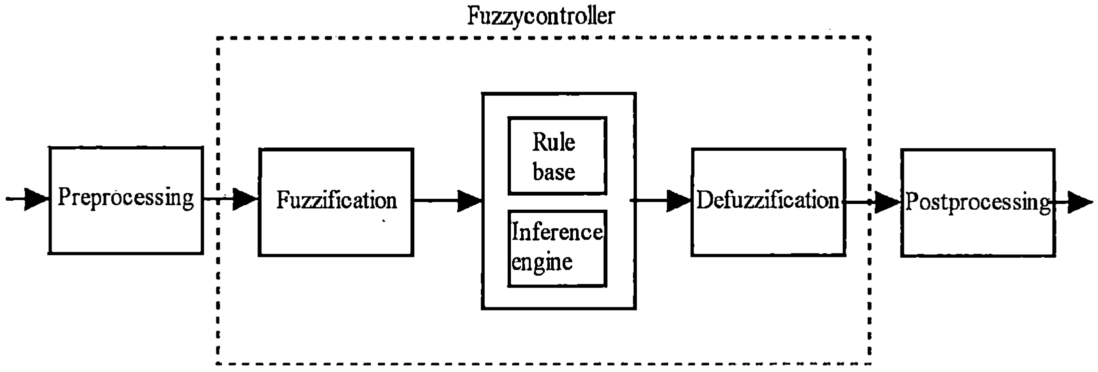


Fig 5.2 Structure of fuzzy controller

5.3.1.2. Rule Base

The rule base is a set of *If-then* rules, which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control. The mapping of the inputs to the outputs for a fuzzy system is in part characterized by a set of *condition* → *action* rules, or in *modus ponens* (*If-Then*) form,

If premise ***Then*** consequent

Usually, the inputs of the fuzzy system are associated with the premise, and the outputs are associated with the consequent. The rules may use several variables both in the condition and the conclusion of the rules. The controllers can therefore be applied to both multi-input-multi-output (MIMO) problems and single-input-single-output (SISO) problems. Basically a linguistic controller contains rules in the *if-then* format, but they can be presented in different formats. In many systems, the rules are presented to the end-user in a following format;

1. If *error* is neg and *change in error* is neg then *output* is *NB*
2. If *error* is pos and *change in error* is neg then *output* is *NM*
3. If *error* is neg and *change in error* is pos then *output* is *PM*
4. If *error* is pos and *change in error* is pos then *output* is *PB*

The linguistic variables *neg*, *pos* and *NM, NB, PM, PB* are labels of input and output fuzzy sets. The same set of rules could be presented in a rational format, a more compact representation as in Table 1.

Error	**Change in Error**	**Output**
neg	*neg*	*NB*
pos	*neg*	*NM*
neg	*pos*	*PM*
pos	*pos*	*PB*

Table 1 Fuzzy rule base

5.3.1.3. Inference Engine

Final calculation of the fuzzified output called an "inference engine" or "fuzzy inference module" which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.

The inference mechanism has two basic tasks;

- determining the extent to which each rule is relevant to the current situation as characterized by the inputs u_i, $i = 1, 2, \ldots, n$ (called as "matching"), and
- drawing conclusions using the current inputs u_i and the information in the rule-base (called as "inference step").

The various operations used in inference mechanism are,

- Aggregation
- Activation
- Accumulation

5.3.1.4. Defuzzification

The resulting fuzzy set after the inference must be converted to a number that can be sent to the process as a control signal. This operation is called Defuzzification. Defuzzification interface converts the conclusions of the inference mechanism into actual inputs for the process. There are several defuzzification methods, two of them are discussed here.

5.3.1.4.1. Center of gravity (COG)

The crisp output value *u* is the abscissa under the centre of gravity of the fuzzy set,

$$\mu = \frac{\sum_i \mu(x_i)x_i}{\sum_i (x_i)} \qquad \text{.... (5.2)}$$

where x_i is a running point in a discrete universe, and $\mu(x_i)$ is its membership value in the membership function. The expression can be interpreted as the weighted average of the elements in the support set. For the continuous case, replace the summations by integrals. It is a much used method although its computational complexity is relatively high. This method is also called *centroid of area*. This is the most often used defuzzification method.

5.3.1.4.2. Mean of maxima (MOM)

An intuitive approach is to choose the point with the strongest possibility, i.e. maximal membership as output. It may happen, though, that several such points exist, and a common practice is to take the *mean of maxima* (MOM). This method disregards the shape of the fuzzy set, but the computational complexity is relatively good.

5.3.2. Postprocessing

Output scaling is also relevant. In case the output is defined on a standard universe this must be scaled to engineering units. The post processing block often contains an output gain that can be tuned, and sometimes also an integrator.

For a feedback control system reference signal *r(t)* and actual output *c(t),* the error signal *e(t)=r(t)-c(t)* is given as the input to the fuzzy control and *u(t)* is the control signal given to the plant. The structure of fuzzy control system is shown in Fig 3.

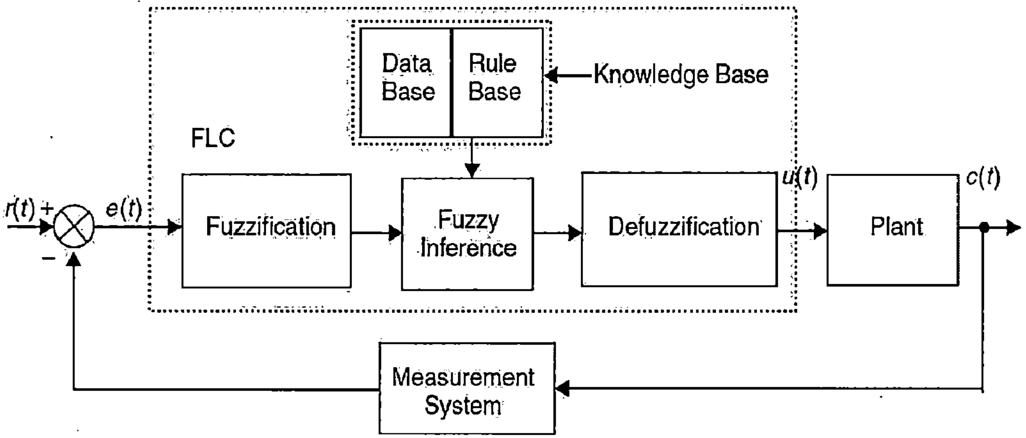


Fig 5.3 Structure of fuzzy control system

5.4. Sugeno-Type Fuzzy Inference

The fuzzy inference process discussed so far is Mamdani's fuzzy inference method, the most common methodology. This section discusses the so-called Sugeno, or Takagi-Sugeno-Kang[15], method of fuzzy inference. Introduced in 1985, it is similar to the Mamdani method in many respects. The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant.

A typical rule in a Sugeno fuzzy model has the form

If Input 1 = x and Input 2 = y, then Output is $z = ax + by + c$

For a zero-order Sugeno model, the output level z is a constant $(a=b=0)$.

The output level z_i of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = x and Input 2 = y, the firing strength is

$$\omega_i = AndMethod\ \ (F_1(x), F_2(y)) \qquad \ldots.(5.3)$$

where $F_{1,2}$ (.) are the membership functions for Inputs 1 and 2.

The final output of the system is the weighted average of all rule outputs, computed as

$$\text{Final Output} = \frac{\sum_{i=1}^{N} \omega_i z_i}{\sum_{i=1}^{N} \omega_i}$$

where N is the number of rules.

A Sugeno rule operates as shown in the following Fig 5.4.

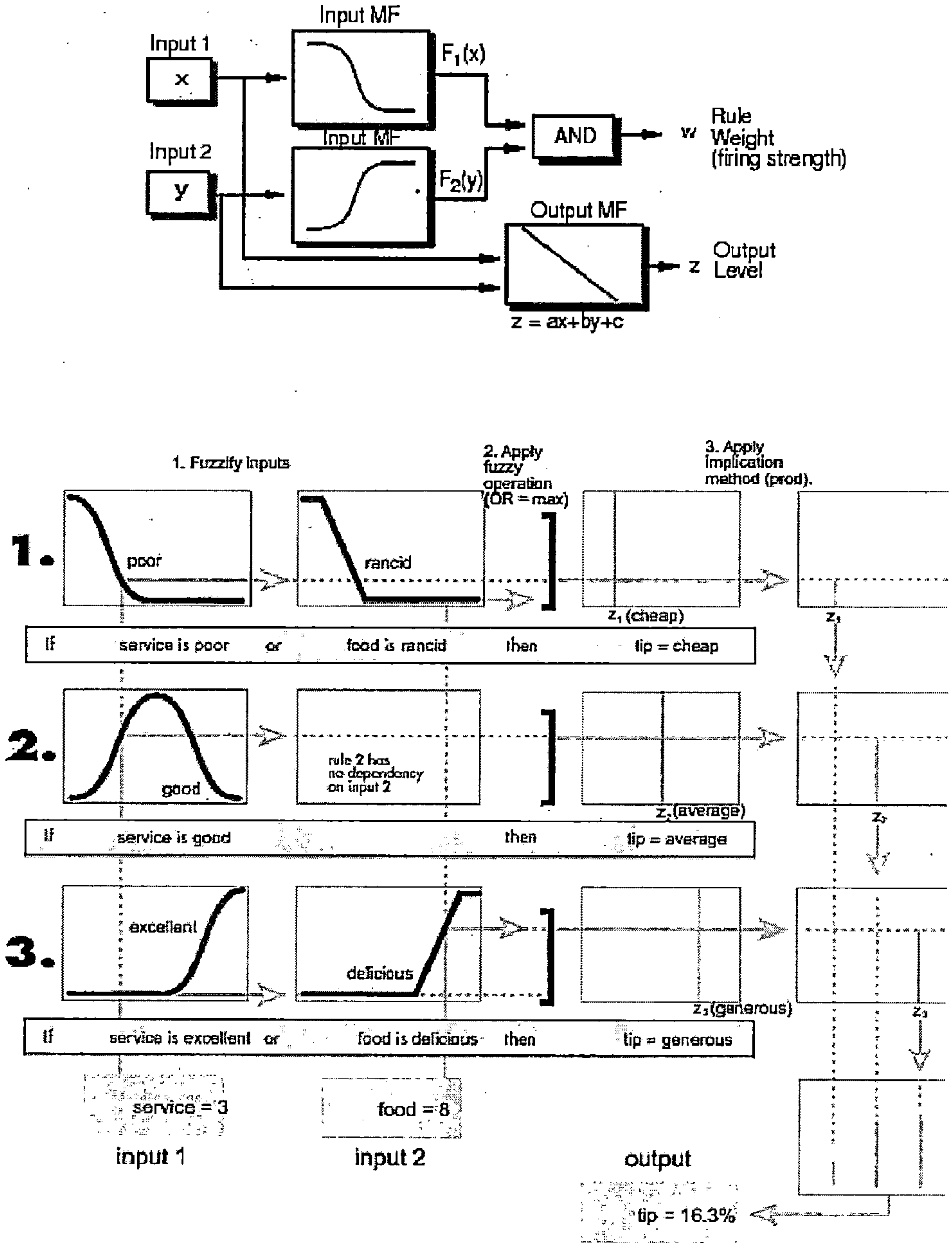


Fig 5.4 Operation of Sugeno rule based system and example

The preceding Fig 5.4 shows the fuzzy tipping model developed in previous sections of this manual adapted for use as a Sugeno system. Fortunately, it is frequently the case that singleton output functions are completely sufficient for the needs of a given problem. As an example, the system **tippersg.fis** is the Sugeno-type representation of the now-familiar tipping model. If you load the system and plot its output surface, you will see in Fig 5.5 that it is almost the same as the Mamdani system you have previously seen.

```
a = readfis('tippersg');
gensurf(a)
```

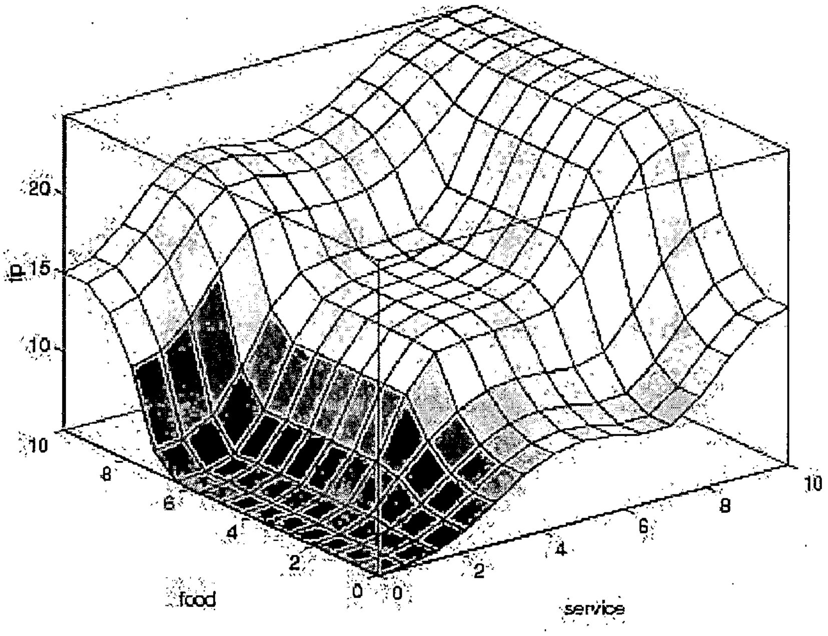


Fig 5.5 Surface viewer of the tipper example considered

The easiest way to visualize first-order Sugeno systems is to think of each rule as defining the location of a moving singleton. That is, the singleton output spikes can move around in a linear fashion in the output space, depending on what the input is. This also tends to make the system notation very compact and efficient. Higher-order Sugeno fuzzy models are possible, but they introduce significant complexity with little obvious merit. Sugeno fuzzy models whose output membership functions are greater than first order are not supported by Fuzzy Logic Toolbox software.

Because of the linear dependence of each rule on the input variables, the Sugeno method is ideal for acting as an interpolating supervisor of multiple linear controllers that are to be applied, respectively, to different operating conditions of a dynamic nonlinear system. For example, the performance of an aircraft may change dramatically with altitude and Mach number. Linear controllers, though easy to compute and well suited to any given flight condition, must be updated regularly and smoothly to keep up with the changing state of the flight vehicle. A Sugeno fuzzy inference system is extremely well suited to the task of smoothly interpolating the linear gains that would be applied across the input space; it is a natural and efficient gain scheduler. Similarly, a Sugeno system is suited for modeling nonlinear systems by interpolating between multiple linear models.

5.5. Comparison of Sugeno and Mamdani Methods

Because it is a more compact and computationally efficient representation than a Mamdani system, the Sugeno system lends itself to the use of adaptive techniques for constructing fuzzy models. These adaptive techniques can be used to customize the membership functions so that the fuzzy system best models the data.

The following are some final considerations about the two different methods.

5.5.1. Advantages of the Sugeno Method

- It is computationally efficient.
- It works well with linear techniques (e.g., PID control).
- It works well with optimization and adaptive techniques.
- It has guaranteed continuity of the output surface.
- It is well suited to mathematical analysis.

5.5.2. Advantages of the Mamdani Method

- It is intuitive.
- It has widespread acceptance.
- It is well suited to human input.

Chapter 6: System implementation

6.1. Traditional / Conventional ABS control system

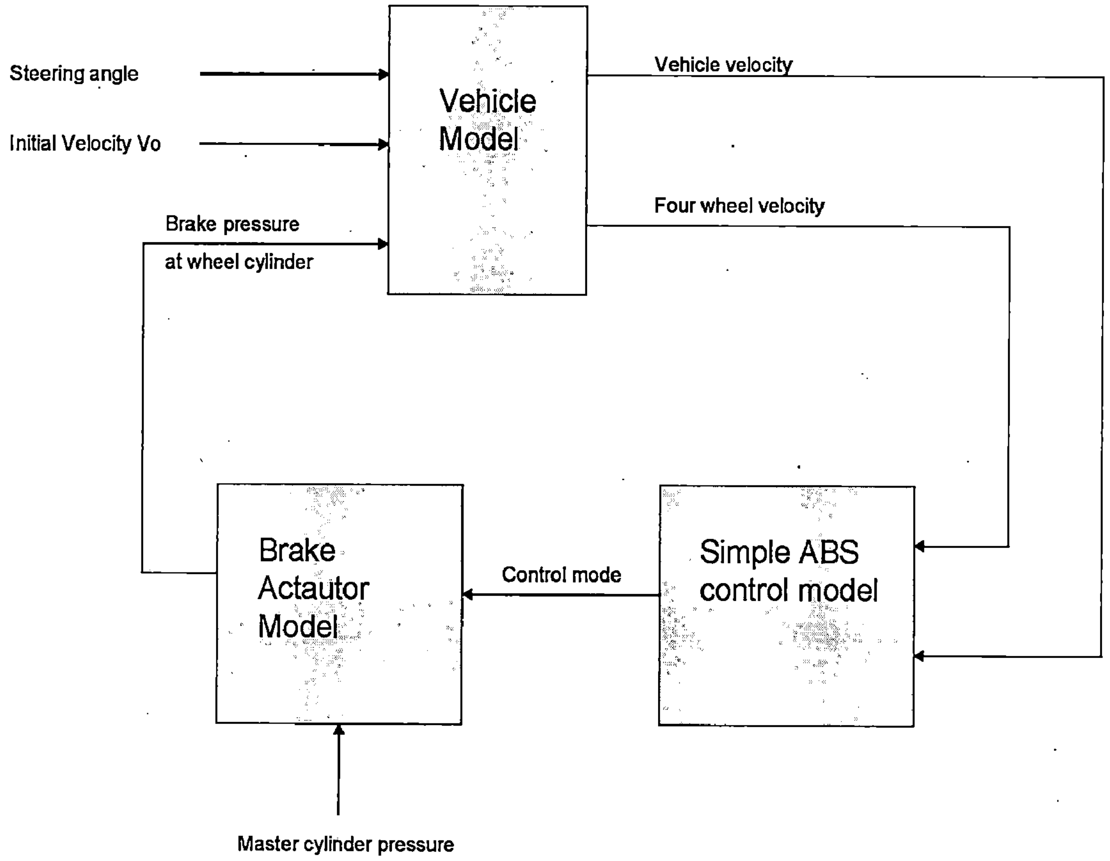


Fig 6.1 Traditional ABS control system

In traditional ABS system control is done by simple ON-OFF controller. It will give an output which we call it as the control mode. It has values only 0 or 1. This controller only checks the wheel slip which should be within the specified range. Once the value crosses the range controller will give an output zero, which will indicate that the brake pressure should be decreased. If the wheel slip is within the specified range controller will give the output one indicating the increasing pressure with the same rate since there is no problem of locking the wheel.

In brake actuator model two inputs are given, first is the applied brake and second is the control model. Since we are suddenly applying the full brake we will put the brake pressure value as high as possible within the range of master cylinder pressure. Second input is the control mode output from this simple ABS controller model. The output of the brake actuator model is the brake wheel pressure.

6.2. Fuzzy ABS control system

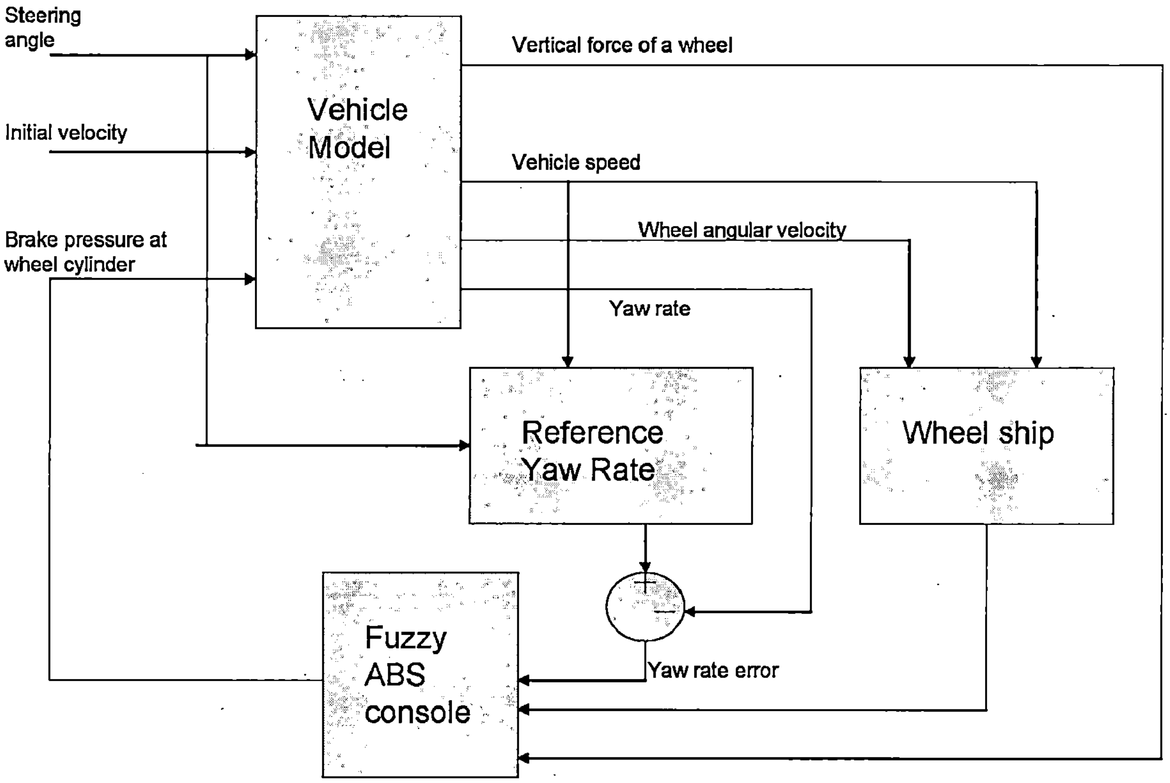


Fig 6.2 Fuzzy ABS control system

The above diagram show the vehicle model fixed with fuzzy ABS controller model. Fuzzy ABS controller has three inputs:

1. Yaw rate error
2. Vehicle slip
3. Vertical force on lateral inner wheel.

This system is implemented for two steering inputs and three road conditions.

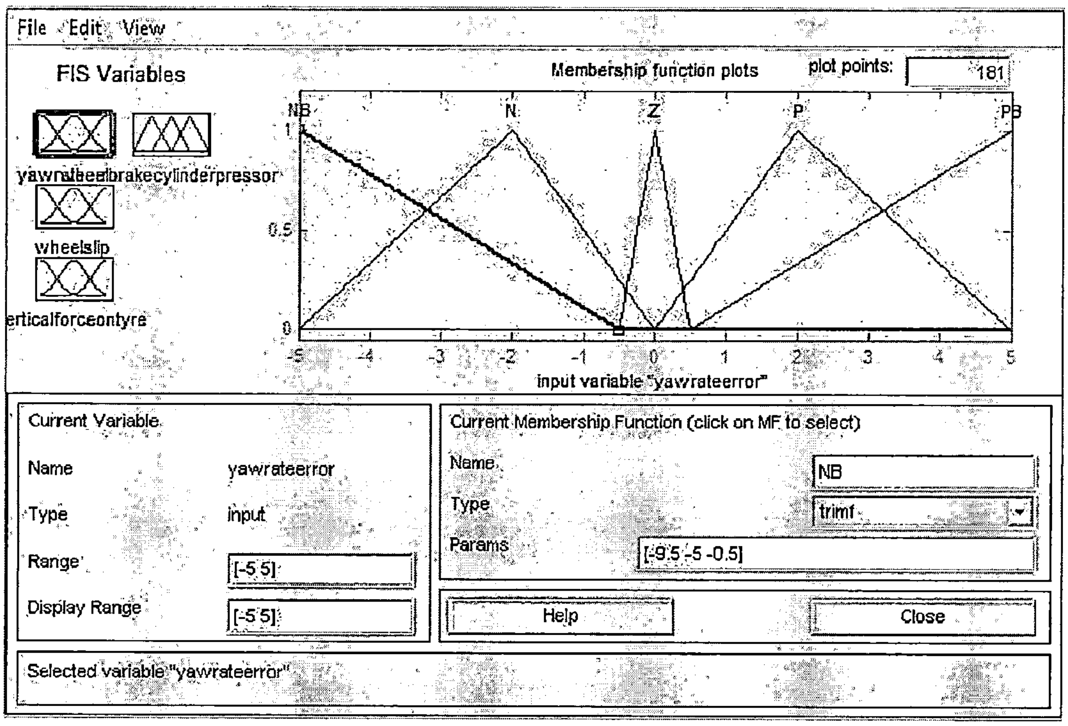
Two steering inputs are

1. J-turn test input
2. Sinusoidal input

Three road conditions are

1. Dry surface road
2. Low frictional surface road, i.e. low μ.
3. Variable frictional surface road, i.e. split μ

Memebership function, rule base and the control surface for fuzzy ABS system are shown below.



Current Variable

Name yawrateerror

Type input

Range [-5 5]

Display Range [-5 5]

Current Membership Function (click on MF to select)

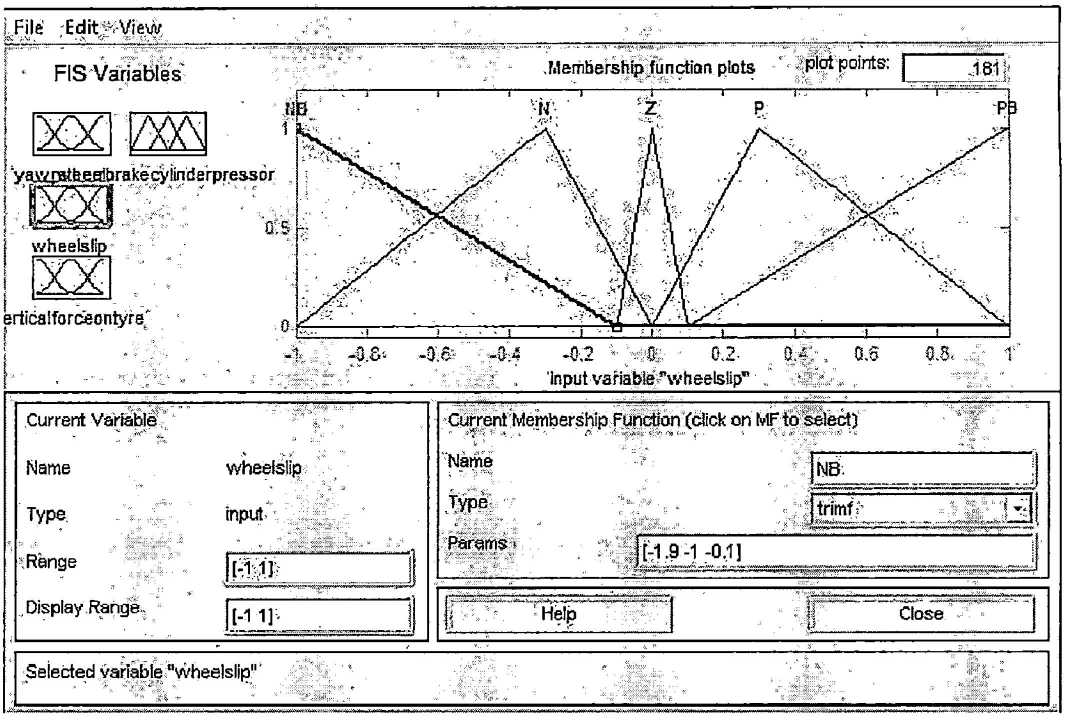
Name NB

Type trimf

Params [-9.5 -5 -0.5]

Selected variable "yawrateerror"

Fig 6.3 Membership function for yaw rate error signal



Current Variable

Name wheelslip

Type input

Range [-1 1]

Display Range [-1 1]

Current Membership Function (click on MF to select)

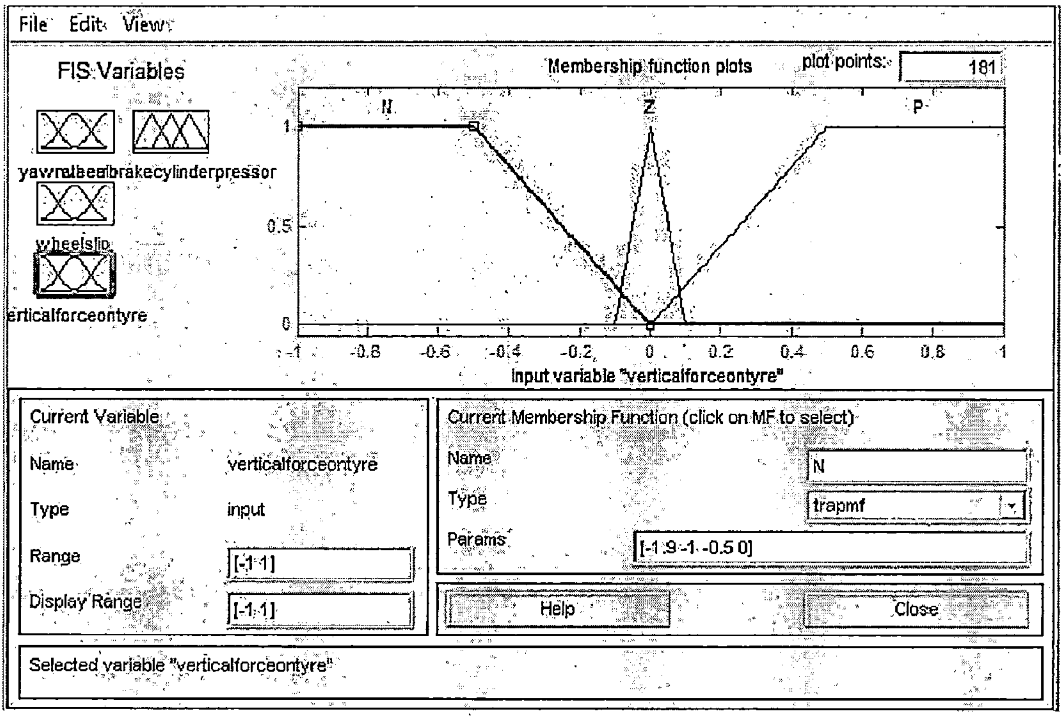
Name NB

Type trimf

Params [-1.9 -1 -0.1]

Selected variable "wheelslip"

Fig 6.4 Membership function for wheel slip signal



Current Variable

Name verticalforceontyre

Type input

Range [-1 1]

Display Range [-1 1]

Current Membership Function (click on MF to select)

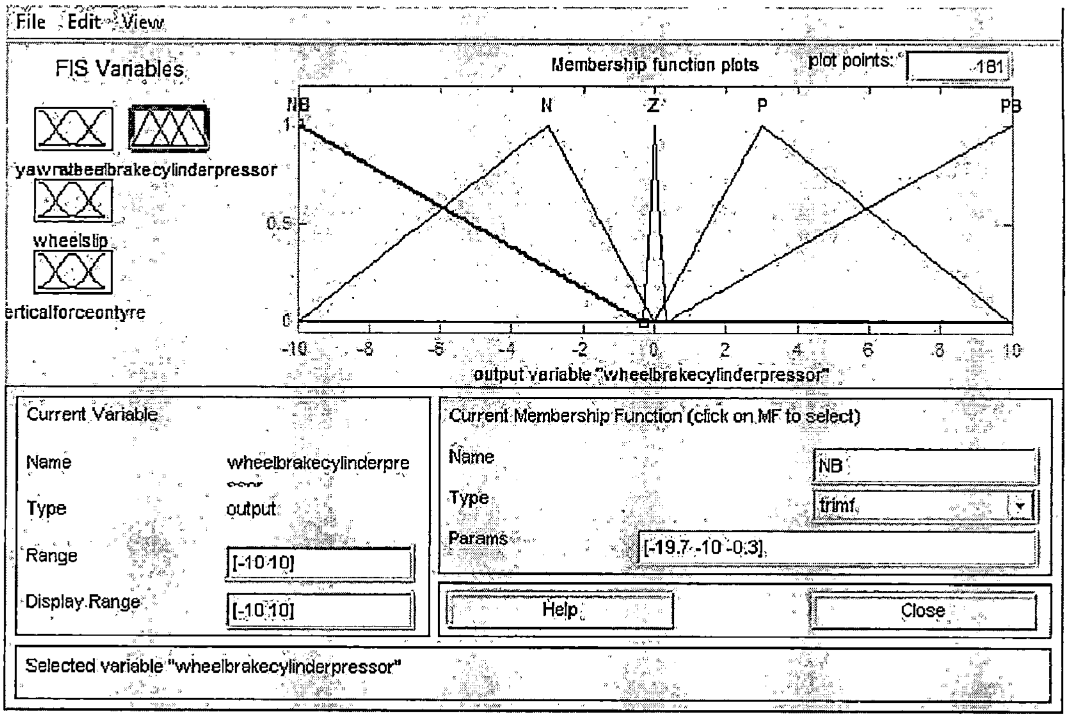
Name N

Type trapmf

Params [-1.9 -1 -0.5 0]

Selected variable "verticalforceontyre"

Fig 6.5 Membership function for vertical force on rear tyre signal



Current Variable

Name wheelbrakecylinderpressor

Type output

Range [-10 10]

Display Range [-10 10]

Current Membership Function (click on MF to select)

Name NB

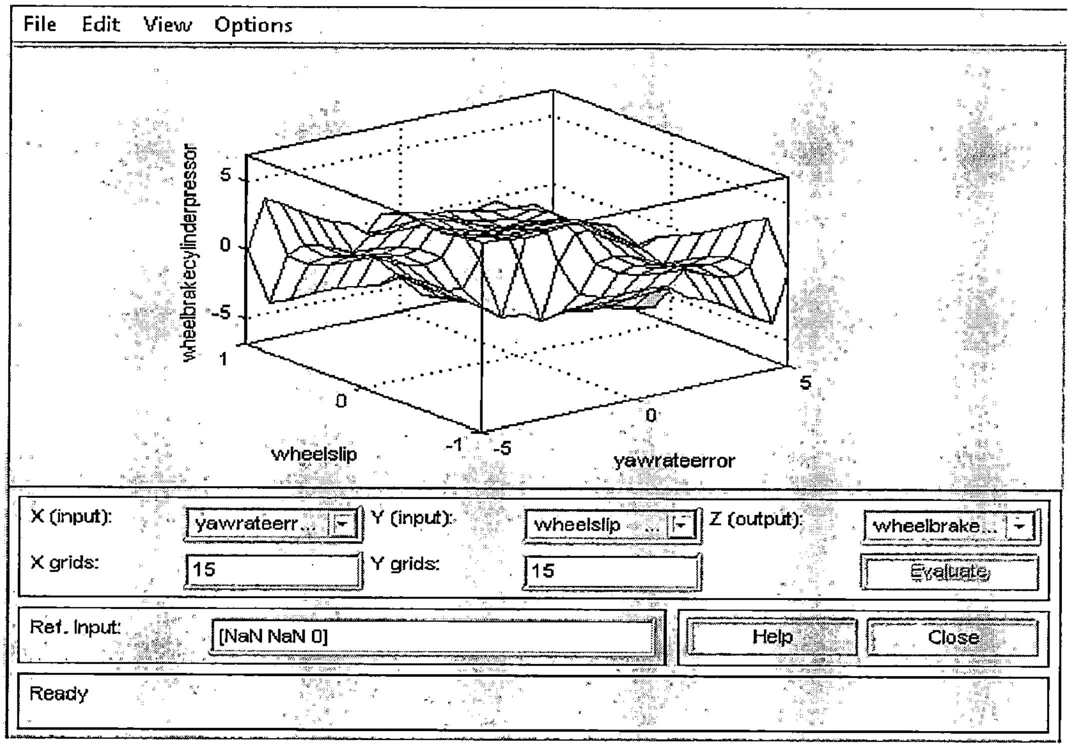
Type trimf

Params [-19.7 -10 -0.3]

plot points: 181

Selected variable "wheelbrakecylinderpressor"

Fig 6.6 Membership function for wheel brake cylinder pressure signal



X (input): yawrateerr...

Y (input): wheelslip

Z (output): wheelbrake...

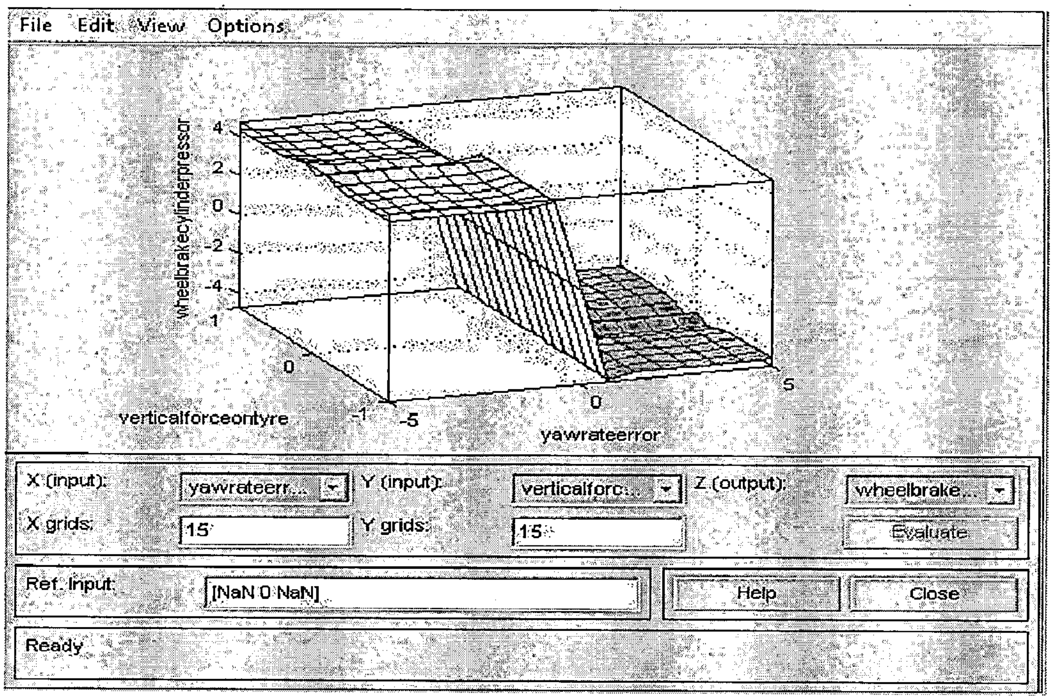
X grids: 15

Y grids: 15

Ref. Input: [NaN NaN 0]

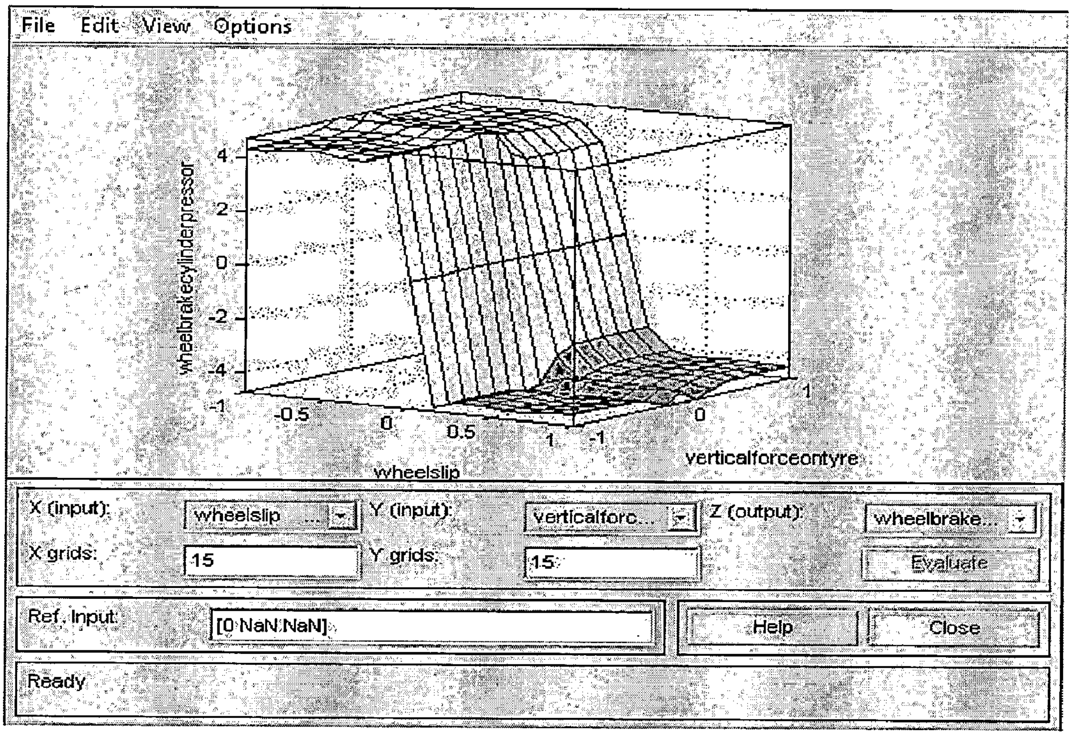
Ready

Fig 6.7 Control surface by considering yaw rate error and wheel slip signal as input



X (input): yawrateerr...
Y (input): verticalforc...
Z (output): wheelbrake...
X grids: 15
Y grids: 15
Ref. Input: [NaN 0 NaN]
Ready

Fig 6.8 Control surface by considering vertical force on inner tyre and yaw rate error signal as input



X (input): wheelslip
Y (input): verticalforc...
Z (output): wheelbrake...
X grids: 15
Y grids: 15
Ref. Input: [0 NaN NaN]
Ready

Fig 6.9 Control surface by considering vertical force on inner tyre and wheel slip signal as input

e Ws	NB	N	Z	P	PB
NB	PB	PB	P	P	Z
N	PB	P	P	Z	N
Z	P	P	Z	N	N
P	P	Z	N	N	NB
PB	Z	N	N	NB	NB

Fig 6.10 Rule base for Zero vertical load on rear inner wheel

e Ws	NB	N	Z	P	PB
NB	PB	P	P	Z	N
N	P	P	Z	N	N
Z	P	Z	Z	N	N
P	P	Z	Z	N	N
PB	Z	Z	N	N	NB

Fig 6.11 Rule base for Positive vertical load on rear inner wheel

Ws \ e	NB	N	Z	P	PB
NB	PB	P	P	Z	N
N	P	P	P	Z	N
Z	P	P	Z	N	N
P	P	Z	N	N	N
PB	P	Z	N	N	NB

Fig 6.12 Rule base for negative vertical load on rear inner wheel

Chapter 7: Simulation Results

7.1. J-turn test

The purpose of the J-turn test is to estimate the response characteristics of a vehicle in a transient state[3]. It estimates the fuzzy ABS response and the path of the vehicle. This test is carried out for three type of road condition. In first test the road surface used is dry i.e. high friction coefficient. Second test is carried out for low friction coefficient road e.g. Ice covered road. In the third test friction coefficient is varying, it is also called as split μ surface. The steering signal used is shown in the fig 7.1. It is the signal which starts at 0.5 sec at 0 degree and increase to 25 degree at 2.5 sec. There will be no change in the steering angle after 2.5 sec till the end of the simulation. Test is carried out for initial vehicle speed of 20 m/sec.

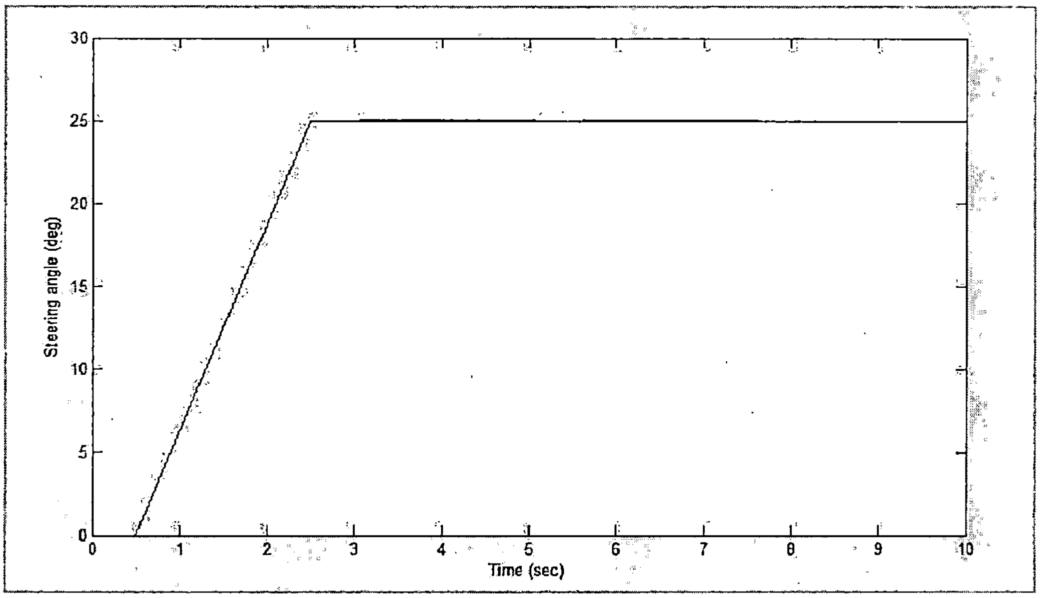


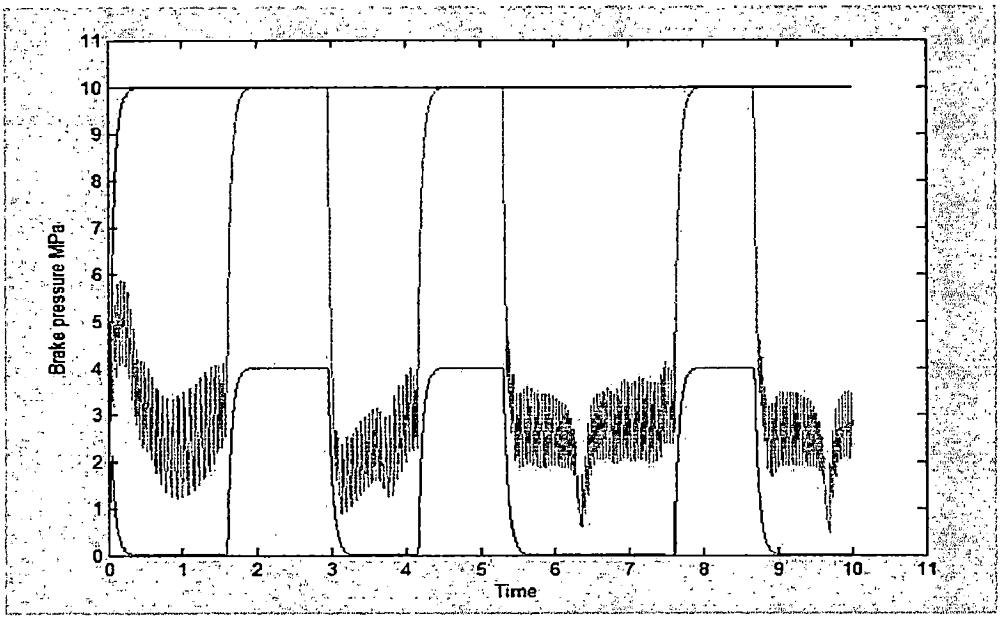
Fig 7.1 Vehicle steering angle

7.1.1. Testing on Dry road

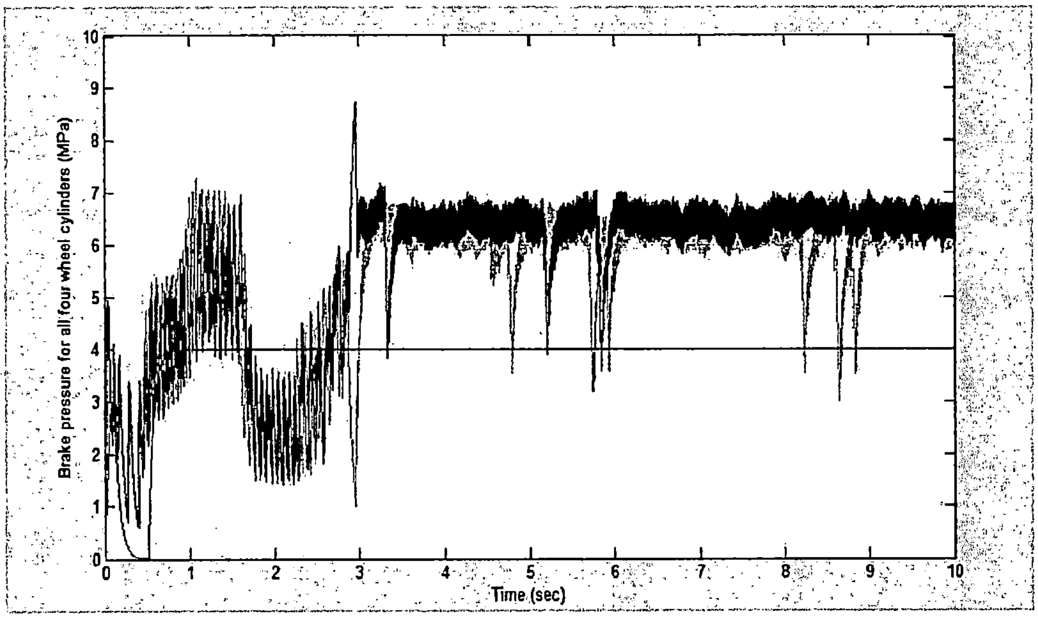
For this test the road surface used is having high friction coefficient which will range from 0.85 to 1.

Fig 7.2.(a) and fig 7.2.(b) shows the brake pressure for all four brake wheel cylinder. Blue colour line indicates the brake pressure of rear left wheel brake cylinder. From the figure we can see that the amplitude of brake pressure for traditional ABS is high.

Also the brake pressure is constant for some time in traditional ABS which will increase the possibility of wheel lock up in that time period.



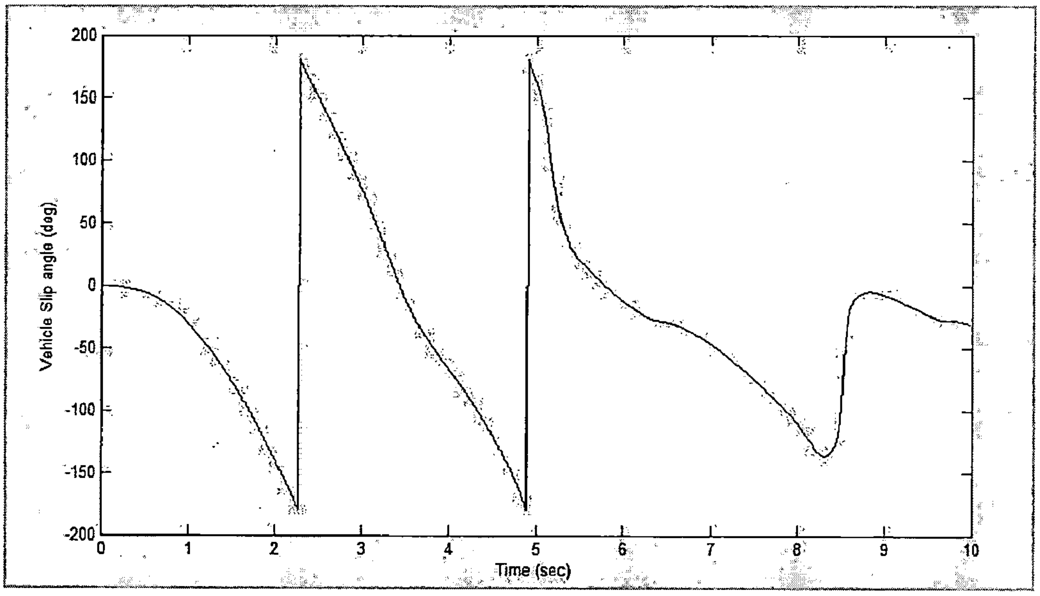
(a)



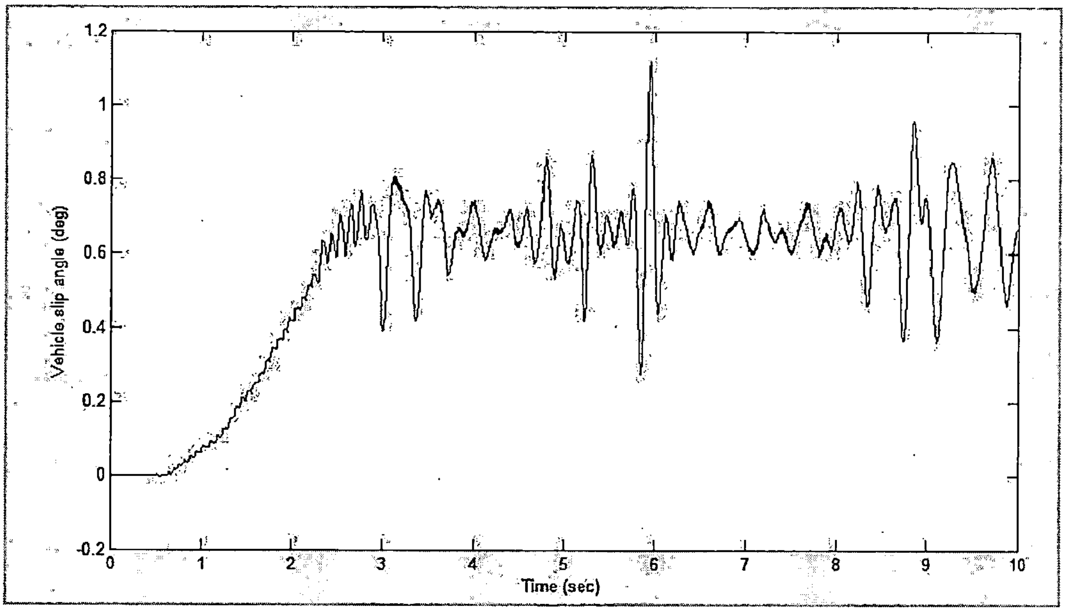
(b)

Fig 7.2 Brake pressure on all four wheels (a) traditional ABS response (b) fuzzy ABS response

Fig 7.3 shows the vehicle slip angle for traditional ABS and Fuzzy ABS. The vehicle slip angle is defined as the angle between the longitudinal axis of the vehicle x and the orientation of the vehicle velocity vector v_{COG} [3]. Vehicle traditional ABS response has a large vehicle slip whereas fuzzy ABS is having very less vehicle slip angle.



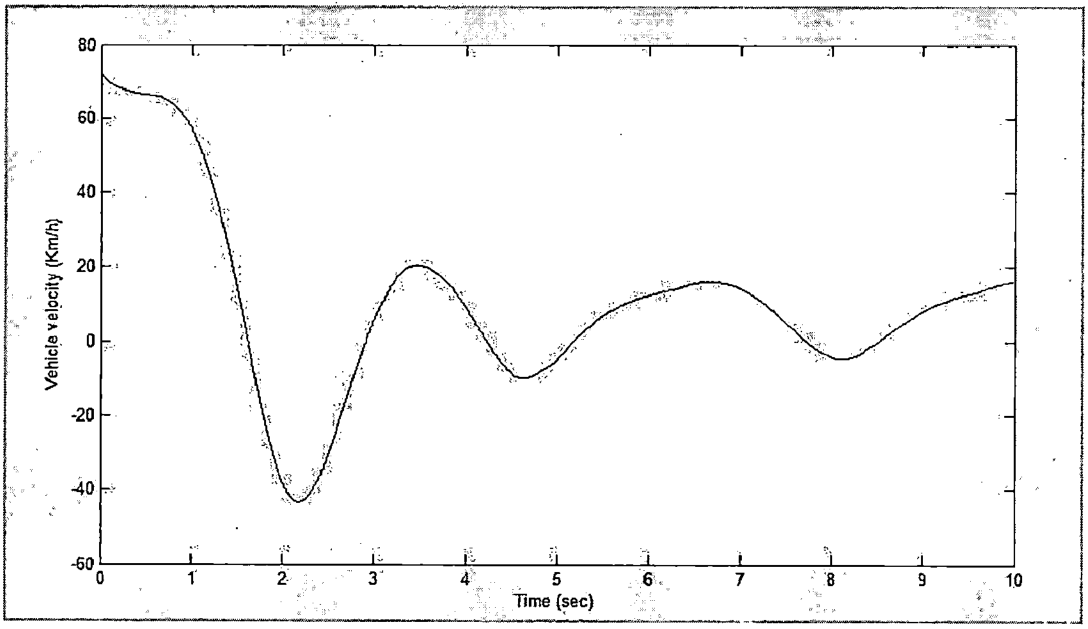
(a)



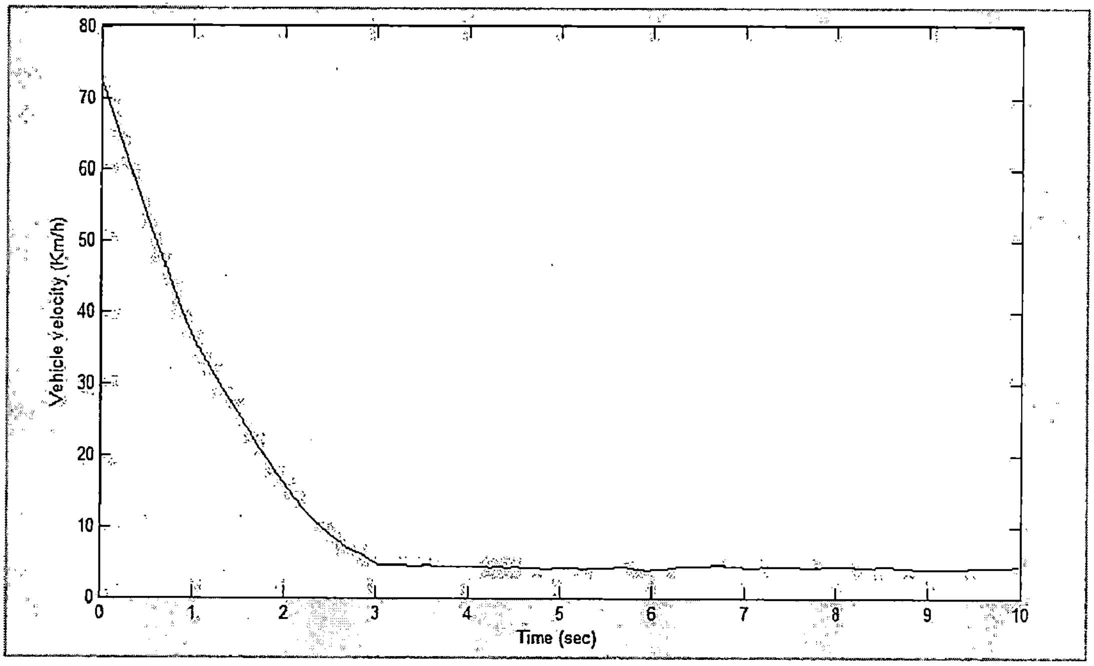
(b)

Fig 7.3 Vehicle Slip angle (a) traditional ABS response (b) fuzzy ABS response

Fig 7.4(a) and Fig 7.4(b) shows vehicle velocity which is nothing but the velocity of COG of the vehicle. From fig 7.4 we can see that the vehicle with fuzzy ABS will slow down smoothly where as this is not the case with traditional ABS vehicle.



(a)



(b)

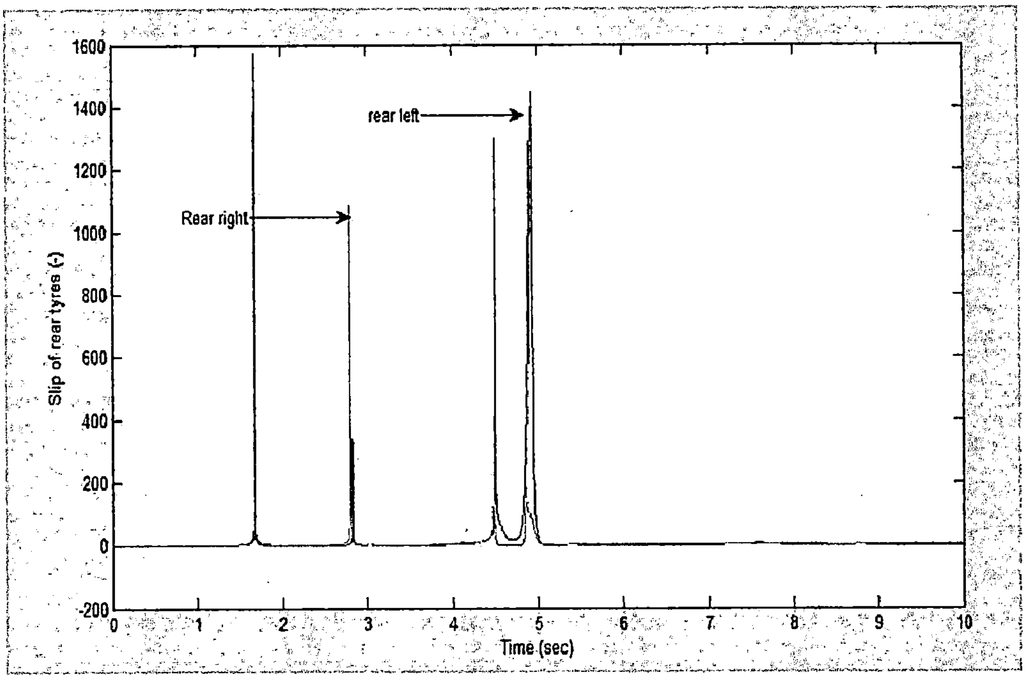
Fig 7.4 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response

Under normal operating conditions, the rotational velocity of the wheel would match the forward velocity of the car. When the brakes are applied, braking forces are generated at the interface between the wheel and the road surface, which causes the wheel speed to decrease. As the force at the wheel increases, slippage will occur between the tire and the road surface, and the wheel speed will tend to be lower than the vehicle speed. The parameter used to specify this difference in these velocities during braking is called wheel slip λ, and it is defined as

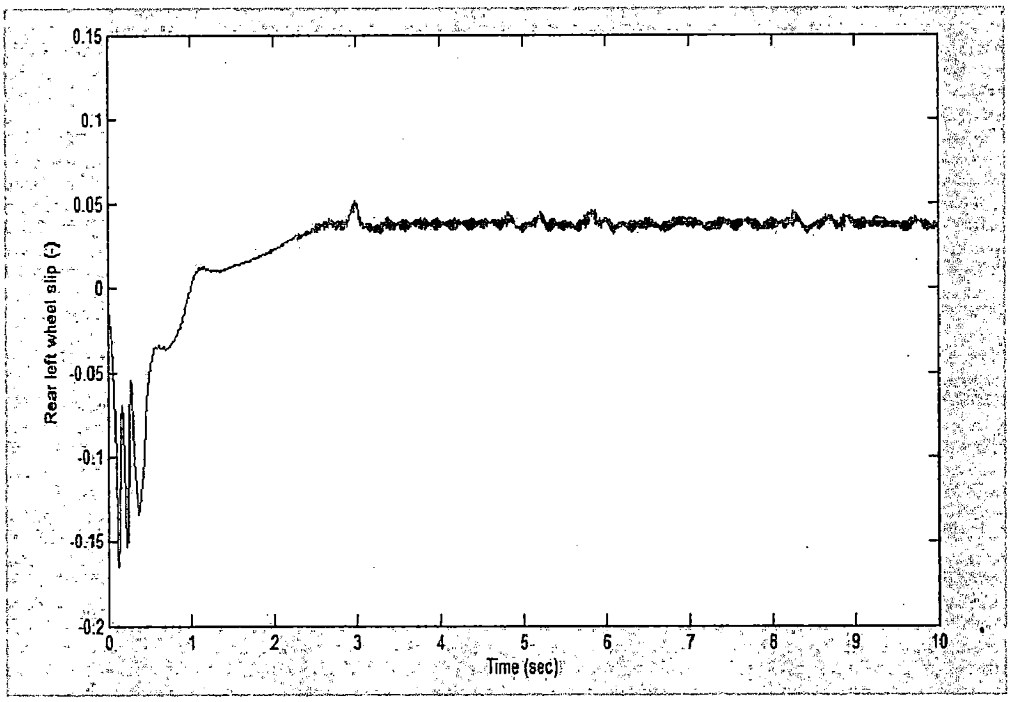
$$\lambda = \frac{V - \omega R}{V}$$

While a wheel slip of zero indicates that the wheel and vehicle velocities are the same, a ratio of one implies that the tire is not rotating and the wheels are skidding on the road surface, i.e., the vehicle is no longer steerable[16].

From fig 7.5(a) and fig 7.5(b) we can say that ABS with fuzzy control is more reliable than traditional ABS.

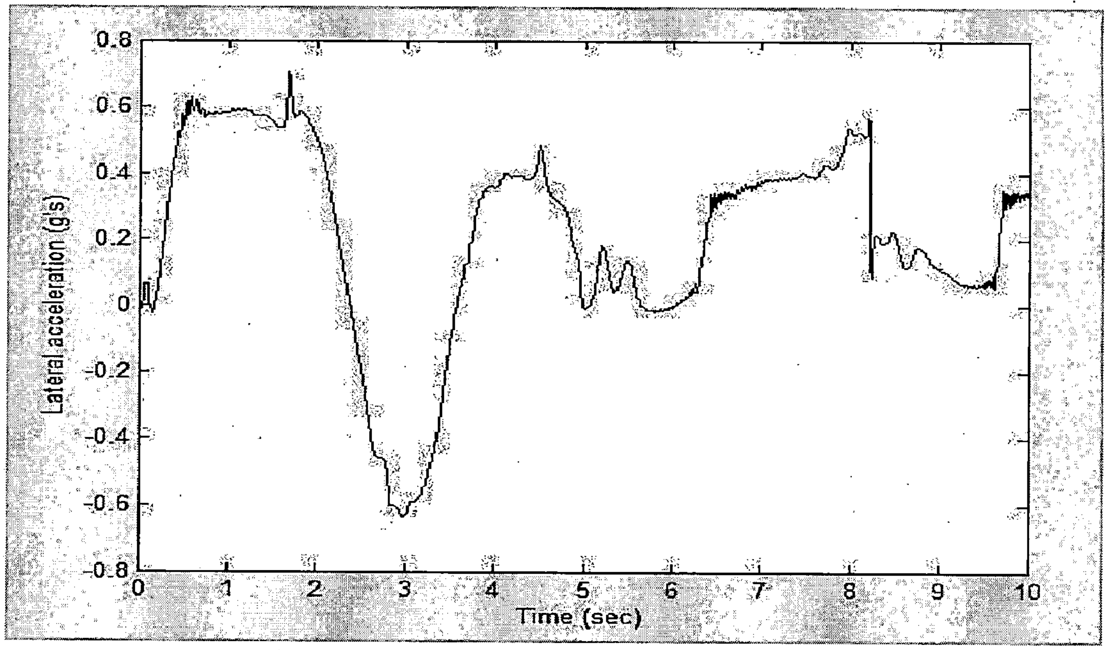


(a)

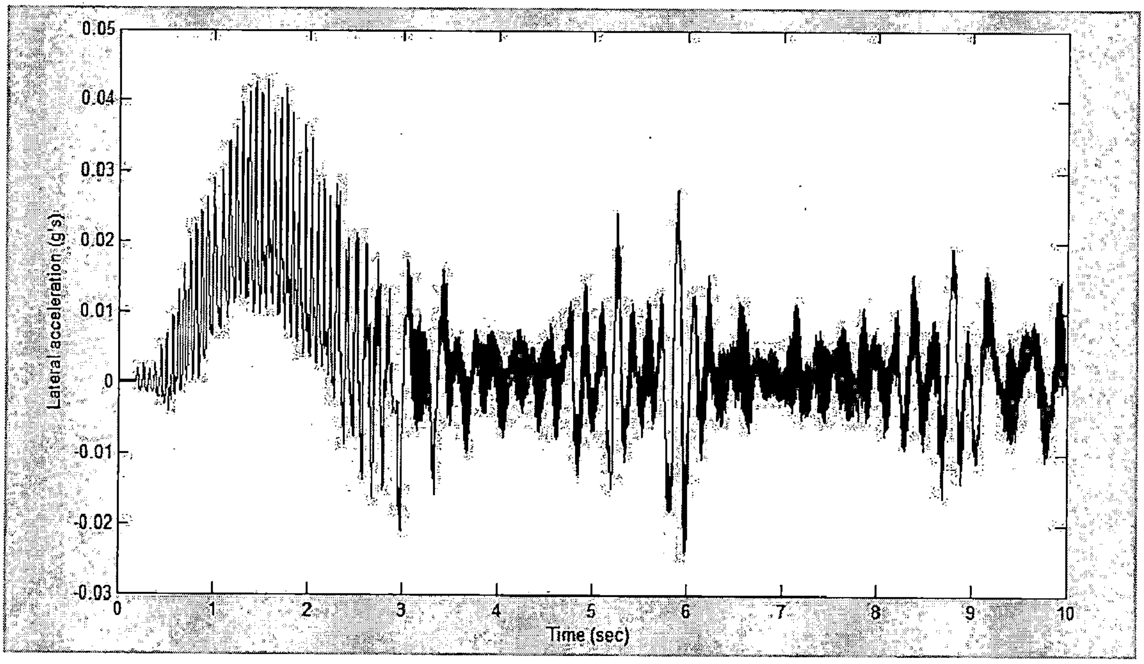


(b)

Fig 7.5 Slip of rear tyres (a) traditional ABS response (b) fuzzy ABS response



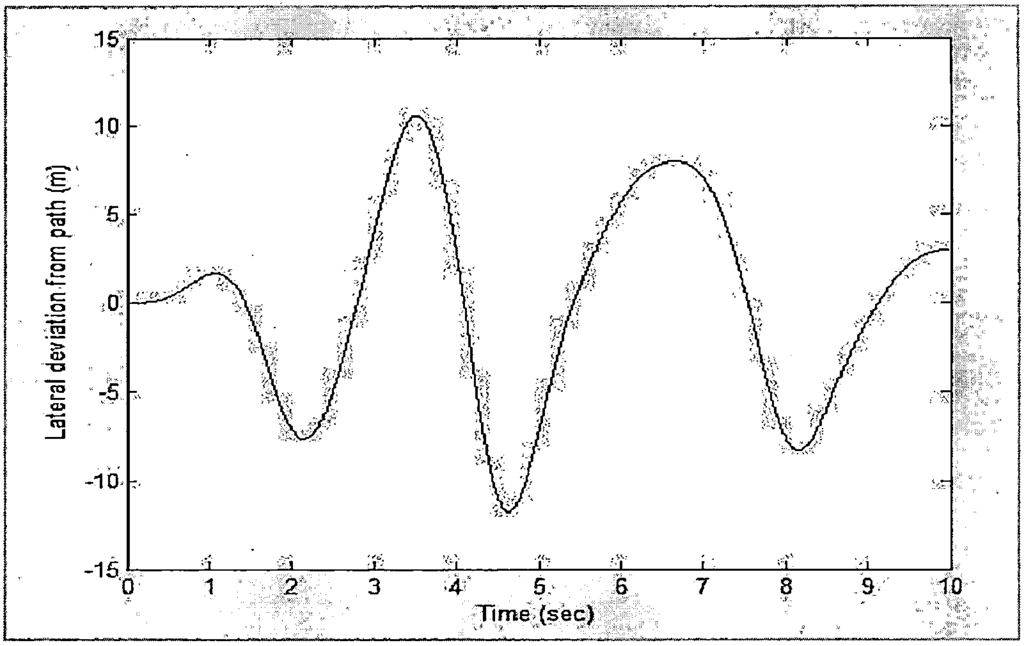
(a)



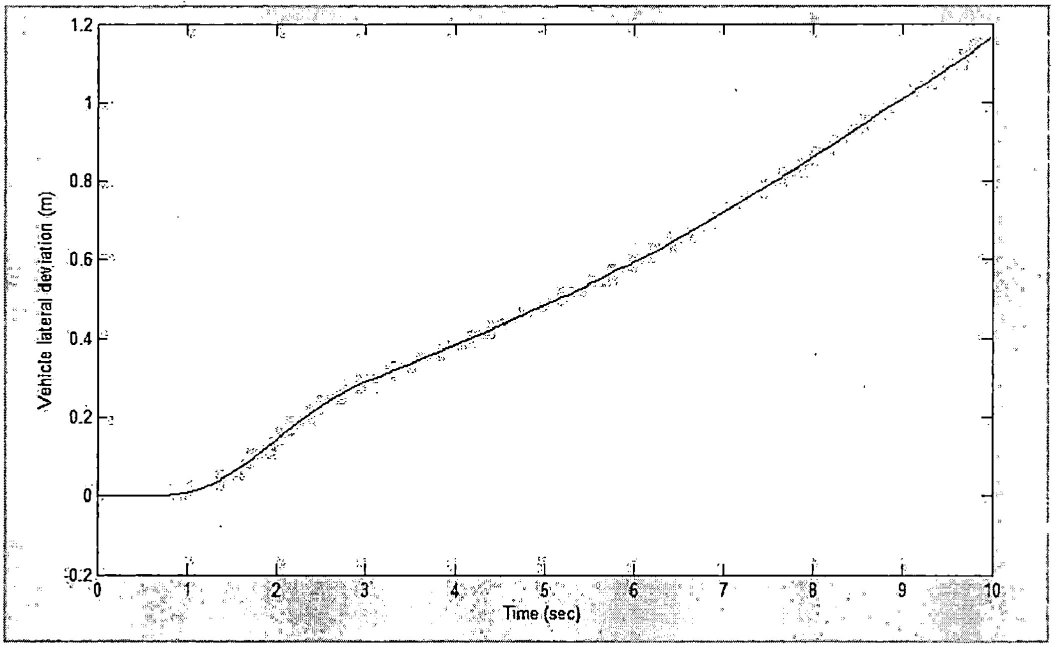
(b)

Fig 7.6 Lateral acceleration (a) traditional ABS response (b) fuzzy ABS response

For steering the vehicle in proper direction, lateral acceleration should be as small as possible. Fig 7.6 shows that the traditional ABS is not good as compared to fuzzy ABS.



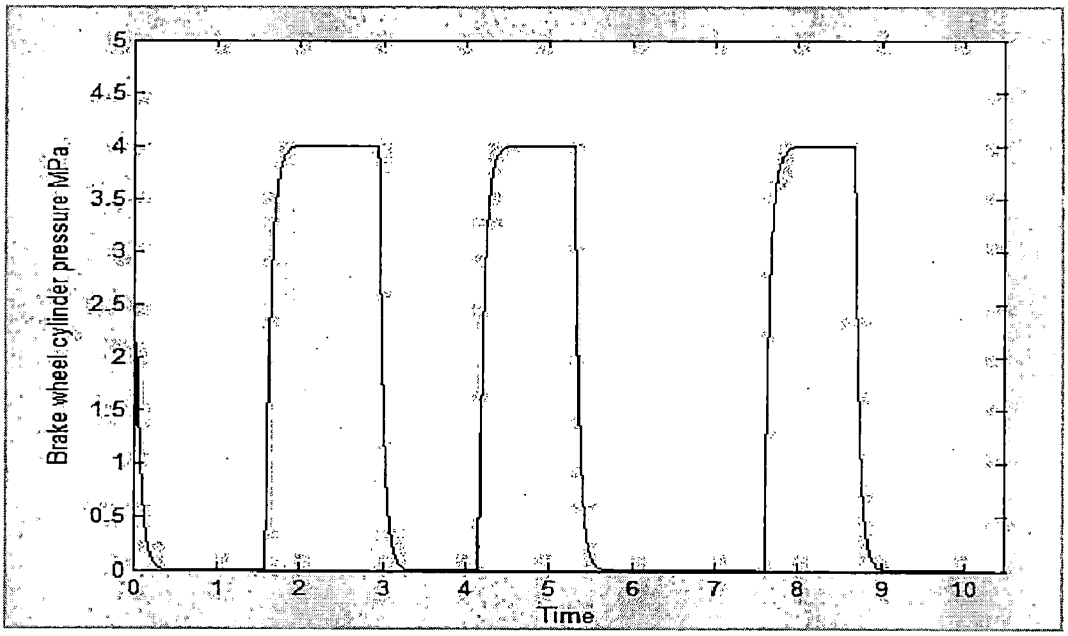
(a)



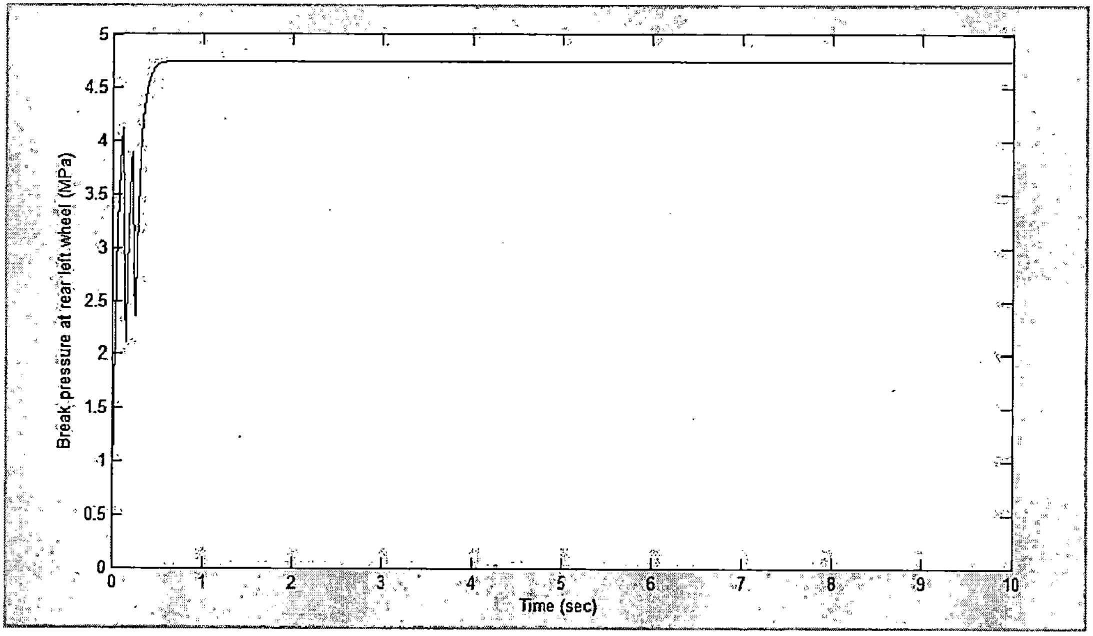
(b)

Fig 7.7 Lateral deviation from path (a) traditional ABS response (b) fuzzy ABS response

From the fig 7.7 we can see that the vehicle with traditional ABS will oscillate around the desired path where as vehicle with fuzzy ABS will deviate little but in smooth manner.

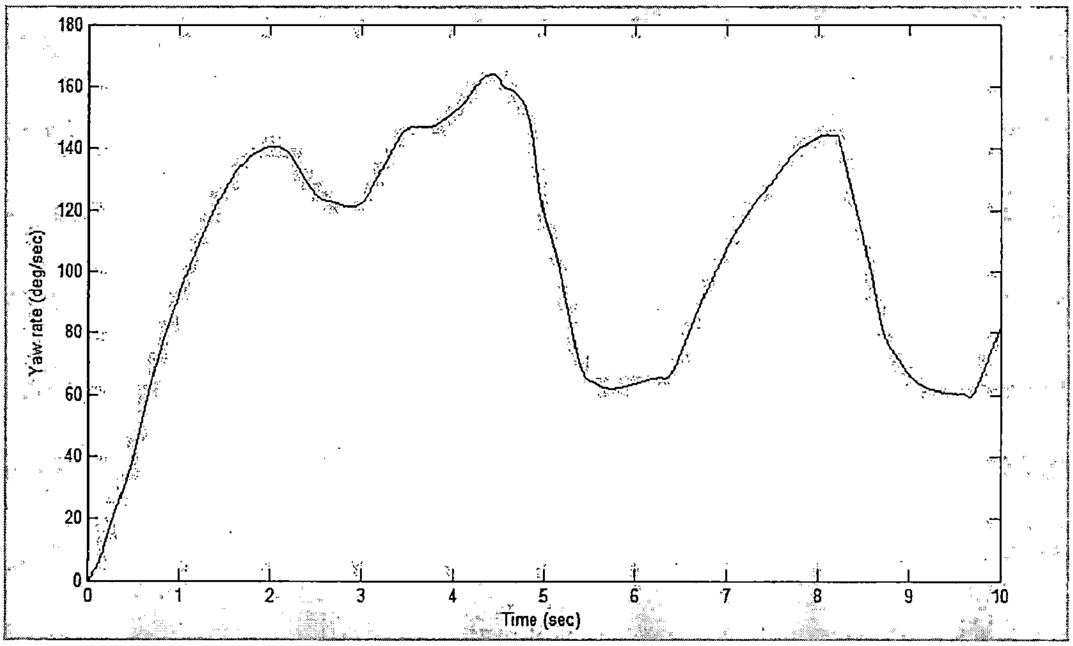


(a)

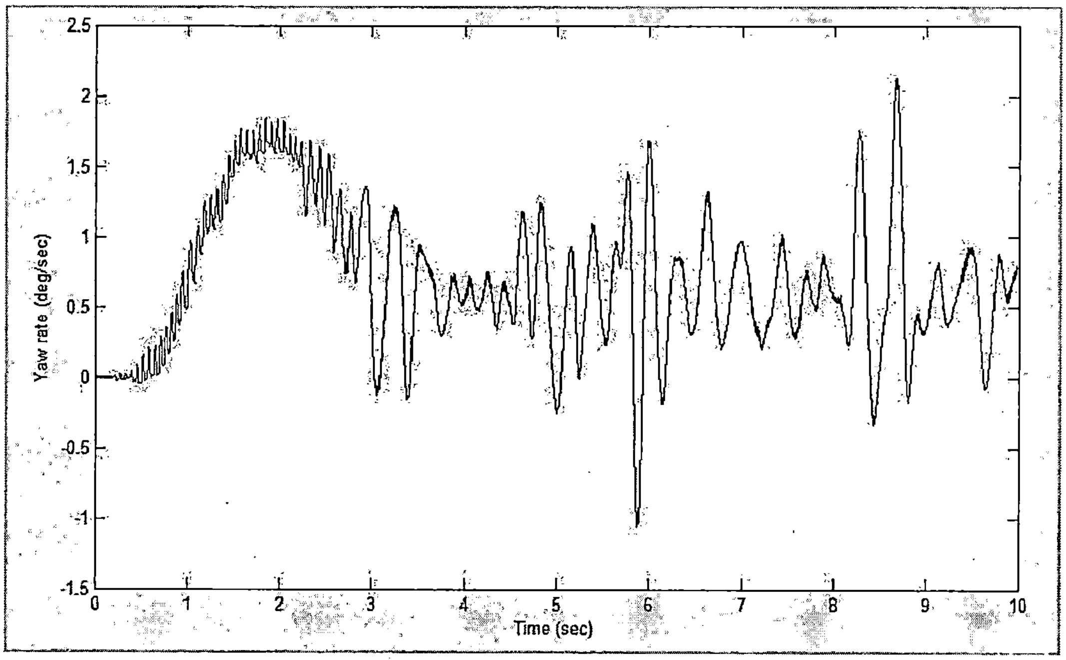


(b)

Fig 7.8 Brake wheel cylinder pressure for rear left wheel (a) traditional ABS response (b) fuzzy ABS response



(a)



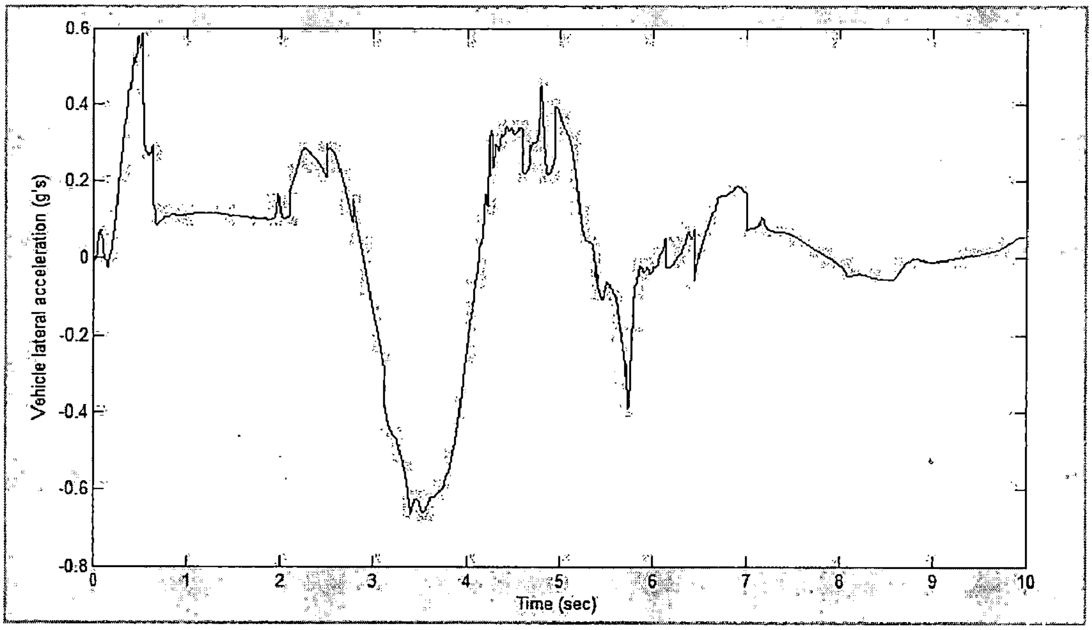
(b)

Fig 7.9 Yaw rate of the vehicle (a) traditional ABS response (b) fuzzy ABS response

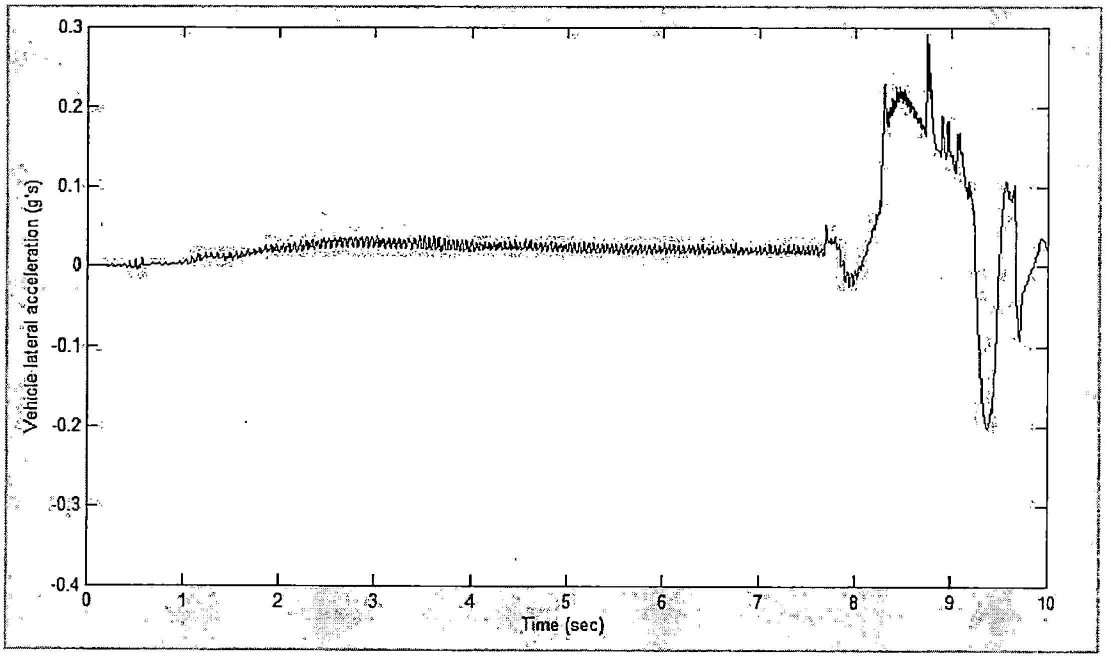
From the fig 7.9 we can see that yaw rate for traditional ABS is more than fuzzy ABS.

7.1.2. Testing on low μ road

For testing on low friction road we use a road with μ=0.2. All the initial condition and inputs are same for this test too.



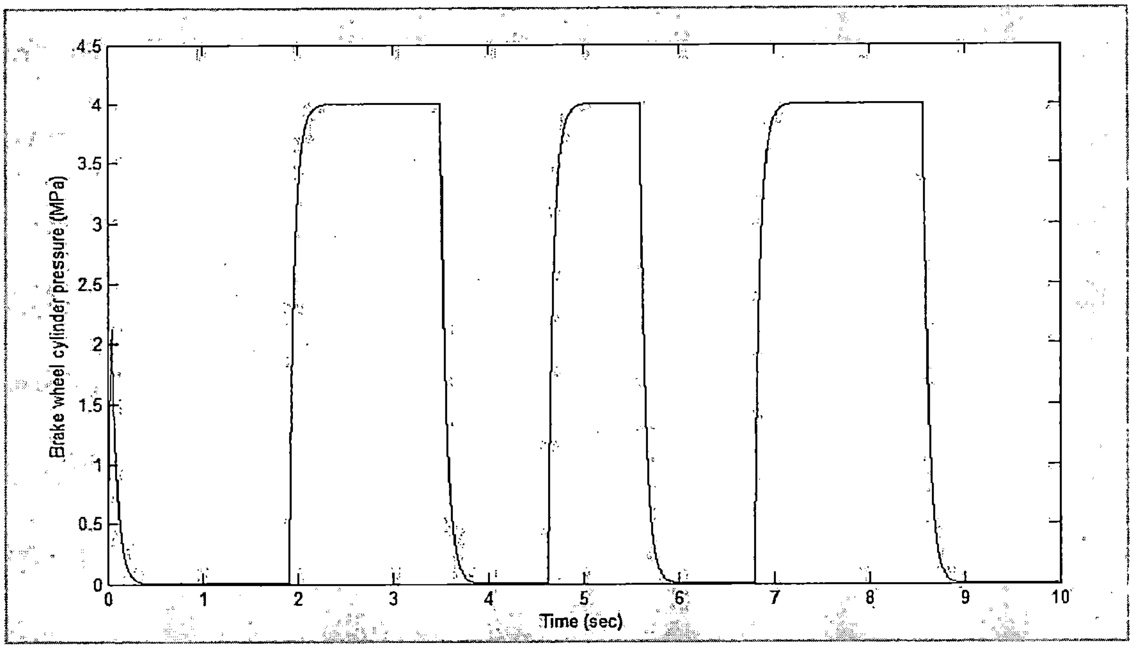
(a)



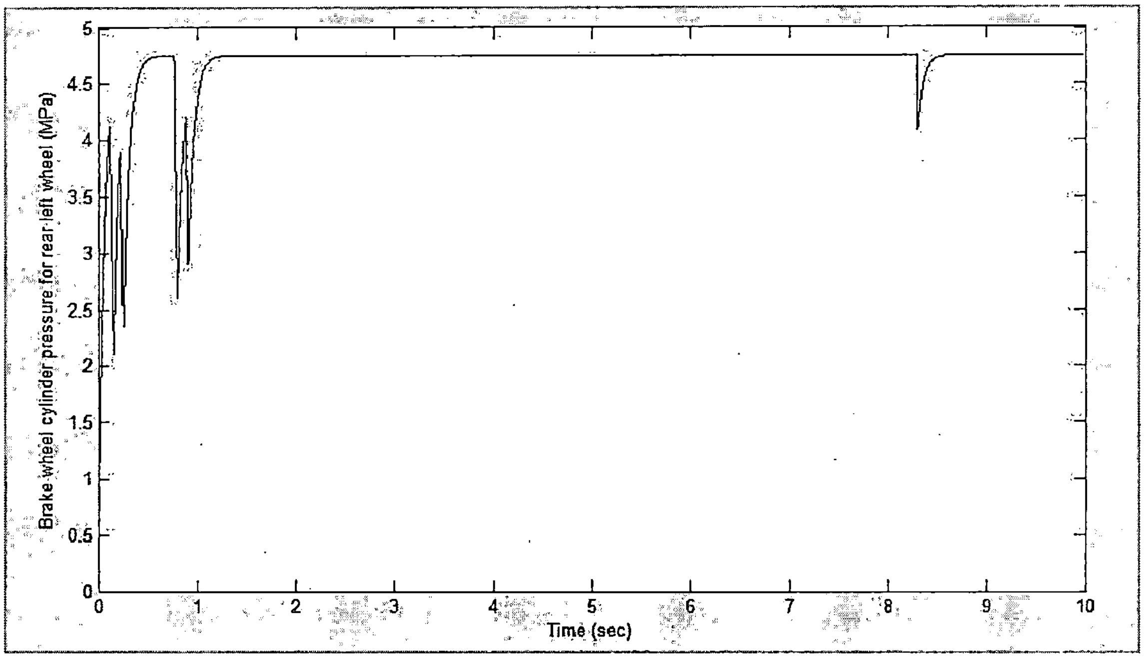
(b)

Fig 7.10 Vehicle lateral acceleration (a) traditional ABS response (b) fuzzy ABS response

From fig 7.10 we can see that the lateral acceleration for fuzzy ABS is less and also it try to settle down to zero as fast as possible.



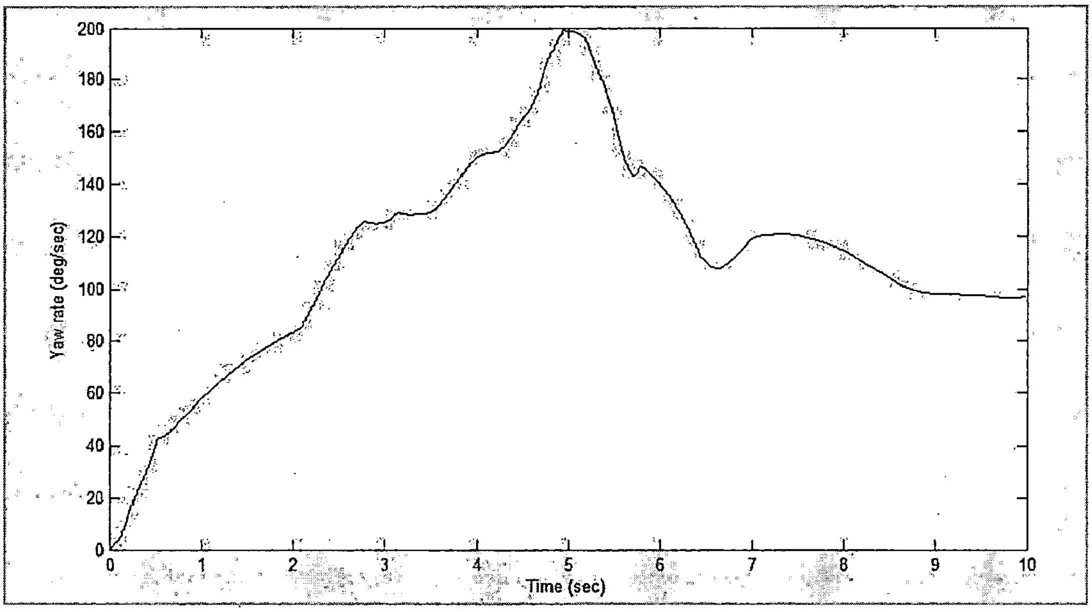
(a)



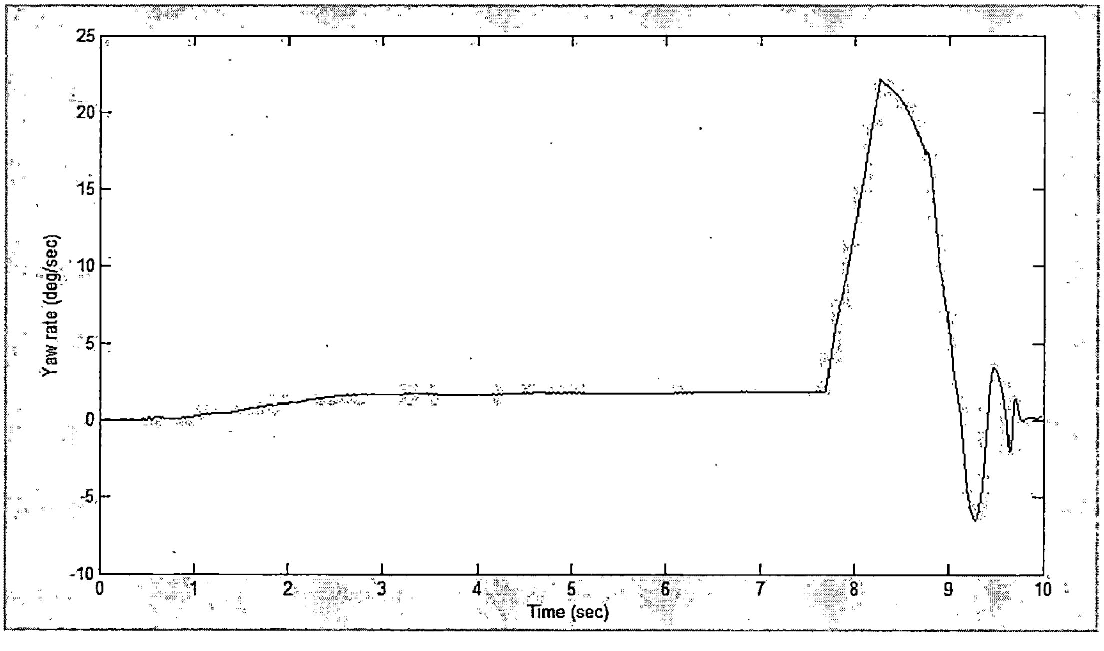
(b)

Fig 7.11 Rear left brake wheel cylinder pressure (a) traditional ABS response (b) fuzzy ABS response

From fig 7.11(b) we can see that while taking turn to left fuzzy ABS will release the pressure on rear left wheel since it may lock up because it has low load in that time. But fig 7.11(a) shows that there is no effect of load on the brake pressure.

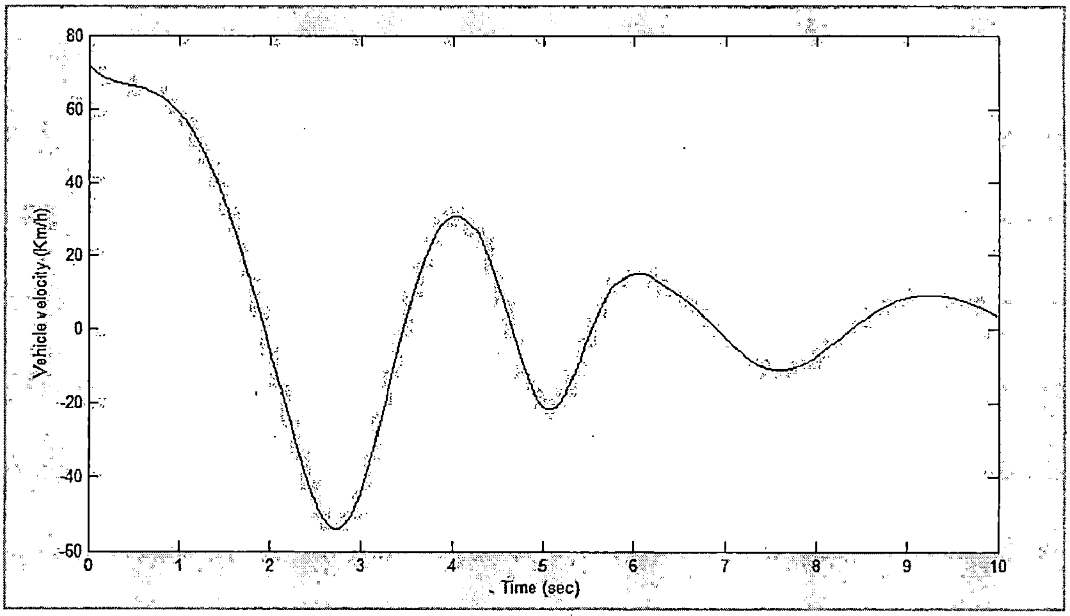


(a)

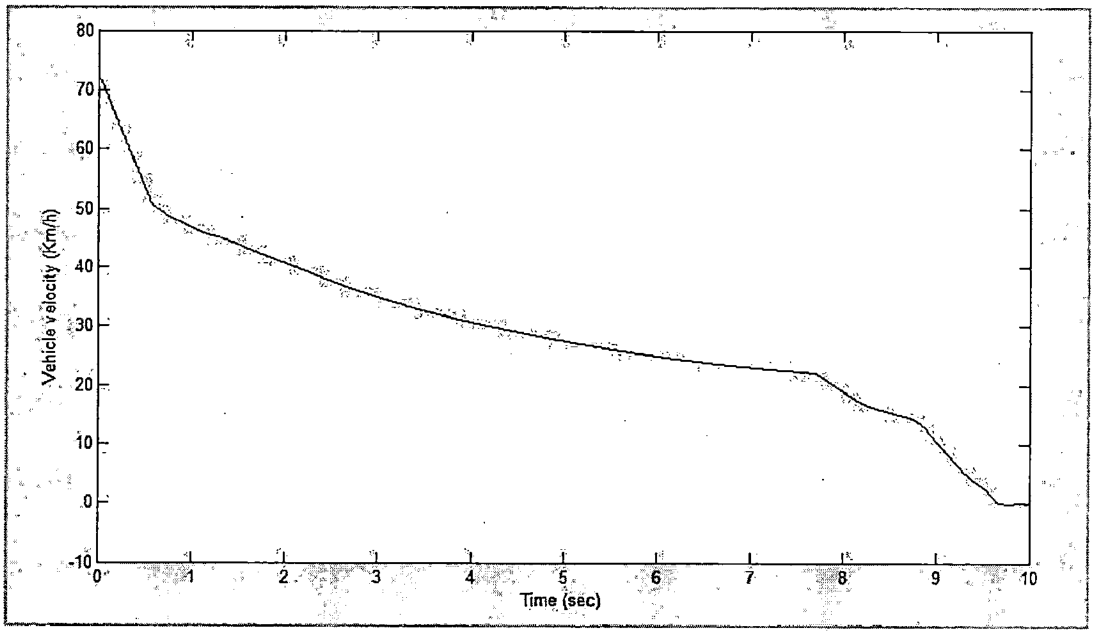


(b)

Fig 7.12 Yaw rate of vehicle (a) traditional ABS response (b) fuzzy ABS response

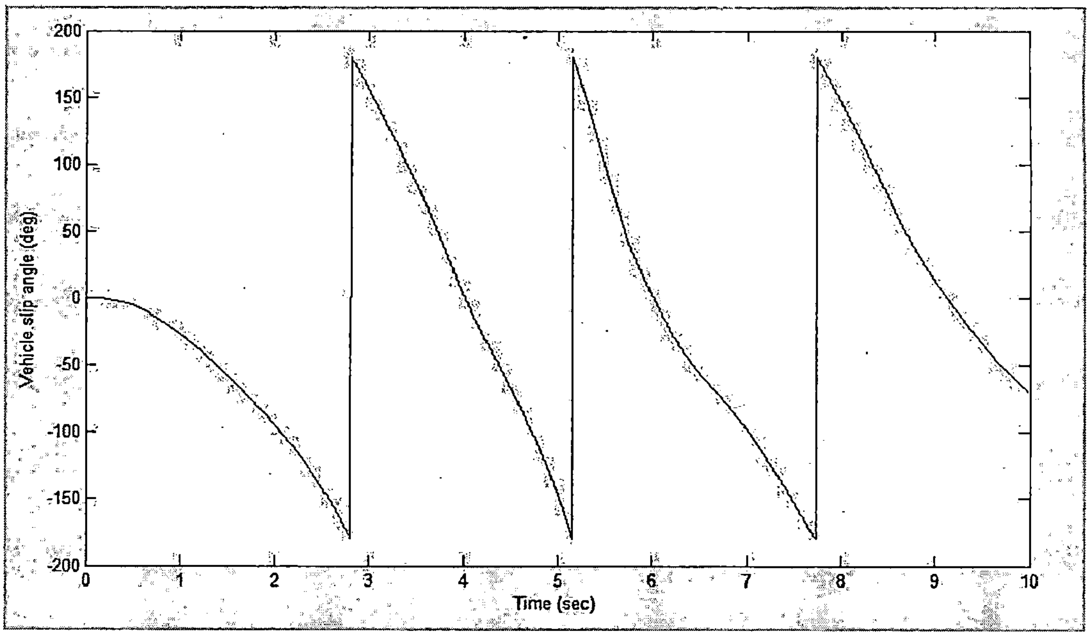


(a)

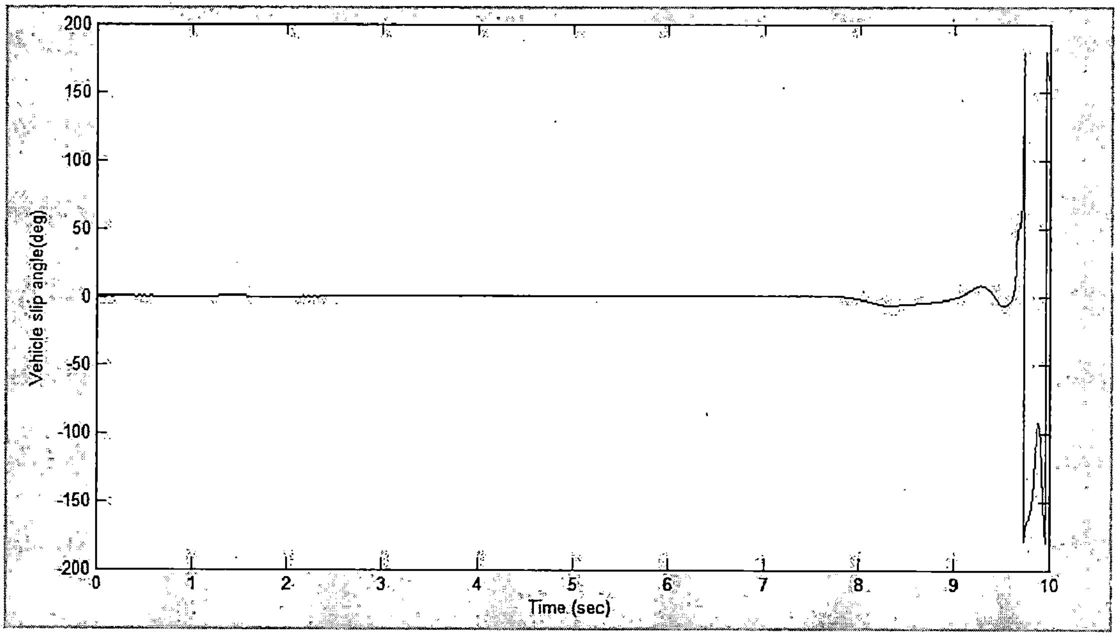


(b)

Fig 7.13 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response



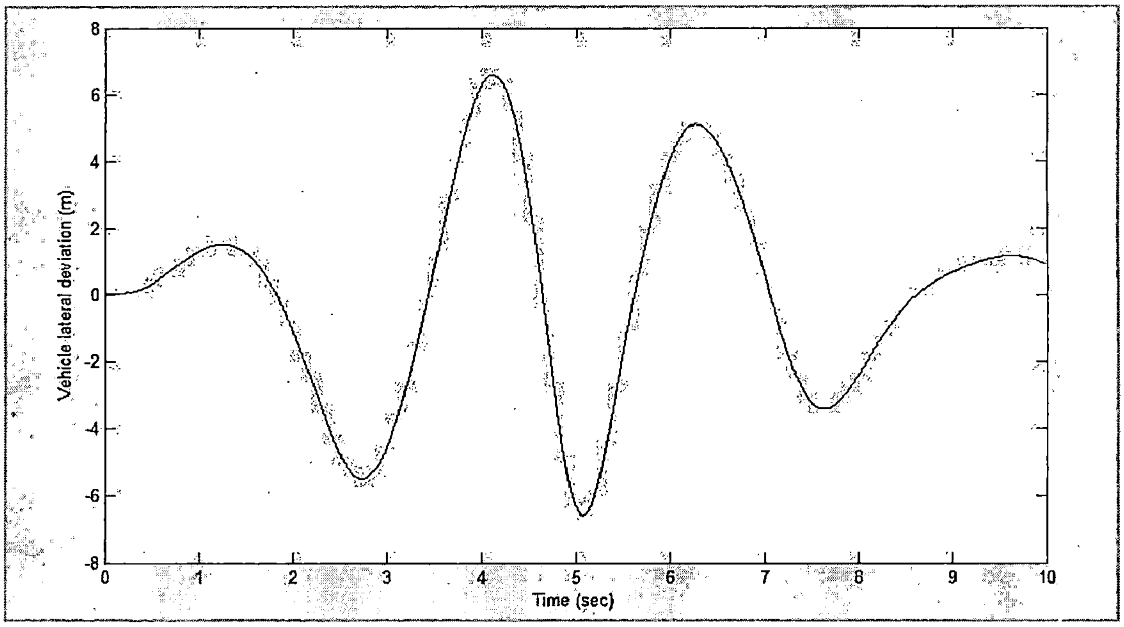
(a)



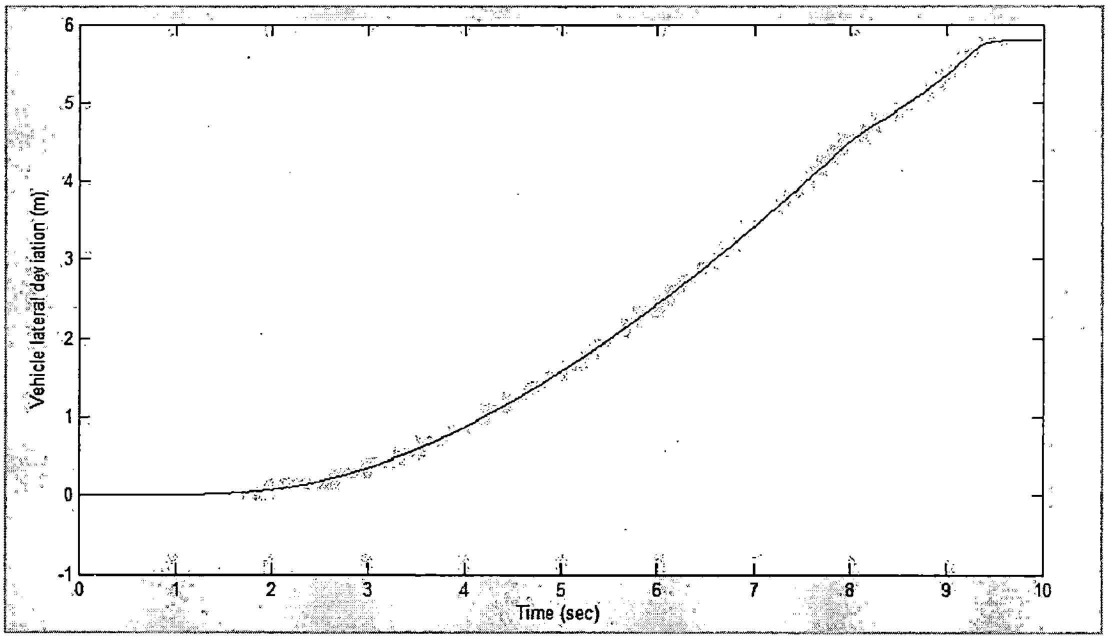
(b)

Fig 7.14 Vehicle slip angle (a) traditional ABS response (b) fuzzy ABS response

Fig 7.14 shows that the fuzzy ABS has a good response for vehicle slip angle as compared to traditional ABS.



(a)



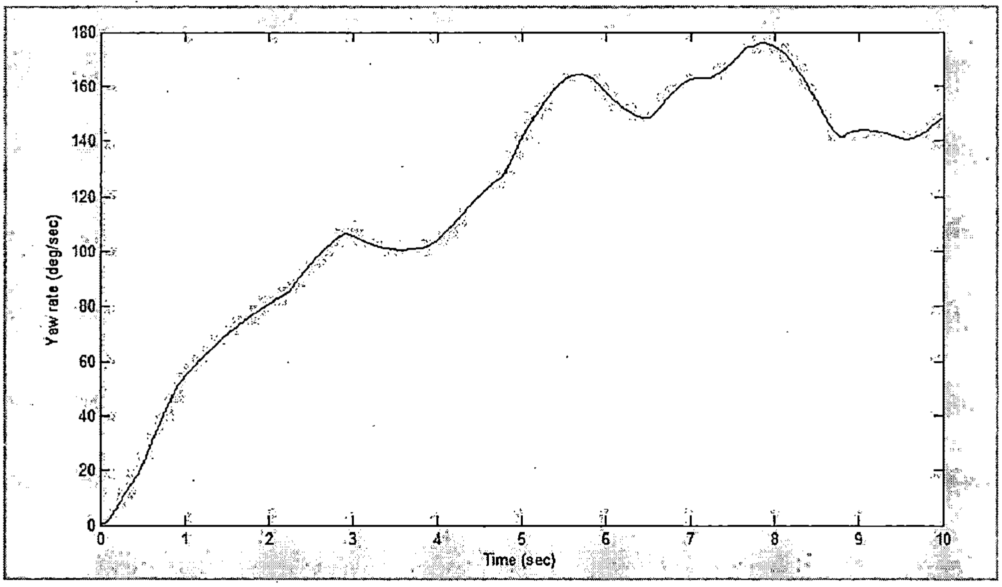
(b)

Fig 7.15 Vehicle lateral deviation (a) traditional ABS response (b) fuzzy ABS response

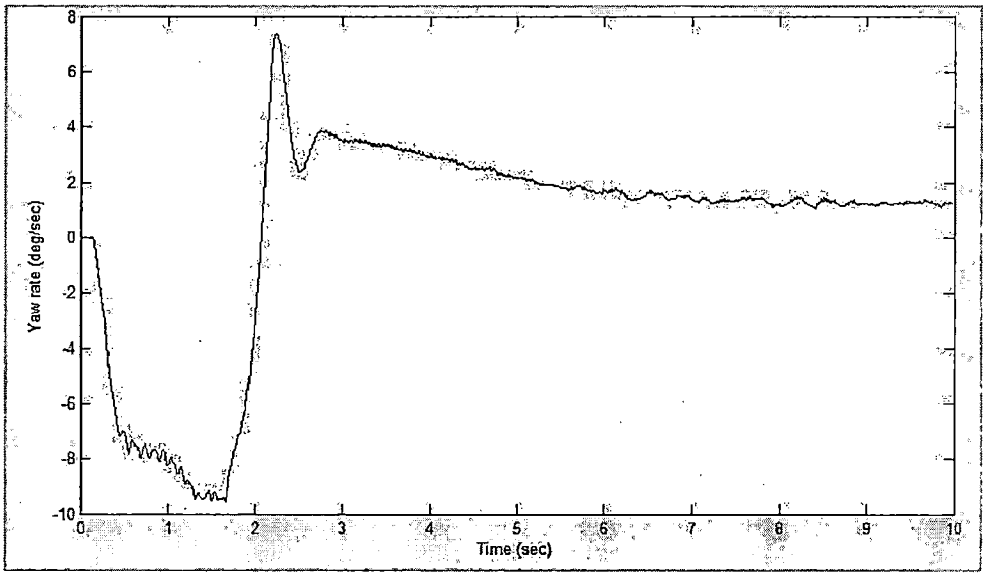
From fig 7.15 we can see that the traditional ABS is good when it comes to lateral deviation on low friction surface. Though it oscillates around zero it will come to rest soon. Whereas in fuzzy ABS a permanent lateral deviation occurs this may settle down after some more time.

7.1.3. Testing on split μ road

Split μ condition occurs on the road with ice spots. It means sudden change in friction coefficient.



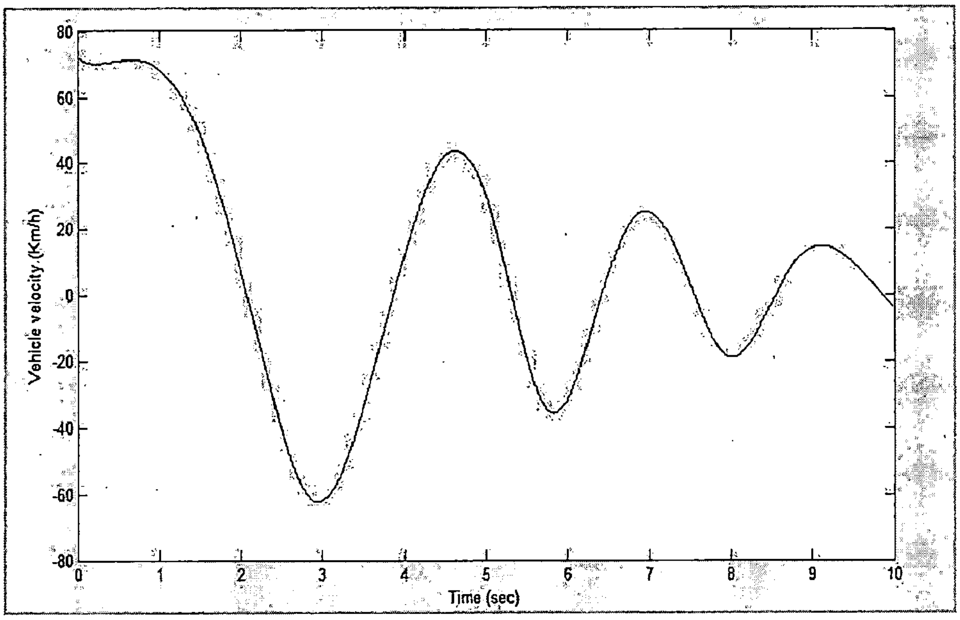
(a)



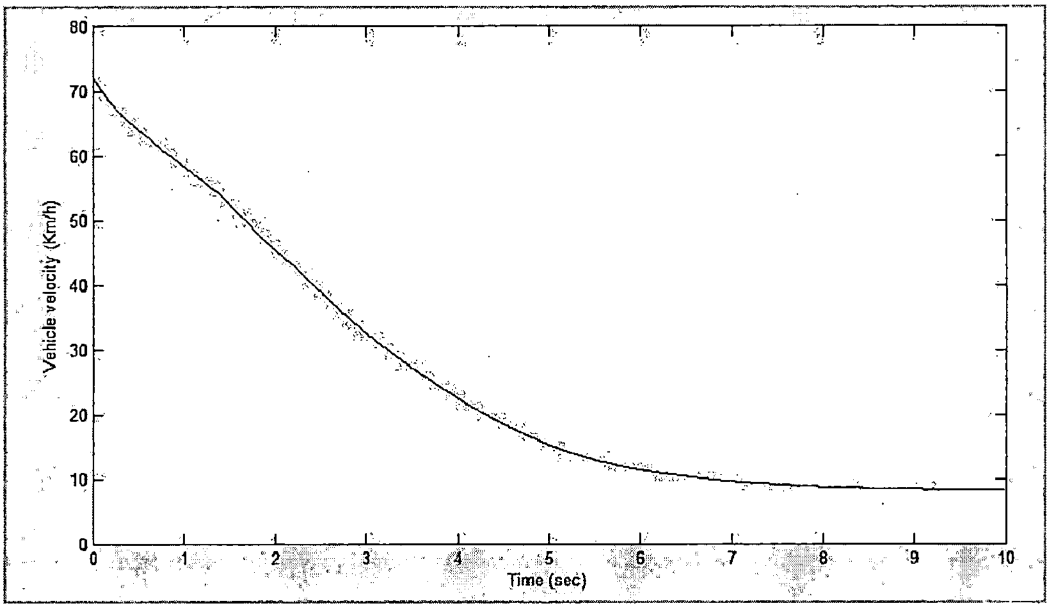
(b)

Fig 7.16 Yaw rate of vehicle (a) traditional ABS response (b) fuzzy ABS response

From fig 7.16 we can see that yaw rate of vehicle with fuzzy ABS will settle down to zero very fast but for traditional ABS this is not the case.



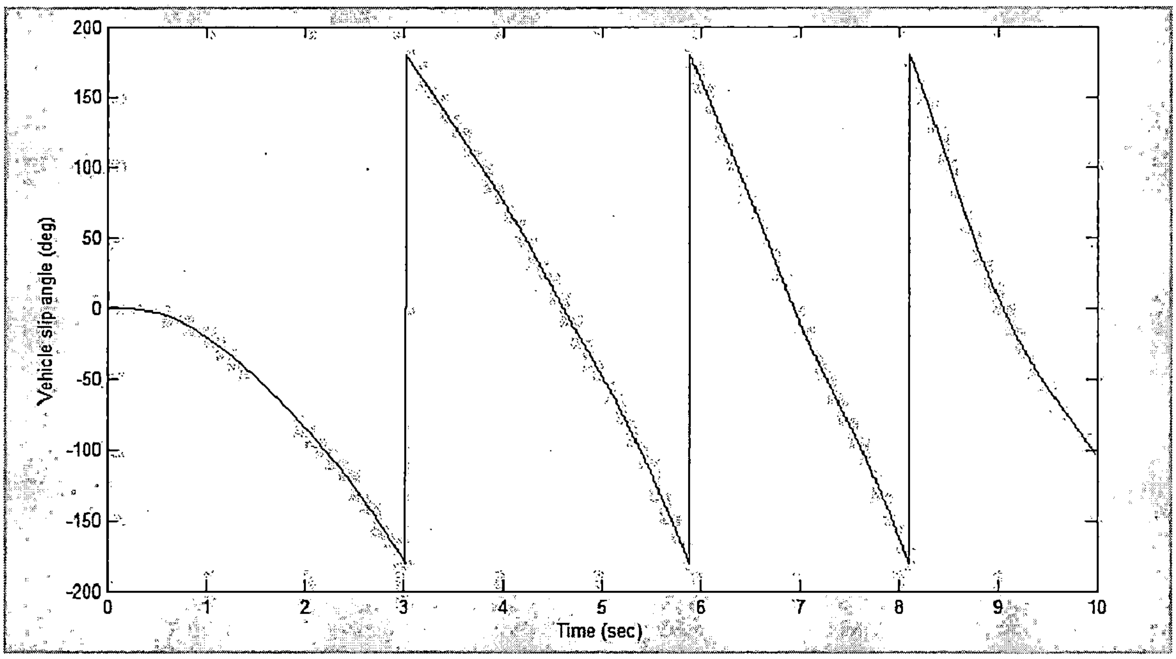
(a)



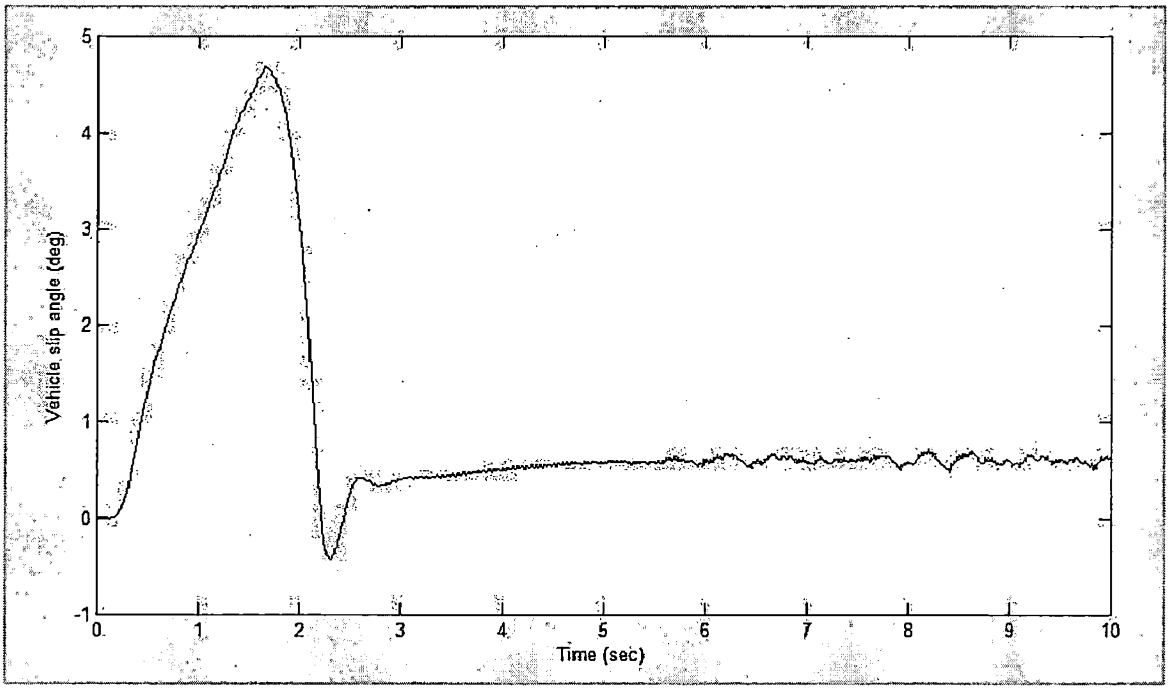
(b)

Fig 7.17 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response

From fig 7.17 we can see that there is smooth change in velocity for fuzzy ABS vehicle, where as in traditional ABS the change in vehicle velocity is oscillating in nature.

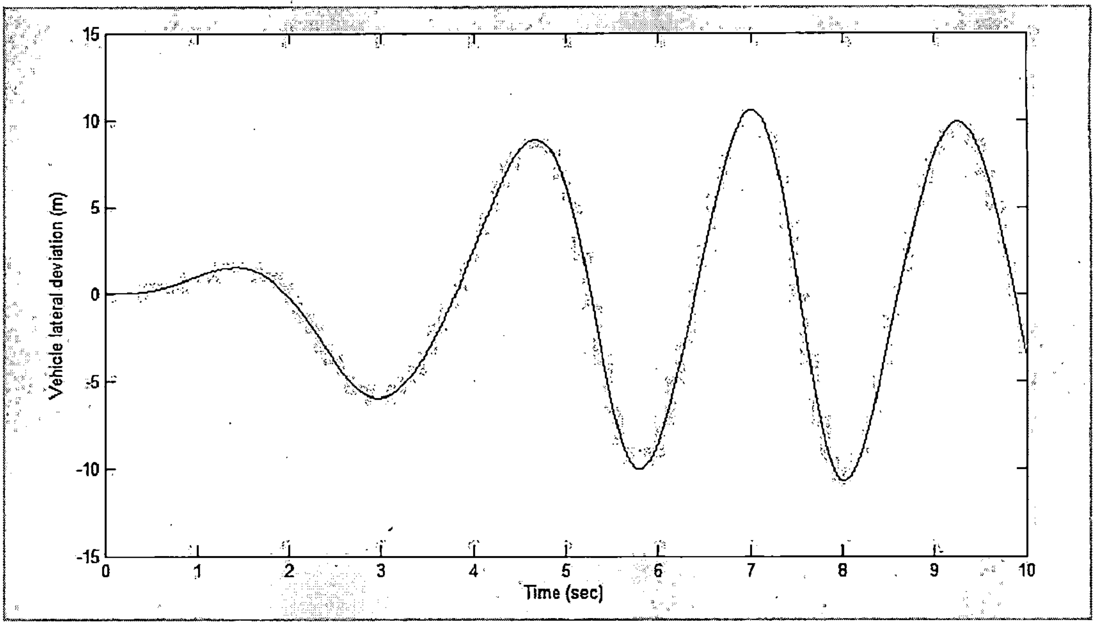


(a)

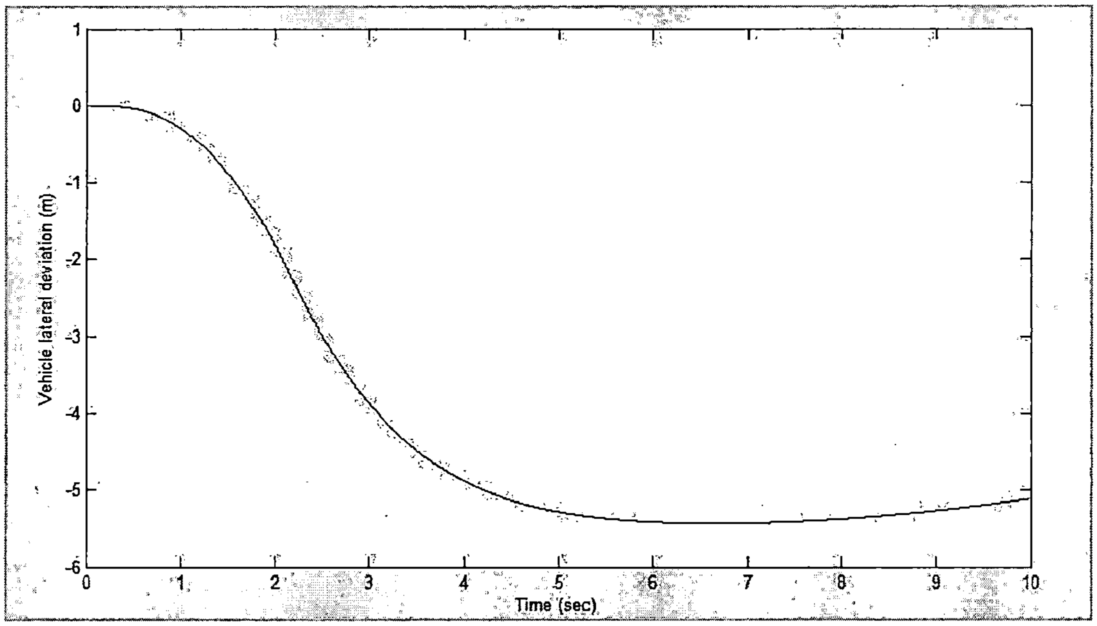


(b)

Fig 7.18 Vehicle slip angle (a) traditional ABS response (b) fuzzy ABS response



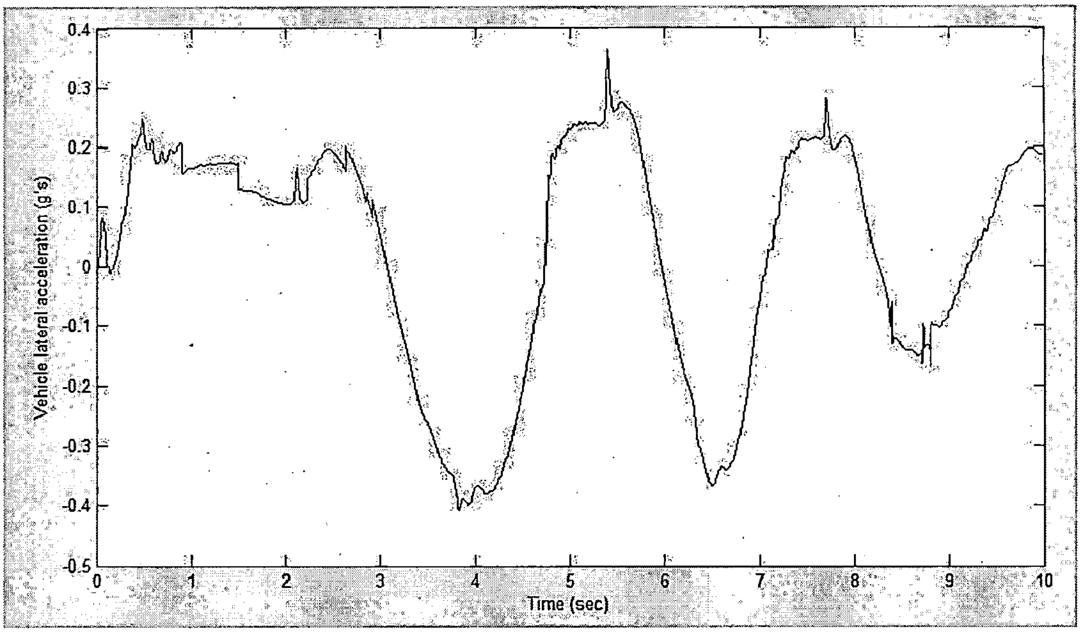
(a)



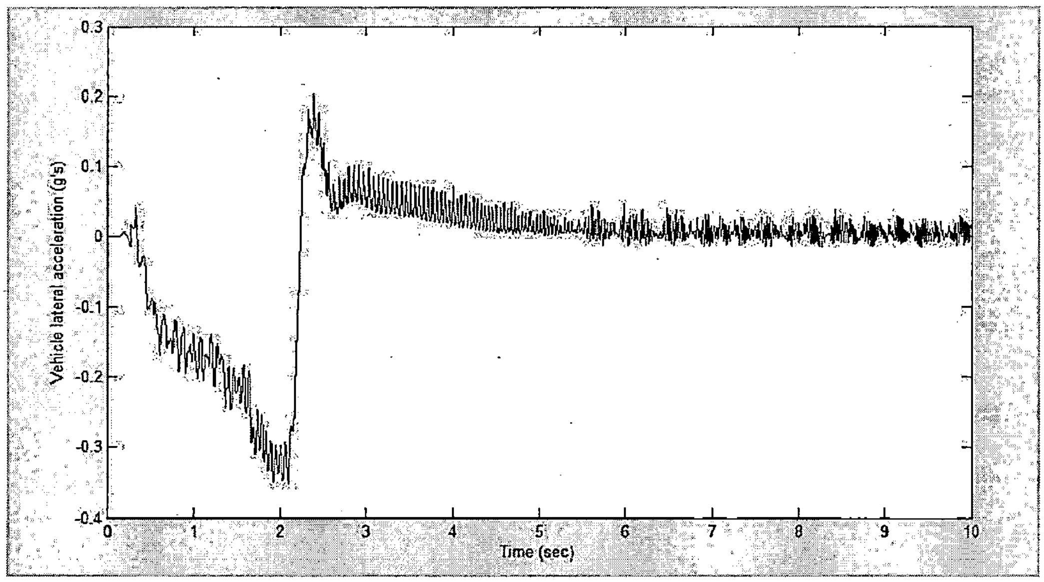
(b)

Fig 7.19 Vehicle lateral deviation (a) traditional ABS response (b) fuzzy ABS response

From fig 7.19 we can see that there is smooth change in lateral deviation for vehicle with fuzzy ABS where as it is in oscillating in nature for vehicle with traditional ABS. It is because of the smooth application of brake pressure in fuzzy ABS and ON-OFF type brake application in traditional ABS.



(a)



(b)

Fig 7.20 Vehicle lateral acceleration (a) traditional ABS response (b) fuzzy ABS response

7.2. Sinusoidal steering input

The sinusoidal steering input test is carried out with the signal having amplitude 30 degree and the frequency 0.2 Hz. The signal used is shown in the fig 7.21. The initial vehicle speed for this test is 20 m/s.

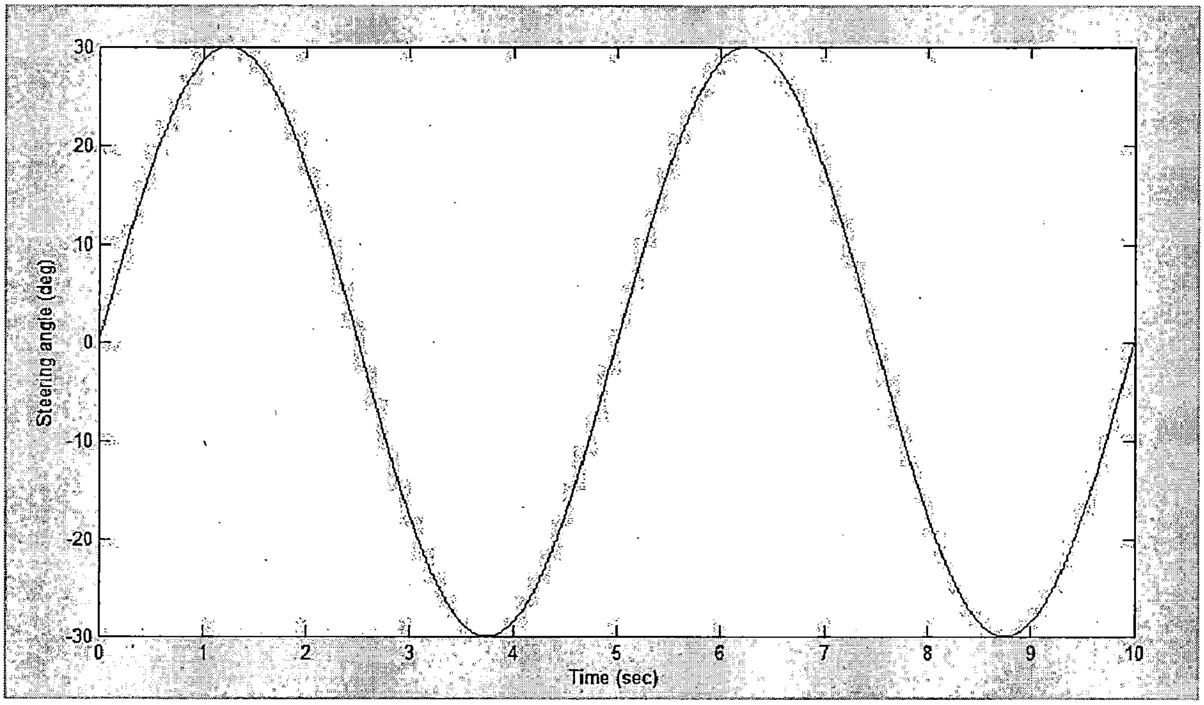
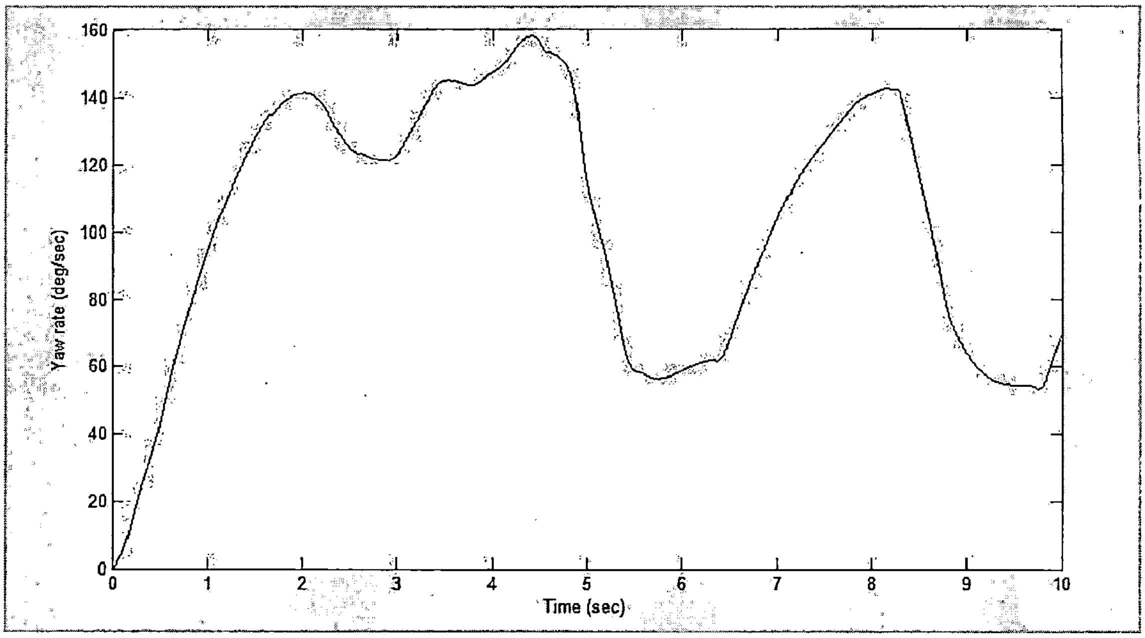


Fig 6.21 Sinusoidal steering input

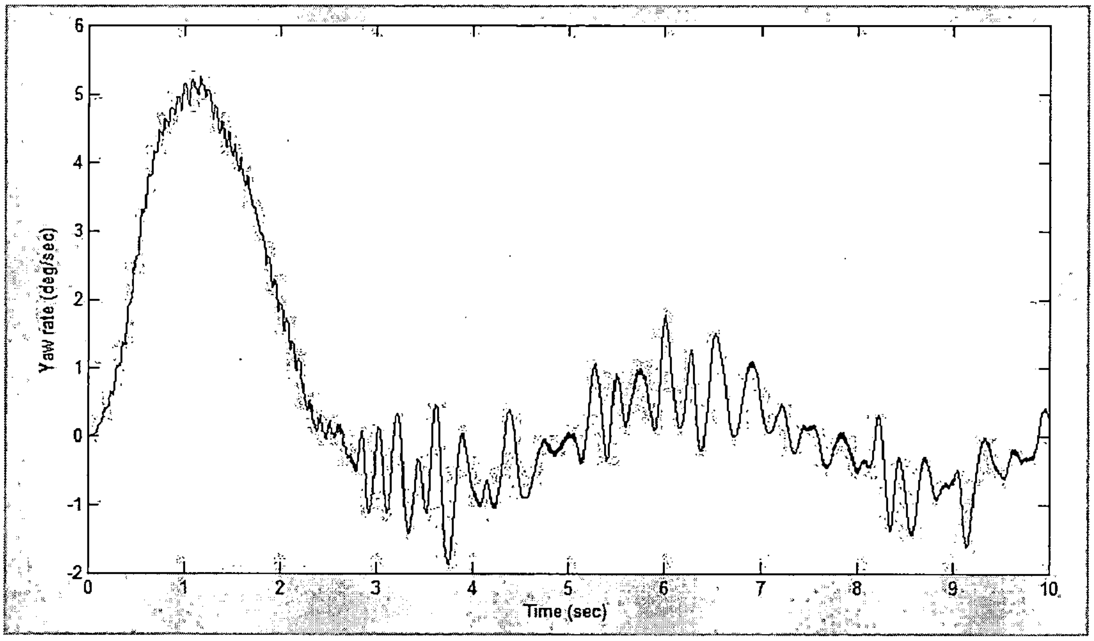
7.2.1. Testing on Dry road

Here for dry road the road surface used is having a high friction coefficient. The initial conditions and the test input signal is as per describe above.

From fig 7.22 we can see that the yaw rate of the fuzzy ABS is settling down to zero very fast whereas traditional ABS is very slow to reduce yaw rate to zero.



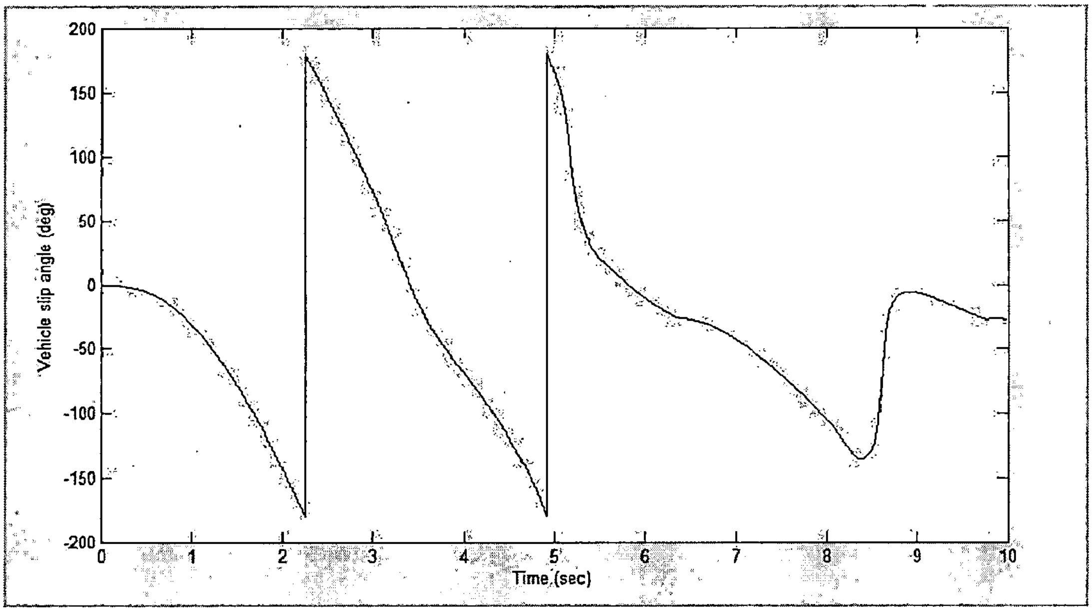
(a)



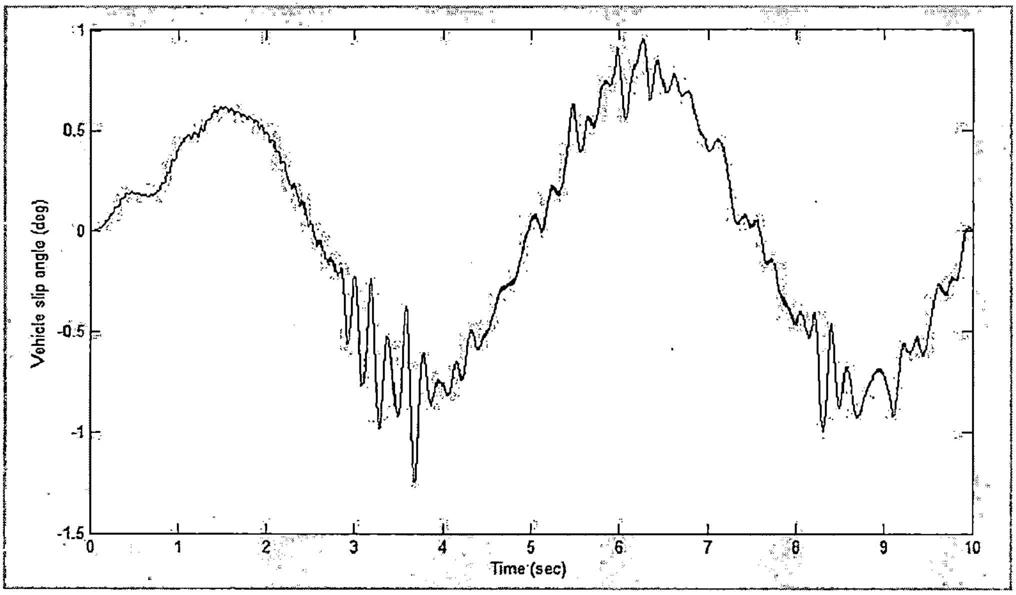
(b)

Fig 7.22 Yaw rate of vehicle (a) traditional ABS response (b) fuzzy ABS response

From fig 7.23 we can see that the vehicle slip angle of fuzzy ABS is try to settle down to zero where as the slip angle for traditional ABS is more or less same irrespective of the initial conditions and input signals.



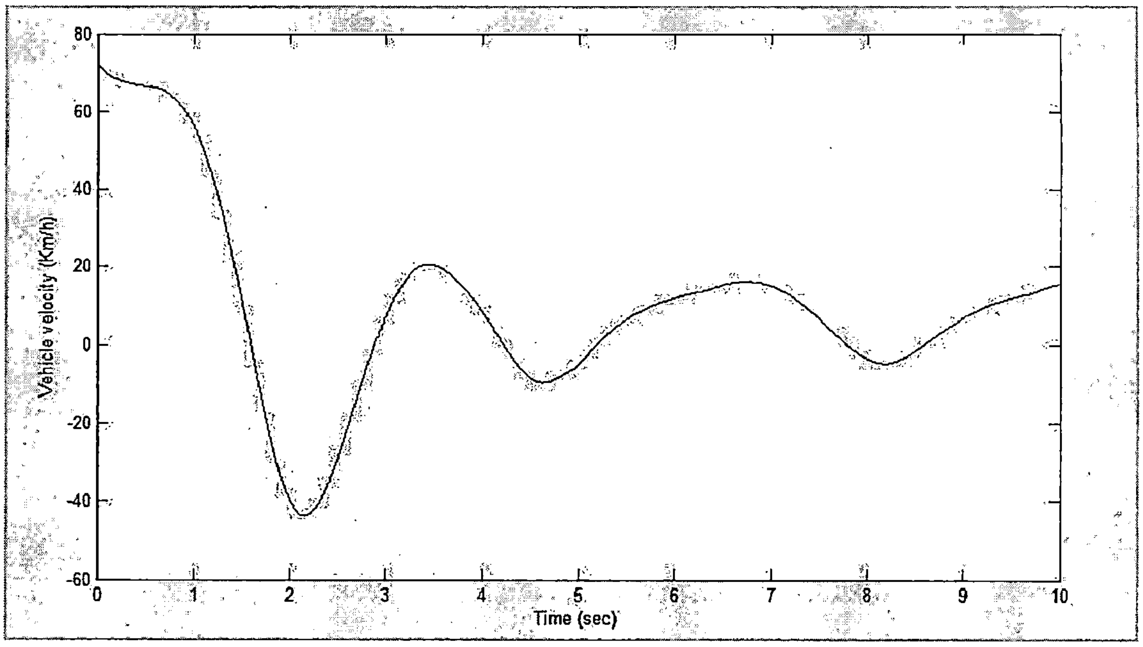
(a)



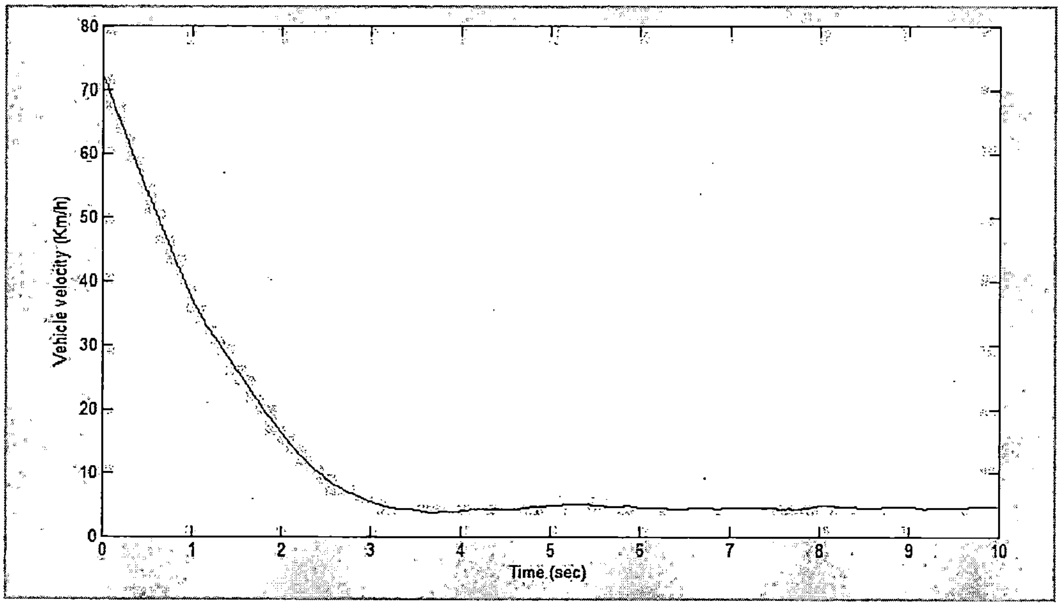
(b)

Fig 7.23 Vehicle slip angle (a) traditional ABS response (b) fuzzy ABS response

On application of brake the vehicle velocity reduces smoothly whereas in traditional ABS vehicle slow down in oscillating manner this is what we can see from fig 7.24.



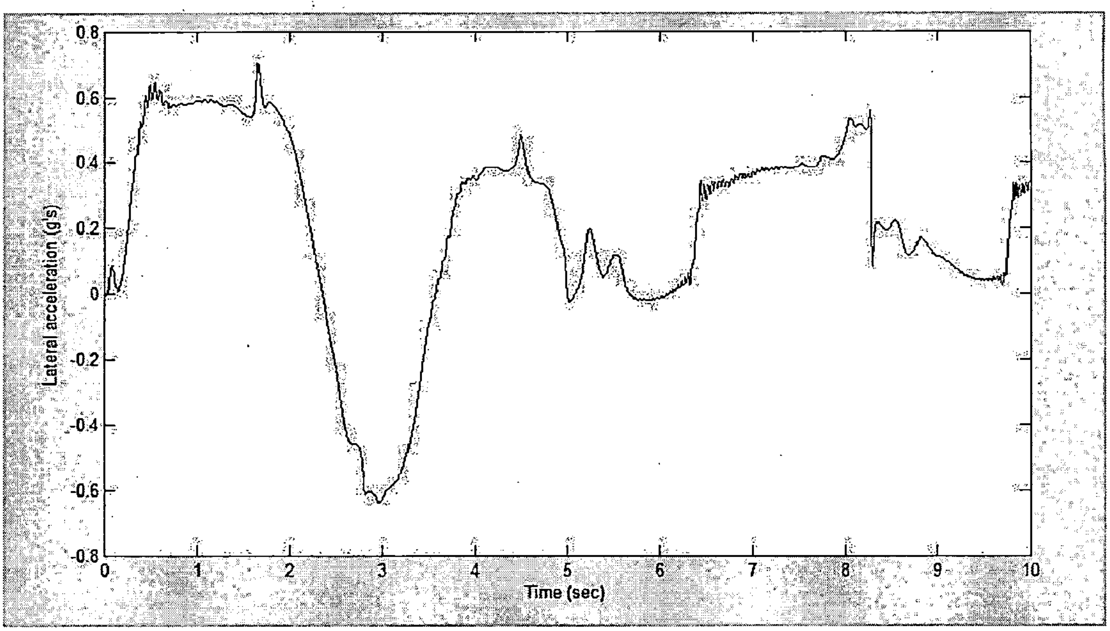
(a)



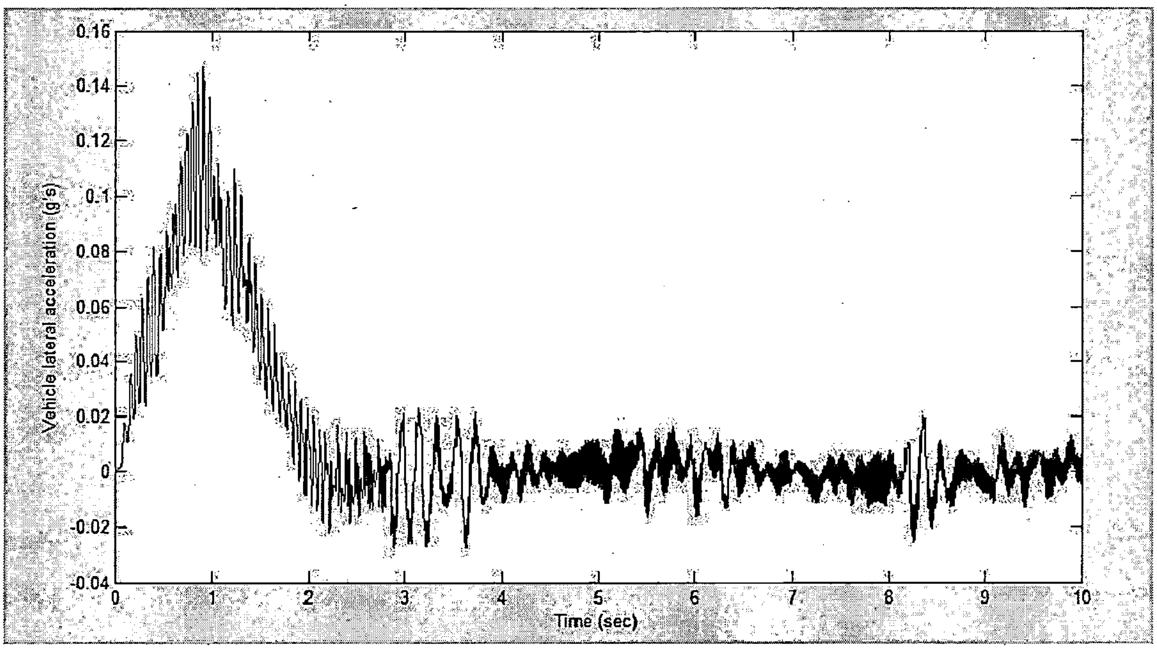
(b)

Fig 7.24 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response

From fig 7.25 we can see that the lateral acceleration for fuzzy ABS is very low as compared to that of traditional ABS.



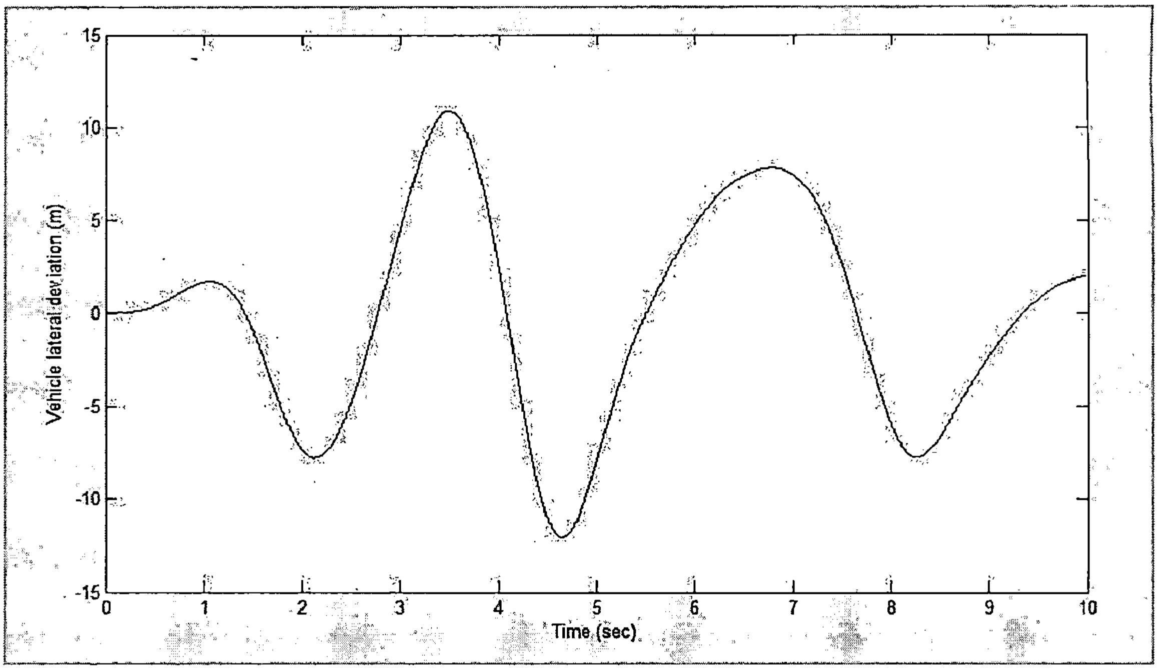
(a)



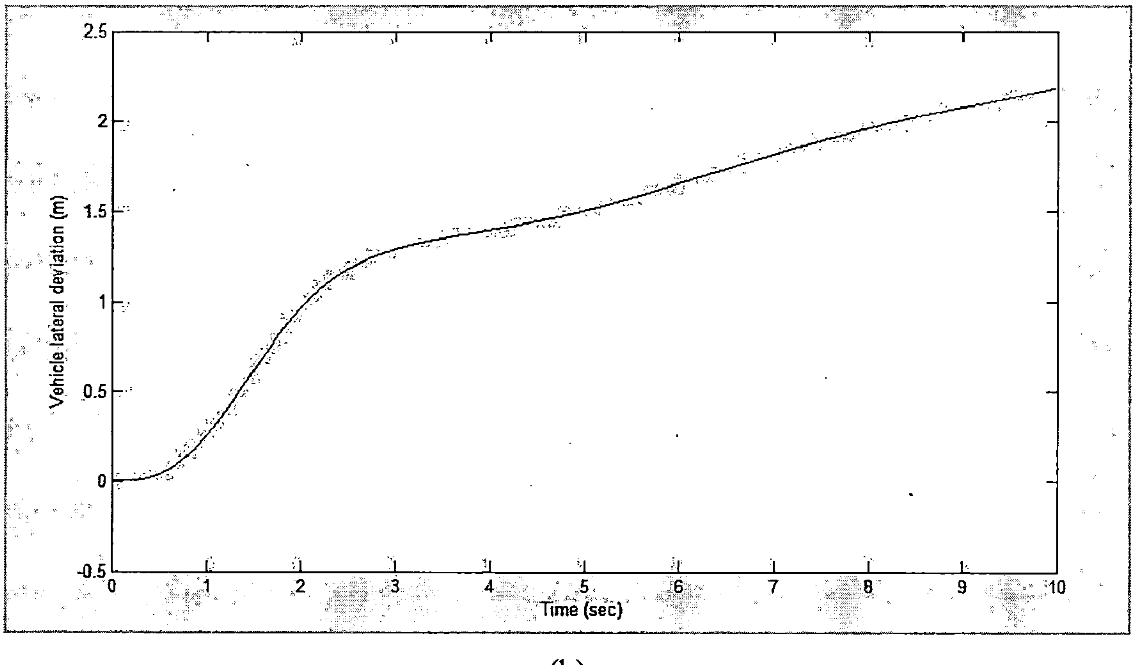
(b)

Fig 7.25 Lateral acceleration (a) traditional ABS response (b) fuzzy ABS response

Fig 7.26 shows that there is smooth change in vehicle lateral deviation for vehicle with fuzzy ABS whereas it is oscillating in nature for tradition ABS controller.



(a)

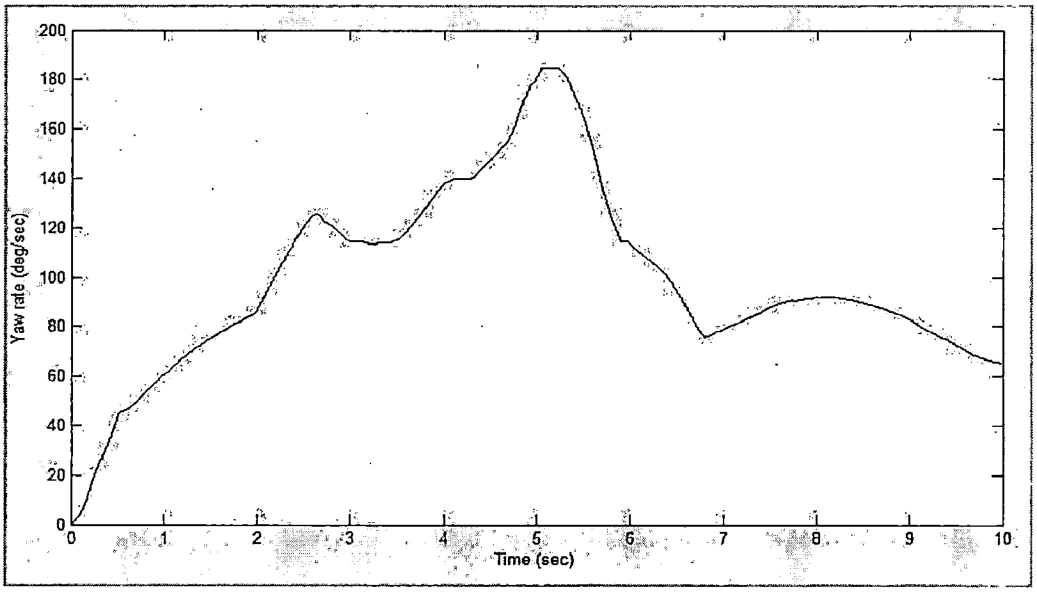


(b)

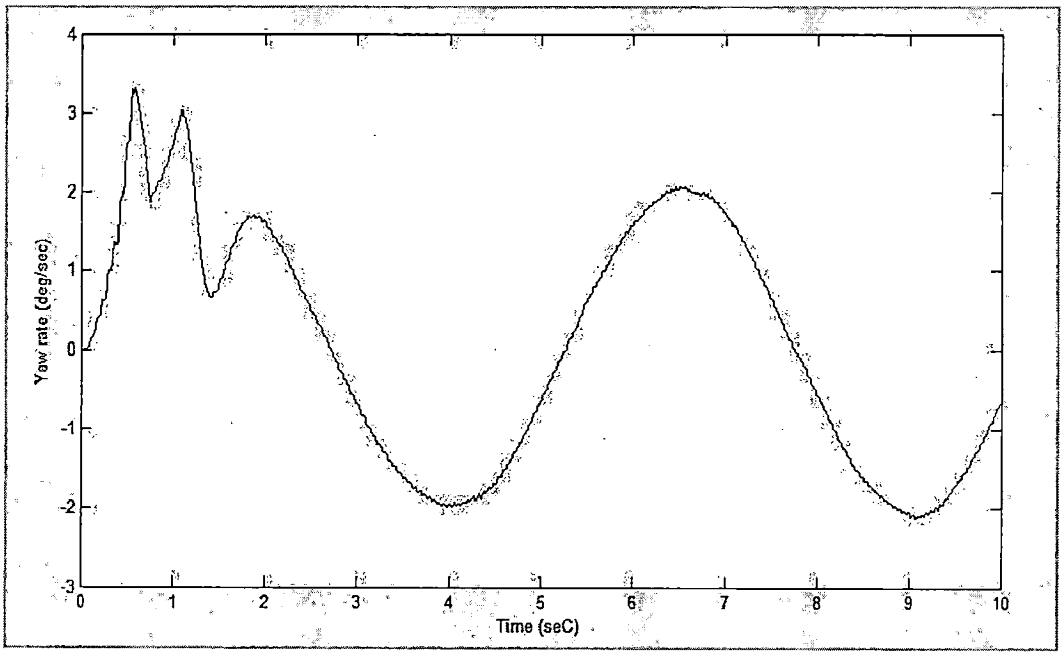
Fig 7.26 Vehicle lateral deviation (a) traditional ABS response (b) fuzzy ABS response

7.2.2. Testing on low μ road

Fig 7.27 shows that the yaw rate for fuzzy ABS is very small as compared to that of traditional ABS. It means vehicle is oscillating very slowly about vertical in case of fuzzy ABS but it is oscillating very fast in case of traditional ABS.

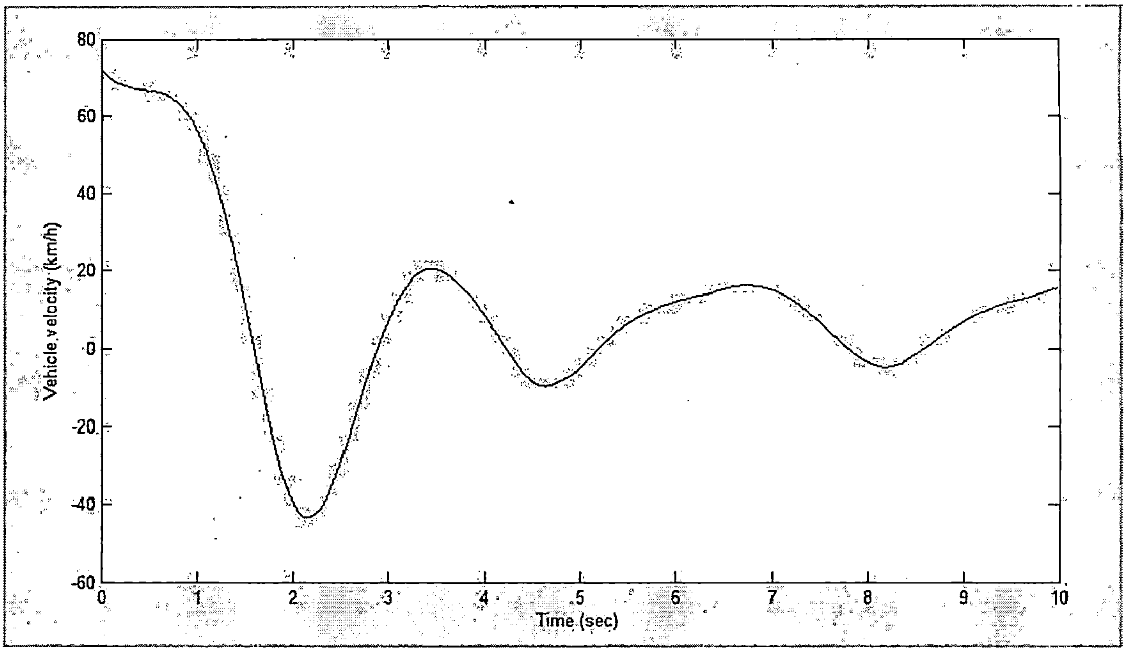


(a)

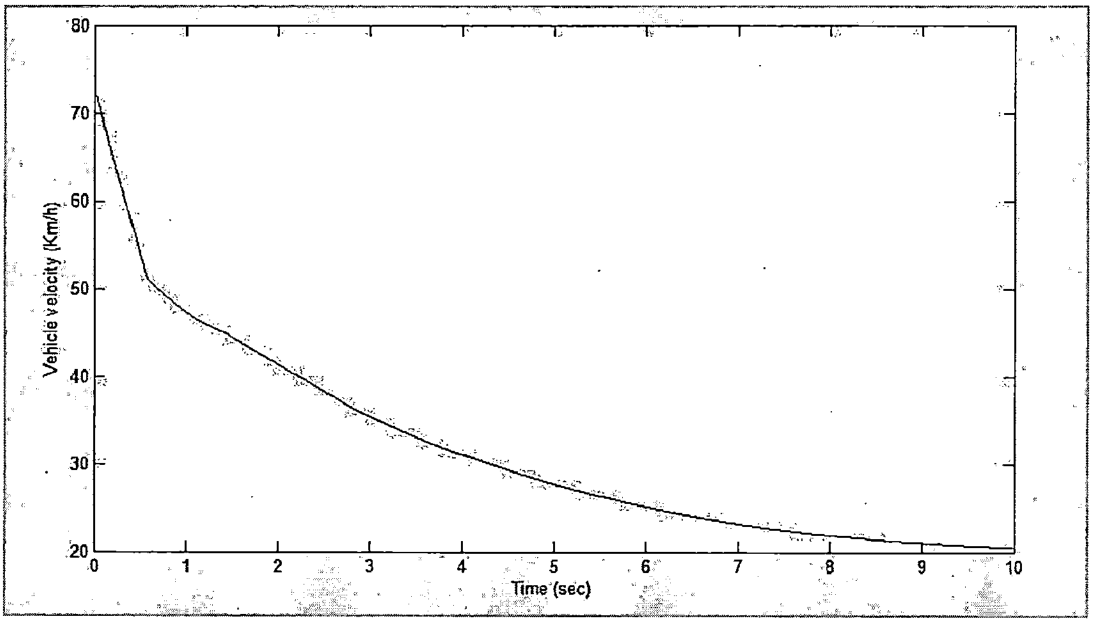


(b)

Fig 7.27 Yaw rate (a) traditional ABS response (b) fuzzy ABS response



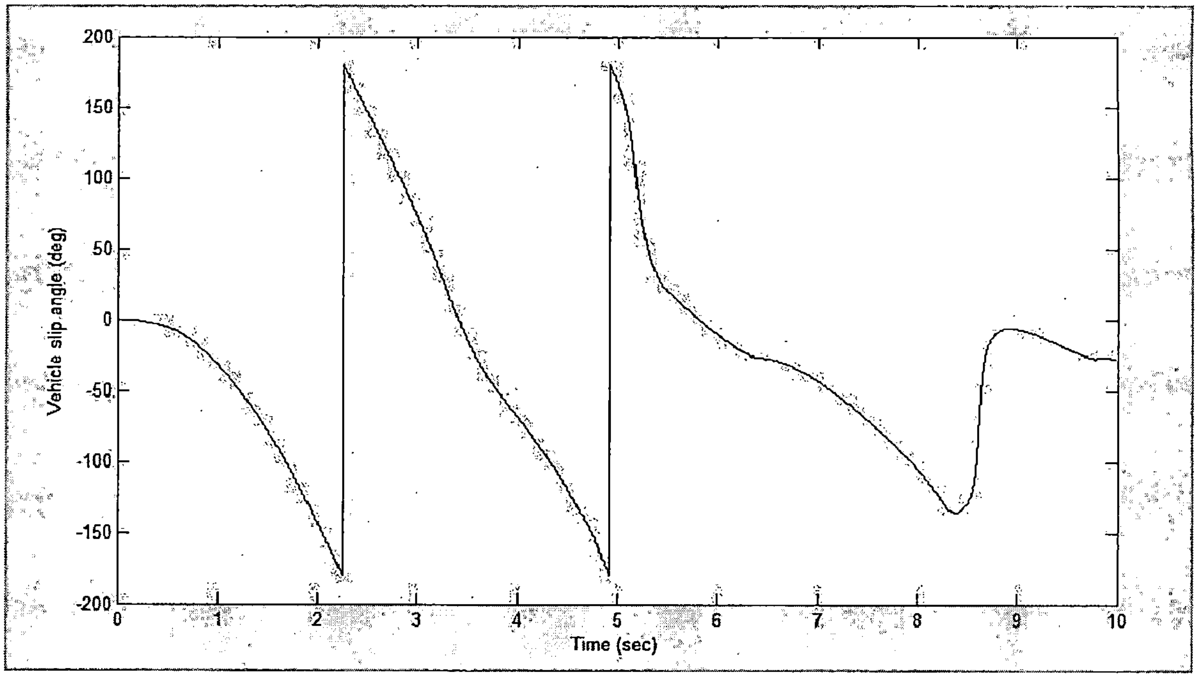
(a)



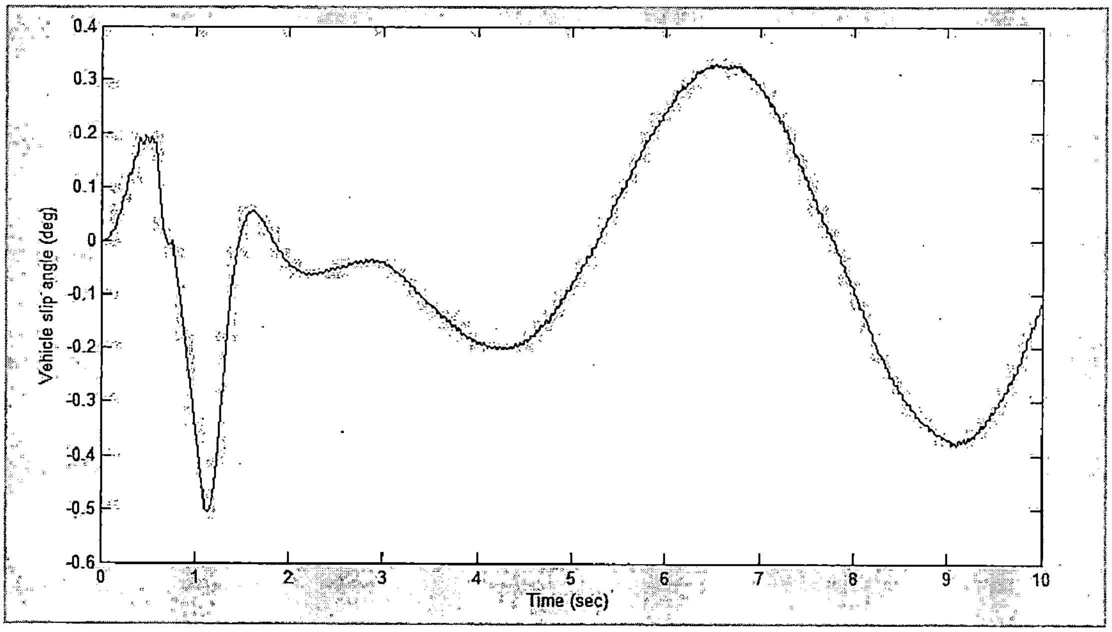
(b)

Fig 7.28 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response

From fig 7.28 we can see that there is smooth change in velocity for fuzzy ABS equipped vehicle where is this is not the case with traditional ABS system.



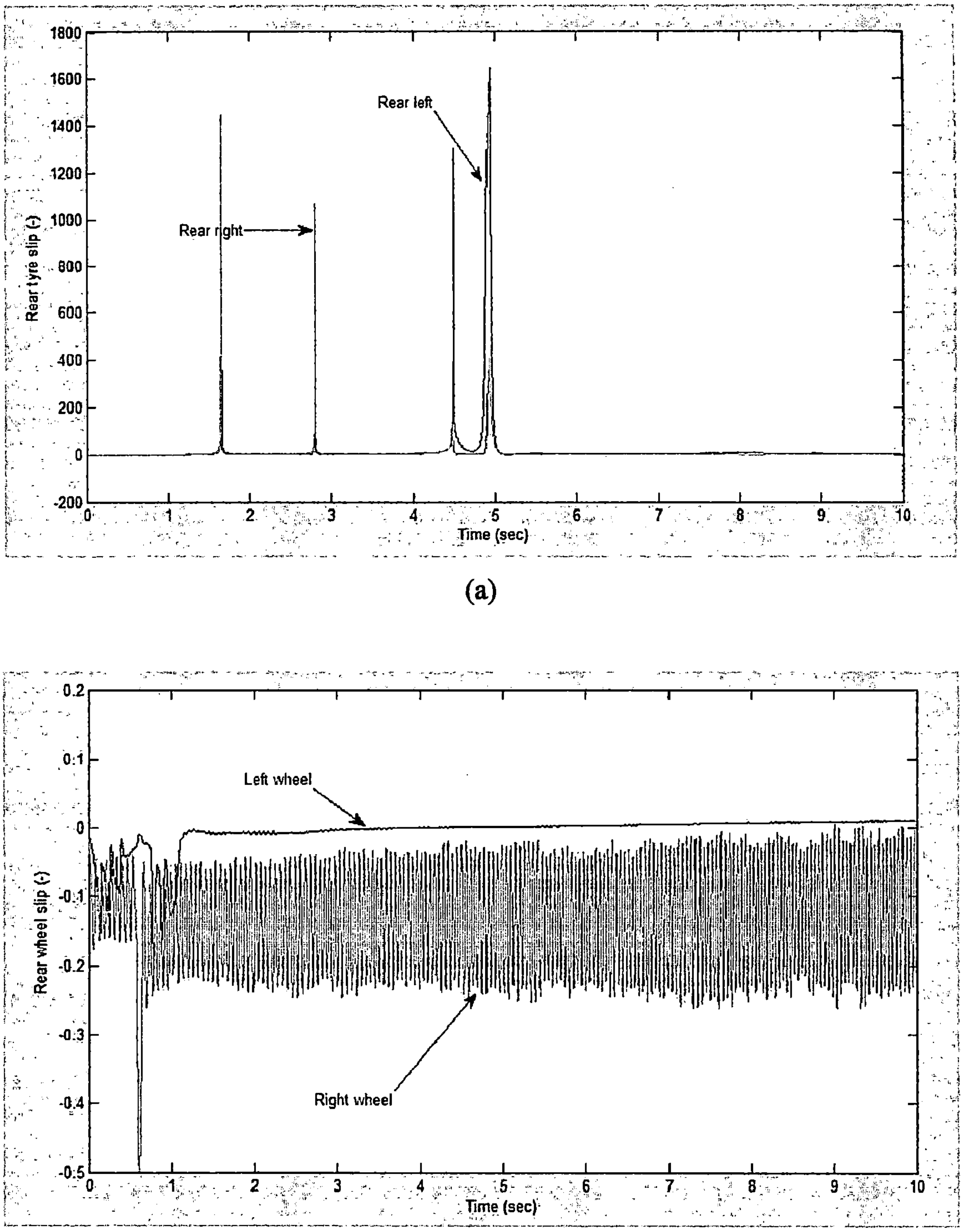
(a)



(b)

Fig 7.29 Vehicle slip angle (a) traditional ABS response (b) fuzzy ABS response

From the fig 7.29 we can see that the condition of vehicle slip angle is better in case of vehicle with fuzzy ABS as compared with the traditional ABS equipped vehicle

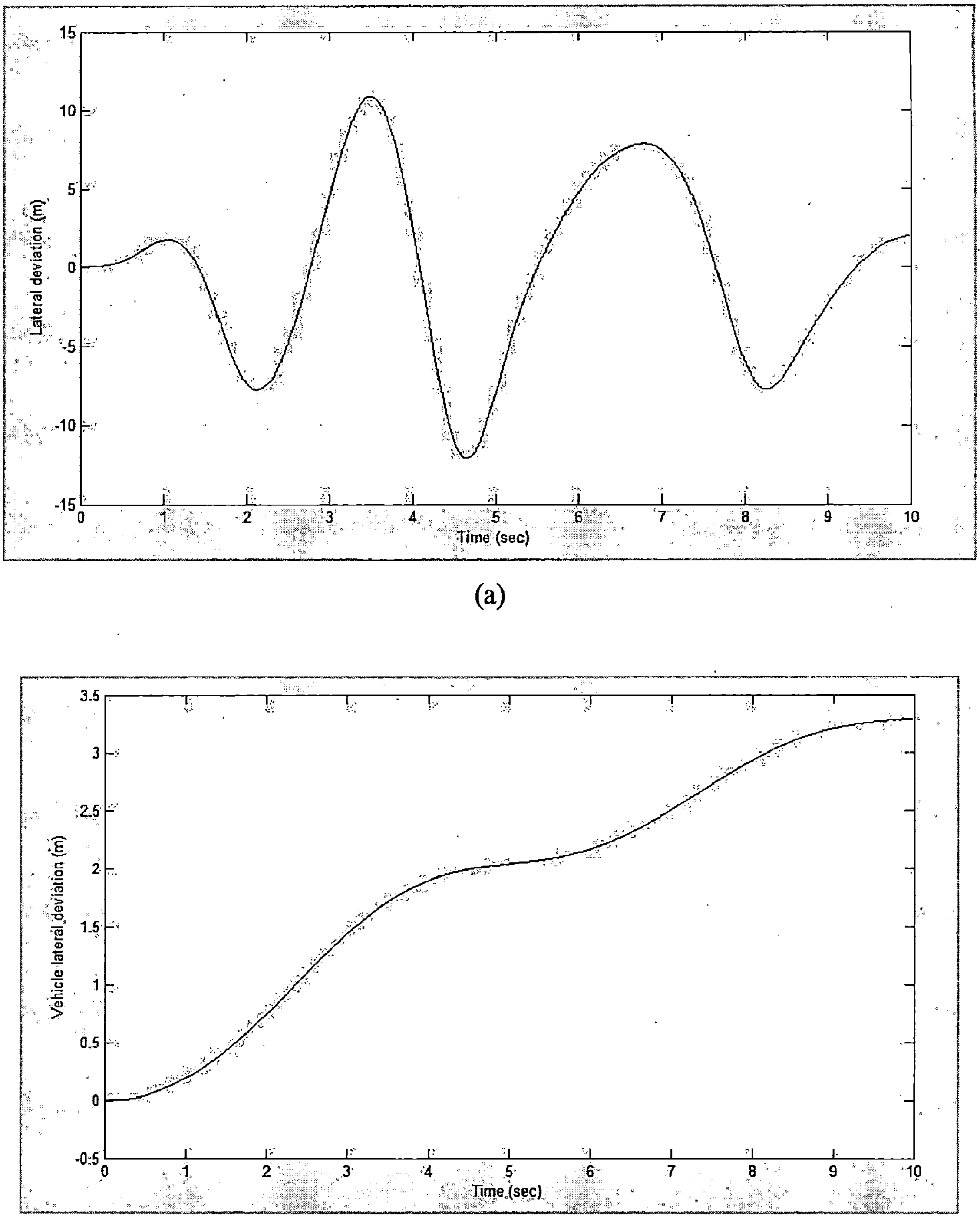


(a)

(b)

Fig 7.30 Rear wheel slip (a) traditional ABS response (b) fuzzy ABS response

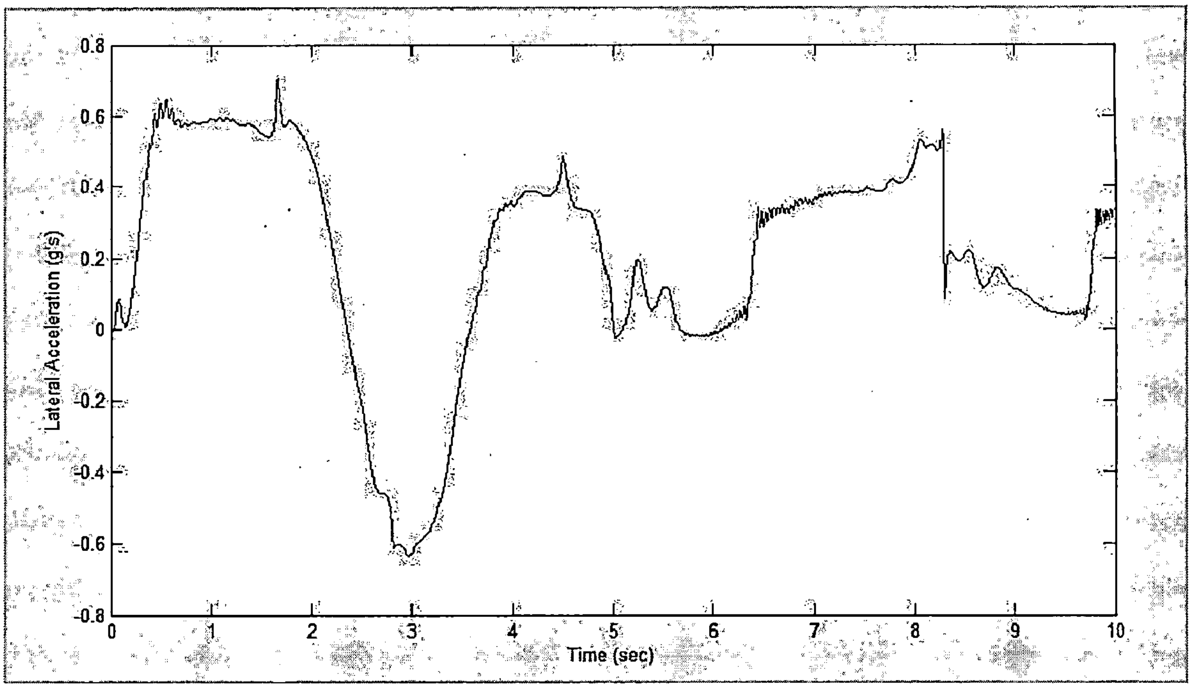
Fig 7.30 shows that the wheel slip for fuzzy ABS equipped vehicle is very less as compared with the vehicle having traditional ABS installed in it.



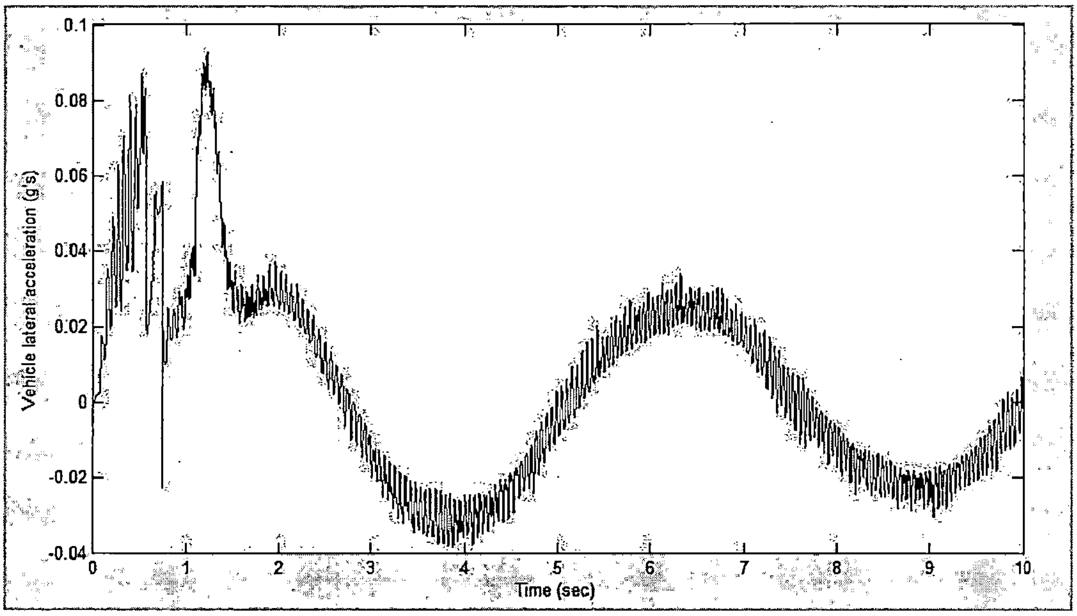
(a)

(b)

Fig 7.31 Lateral deviation of vehicle from path (a) traditional ABS response (b) fuzzy ABS response



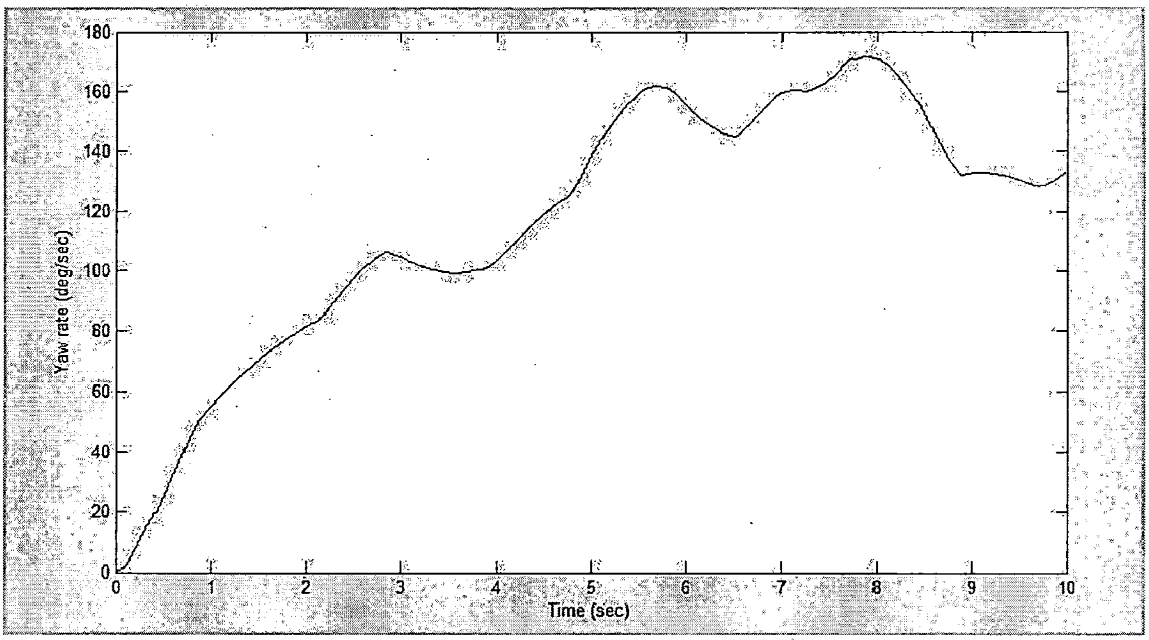
(a)



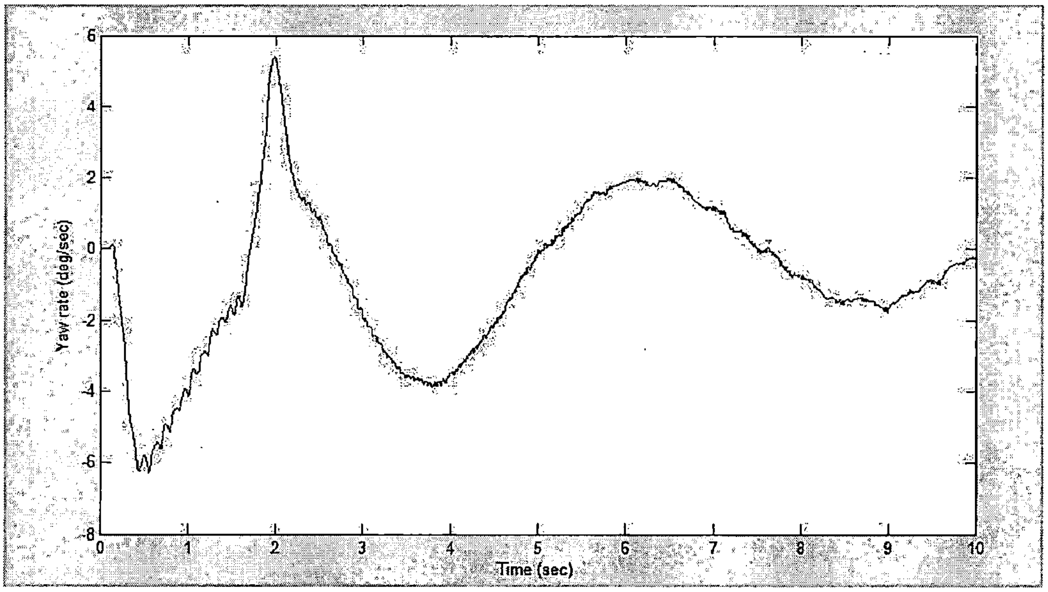
(b)

Fig 7.32 Lateral acceleration of vehicle (a) traditional ABS response (b) fuzzy ABS response

7.2.3. Testing on split μ road



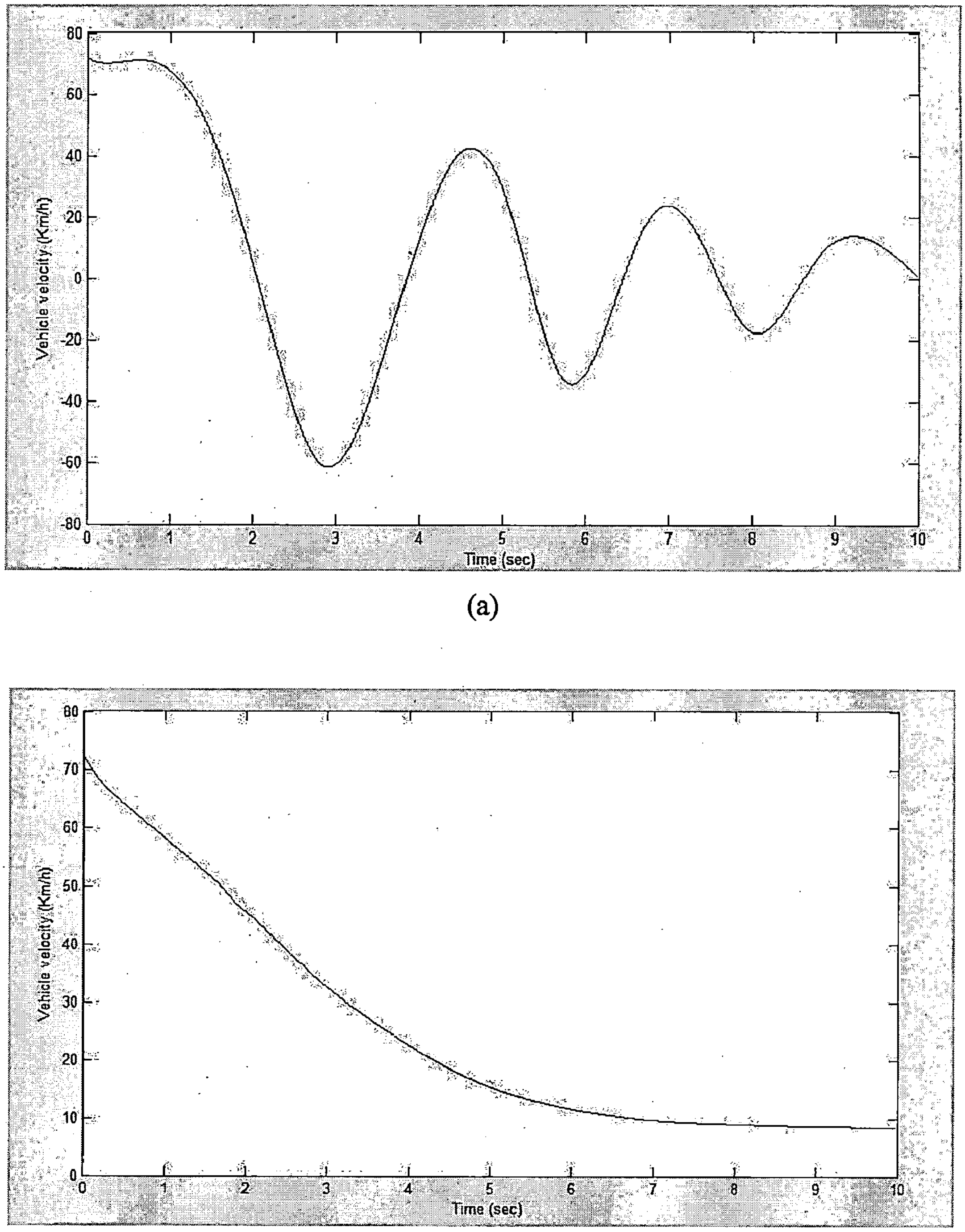
(a)



(b)

Fig 7.33 Yaw rate of vehicle (a) traditional ABS response (b) fuzzy ABS response

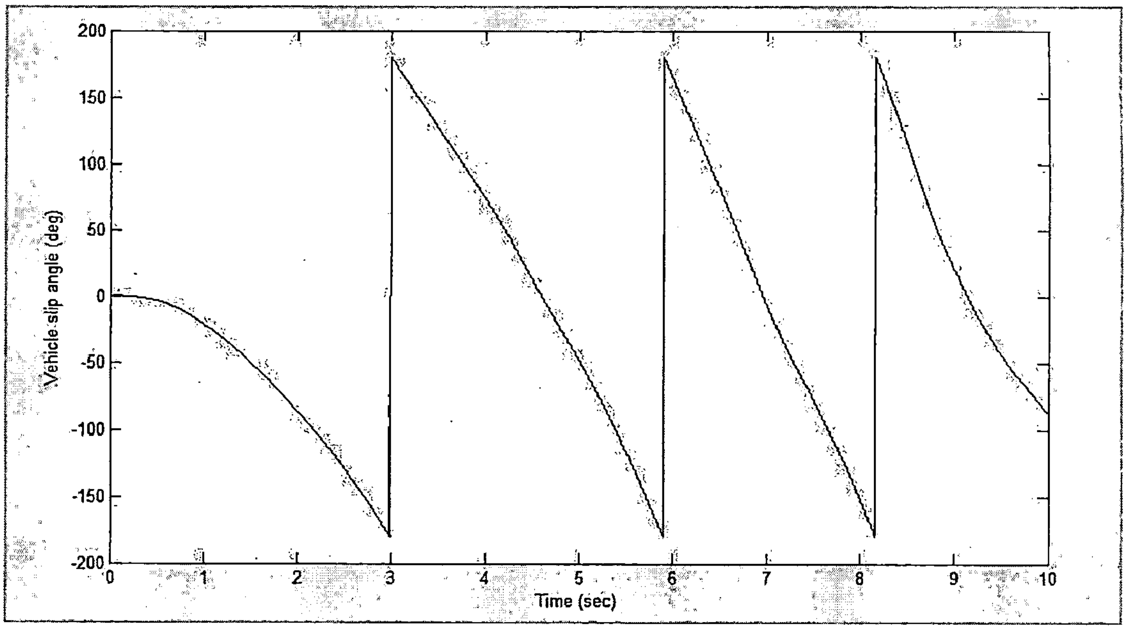
From fig 7.33 we can see that the yaw rate of vehicle is small for fuzzy ABS equipped vehicle as compared to that of traditional ABS controlled vehicle.



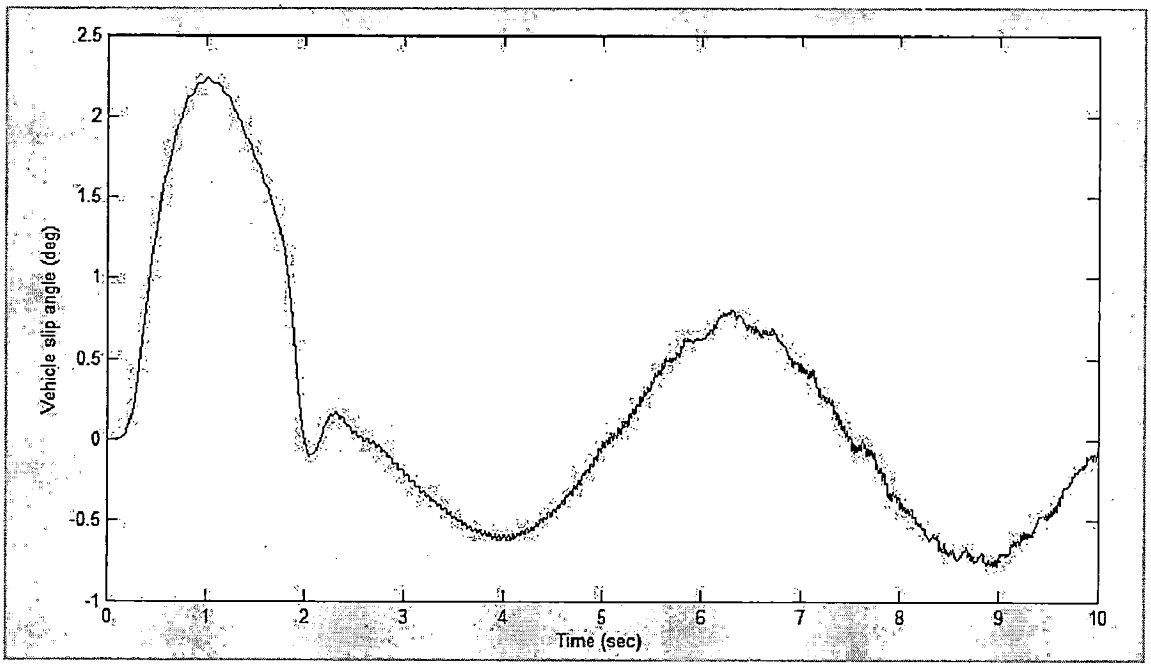
(a)

(b)

Fig 7.34 Vehicle velocity (a) traditional ABS response (b) fuzzy ABS response

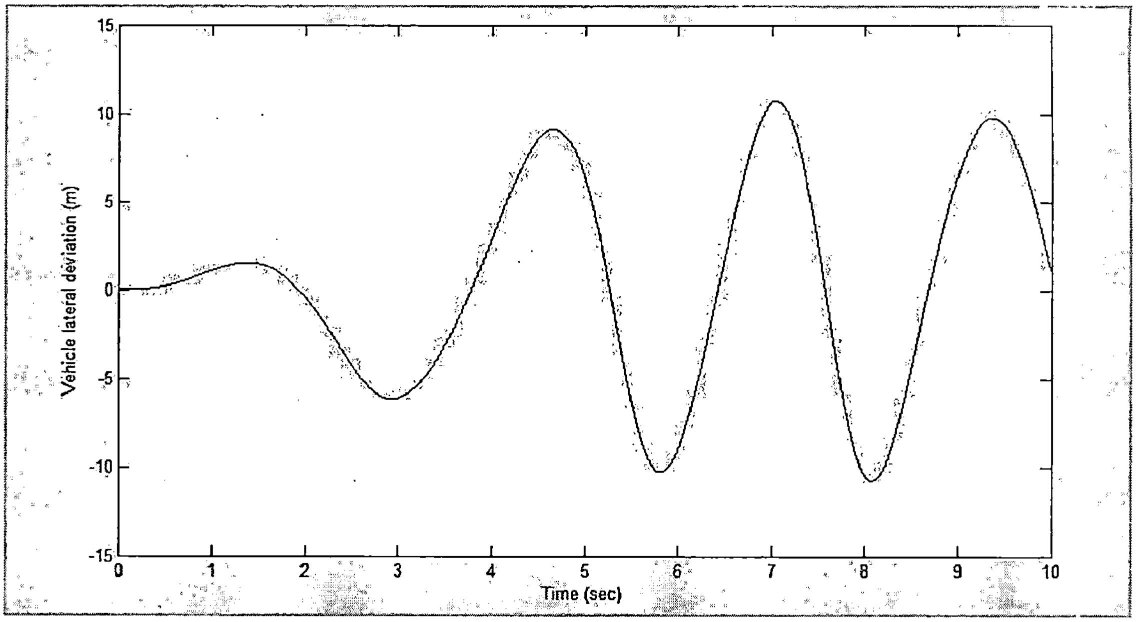


(a)

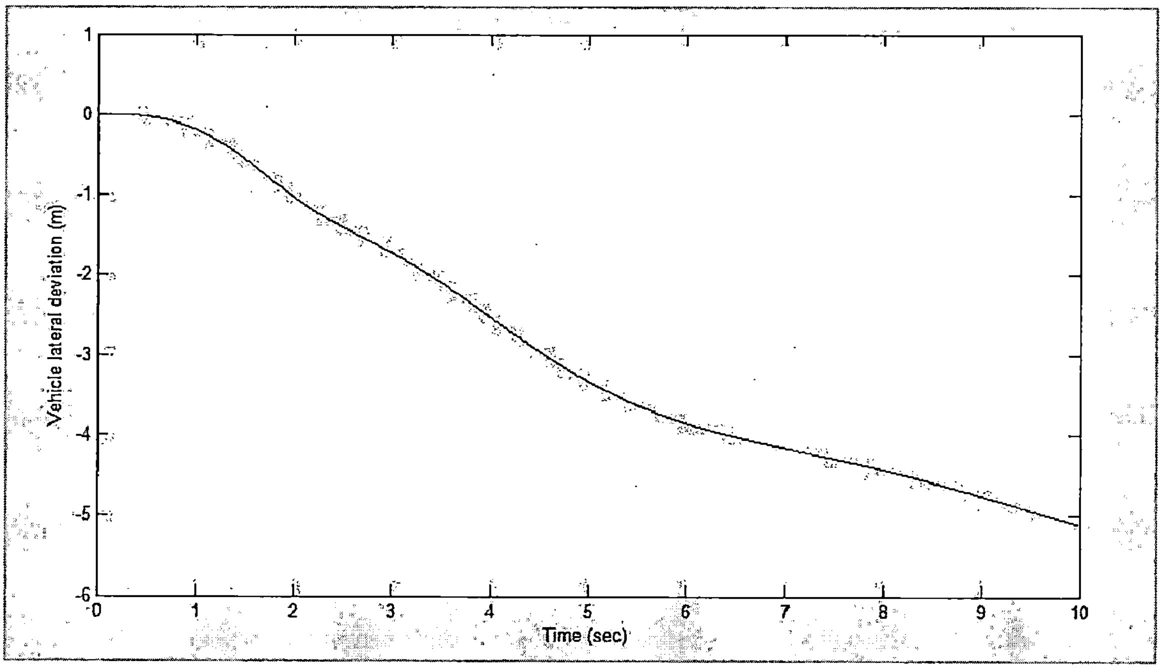


(b)

Fig 7.35 Vehicle slip angle (a) traditional ABS response (b) fuzzy ABS response



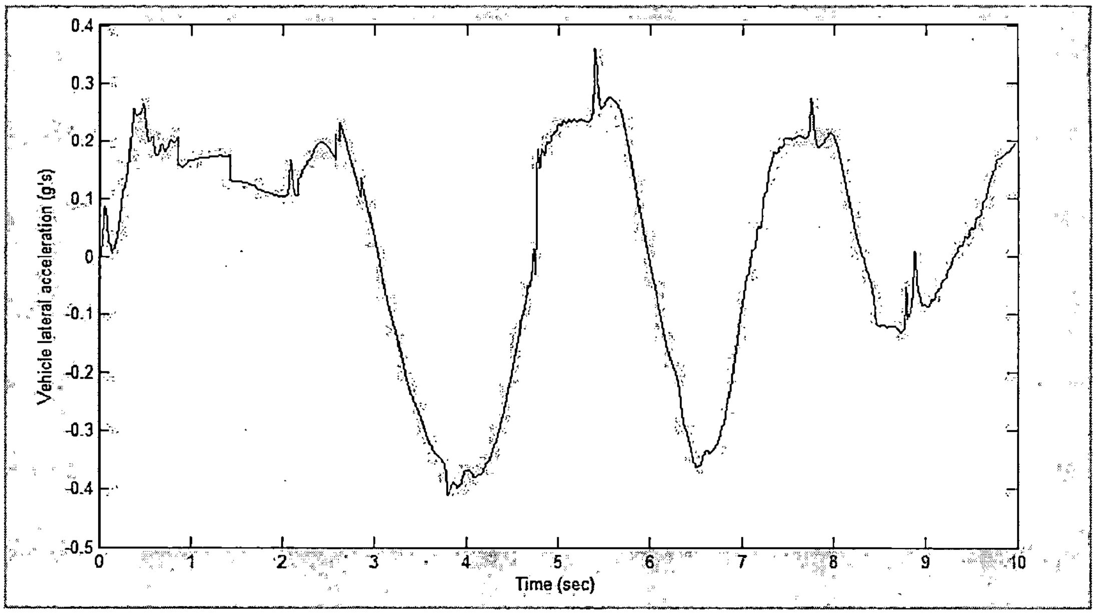
(a)



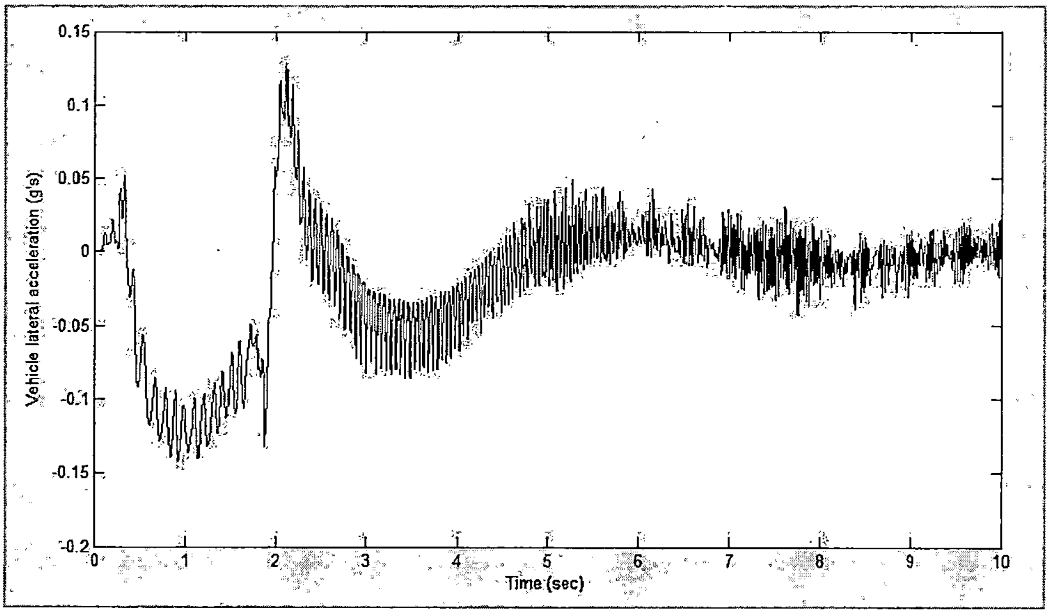
(b)

Fig 7.36 Vehicle lateral deviation (a) traditional ABS response (b) fuzzy ABS response

From fig 7.36 we can see that fuzzy ABS controller is performing well as compared with traditional ABS controller. The lateral part of the vehicle is oscillating for traditional ABS whereas it is changing smoothly in fuzzy ABS.



(a)



(b)

Fig 7.37 Vehicle lateral acceleration (a) traditional ABS response (b) fuzzy ABS response

Fig 7.37 shows that the lateral acceleration for fuzzy ABS equipped vehicle is very less as compared with the traditional ABS equipped vehicle.

Chapter 8: Conclusion and Future Prospective

8.1. Conclusion

Owing to the complexity of the detailed ABS control system modelling and the large number of degrees of freedom on a full vehicle dynamic model, it is difficult to model and analyse an ABS-equipped vehicle using a single code. Co-simulation provides a more complete representation of the vehicle and the control system be selectively using the strengths of each application. Two computer codes execute concurrently to resolve the vehicle dynamics (full vehicle model) and control algorithm (ABS system).

A full-vehicle dynamic model integrated with an ABS control algorithm has been developed using CarSim8 and MATLAB & Simulink. Developed vehicle modle predicts the dynamic behaviour of an ABS equipped vehicle resulting from brake pressure input. MATLAB & Simulink is used to incorporate a controlling algorithm in an ABS controller.

The integrated vehicle model is simulated on various frictional surfaces for different steering input signals. The results which are compared for different road condition and steering inputs are listed below.

- Yaw rate
- Vehicle velocity
- Lateral acceleration
- Lateral deviation
- Brake wheel cylinder pressure at rare left wheel

These results show that the lateral stability is improved for fuzzy ABS equipped vehicle over traditional ABS. Traditional ABS controller considers only wheel speeds where as fuzzy ABS controller considers the vertical force on rear tyres also.

8.2. Future prospective

In future work, further coordination or integration of active steering will be investigated to get more stable vehicle response. In addition controlling saturation

Appendix A: CarSim Software

CarSim is a parameter based vehicle dynamics modelling software from Mechanical Dynamics Inc. CarSim is composed primarily of four tightly integrated software modules called Graphical database, Vehicle math model solvers, Surface animator and Engineering plotter.

1. Data screens in the graphical database serve as the principal interface to CarSim. They contain vehicle model parameters, control inputs, and simulation settings. More than 140 libraries of datasets are linked together to make up the CarSim database. Each library has a different screen display to view the multiple data sets in that library.
2. Vehicle dynamics math models use *equations of motion* to calculate output variables. The process of performing these calculations is called making a *simulation run* or simply a *run*.
3. The surface animator (SurfAnim) shows the resultant vehicle motions. One can view the simulated motions, zoom in and out with a simulated camera, and interactively move around the simulated vehicle to change your point of view. Animated overlays show differences in behaviour between different runs.
4. The Windows Engineering Plotter (WinEP) creates plots of vehicle variables. This tool can be used to view any of the hundreds of variables computed by the simulation models. Plotting any combination of variables and overlaying plots from different runs for comparison is possible[17].

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