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Wheel Slip-Based Intelligent Controller Design for Anti-Lock Braking System

Meenakshi Singh[1], Asha Rani[2], Vijender Singh[3]

[1,2,3]Netaji Subhash Institute of Technology
Department of Instrumentation and Control Engineering

Abstract: Antilock-braking system have been developed to keep a vehicle steerable and stable during heavy braking moments by preventing wheel lock. **It is essentially comprised of an electronic control unit, a brake force actuator and wheel speed sensors. It is the objective of an ABS to achieve shorter stopping distance, limit slip ratio and maintain a good steering stability during braking. This system which is a nonlinear system may not be easily controlled by classical control methods like PID. An intelligent fuzzy control method is very useful for this kind of nonlinear dynamics and variable parameters. In this paper, the simulation results compare with a PID control, ideal ABS control and the fuzzy control. The results show the fuzzy controller can effectively improve the response of automobile ABS.**

Keywords: **Antilock Braking System (ABS), PID controller, Fuzzy Controller.**

1. INTRODUCTION

Current antilock braking system (ABS) research is based on slip control. During driving, the speed of the vehicle and rotational velocity of the wheel have matching values. In the case of braking, a torque is applied to the wheel, which causes the wheel to slow down. That accounts, the wheel speed will tend to be lower than the vehicle speed [1]. The parameter used to specify this difference in these velocities is called the wheel slip, denoted by λ:

$$\lambda = \frac{v-\omega R}{v} \tag{1}$$

Where v, w and R denote the vehicle velocity, wheel angular velocity and wheel rolling radius respectively.

Above relation shows a zero wheel slip when the wheel velocity is equal to the speed of car, whereas a ratio of one indicates that the wheel circumferential velocity is equal to zero i.e. w=0, consequently the wheel is not rotating, but the car is still moving. That is the wheels are skidding on the road and the vehicle is no longer steerable [5]. It is well known that the adhesion coefficient is a nonlinear function of the slip. The ideal goal for the control design is to regulate the wheel velocity. Such that an optimal slip which corresponds to the maximum friction is obtained [6]. The ABS controller must deal with the brake dynamics and the wheel dynamics as a whole plant, [2].

The aim of the controller is to continuously monitor the slip value (λ) and by manipulating the braking pressure (p_b) it is possible to avoid a slip value of 100% (wheel lock) and maintain the slip at about the desired (λ_d) value, which is estimated for most road conditions to be about 20% [13].Many researchers used various control strategies to facilitate the ABS phenomenon. The major challenge in controlling the wheel slip is the fact that the tyre and road interaction is highly non-linear [3]. Therefore it requires a more robust non-linear control scheme. However, the proportional integral derivative (PID) controller, which is basically a linear controller, has been applied to ABS. Ziegler Nichols method is used to tune the coefficient of a PID controller; it is very simple but cannot guarantee to be always effective [18].

Fuzzy logic controller can provide an efficient solution for the direct slip control and its tuning based on ABS performance described in [3].An optimal fuzzy controller allowing for maximum wheel traction force and maximum vehicle deceleration is discussed in [5]. The integration of a fuzzy observer in an ABS control strategy is described in [7]. PID controller parameter mapping onto the fuzzy controllers and real-time experimental results are presented in [19]. In this paper the fuzzy controller is designed with three control objectives consist of reducing stopping distance, limit slip ratio and improve the performance of the controlling system (reducing rise time and overshoot) on the ABS brake. It is different from other solutions reported in the literature [6].

The paper is organised as follows: In section II, the vehicle brake system dynamics is described. Section III, presents the control objective and fuzzy-logic and PID control schemes. Proposed methodology of FLC controller is given in section IV. Simulation results obtained from the proposed controller are given in section IV and Section V, concludes the work.

2. SYSTEM DYNAMICS

The vehicle dynamic model is dealing with the movements of vehicles on a road surface. The movements of interest are acceleration, braking, ride, and turning. Dynamic behaviour is determined by the forces imposed on the vehicle from the tires, gravity, and aerodynamics. A simplified longitudinal vehicle model considering vehicle/tire/road dynamics and hydraulic brake system dynamics is described in this section [1-2].

A list of variables and parameters used in this model is given in Table I.

Table I

Parameter	Description	Value
m	Quarter car ass	55 kg
v_0	Initial vehicle velocity	70(m/sec)
ω_0	Initial wheel velocity	130(rad/sec)
R	Wheel radius	1.25 m
G	Gravitational constant	9.81(m/s^2)
J	Moment of inertia of wheel	1.6 kg.m^2
f_z	Normal force	49 N
PB_{max}	Maximum Braking Pressure	1200 N-m
λ_d	Desired slip	0.2

The goal of the Anti-lock brake system is to hold each tire of the vehicle operating near the peak of the λ -μ curve for that tire, which implies performance of an ABS, is strongly related to the surface condition. There are several models that approximate the λ -μ curve. In literature, the most known are Pacejka's magic formula and Lu-Gre Model [10]. The dependence between the longitudinal slip and the friction coefficient is shown in Fig. 1.

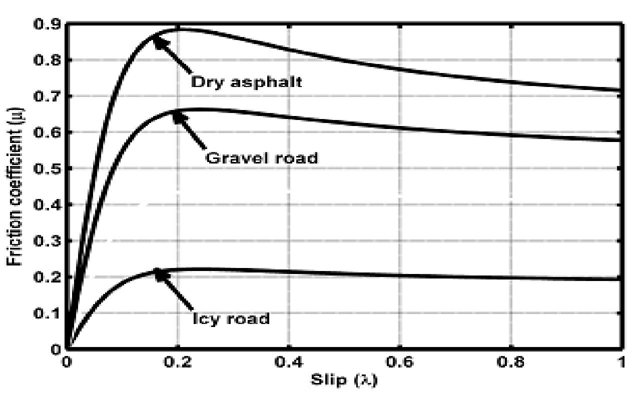


Fig.1. $\mu{-}\lambda$ Curves for different road conditions

The frictional forces developed between the tyre and the road surface is a complex non-linear function of the slip. The current design strategy is to keep the wheel slip (λ) as close as possible to the optimum slip ratio (λ_d), which is the desired slip point, thereby getting the vehicle velocity to converge to zero as quickly as possible. The non-linear friction curve is linearised around its optimum value, which is the ABS operating point. But, the position of the peak varies for different road conditions, different vehicle speeds, and tire types. Most control strategies define their performance goal as maintaining slip near a value of 0.2 throughout the braking trajectory [1].

A. Quarter-Car Model

A quarter-car model is used to develop the longitudinal braking dynamics. It consist of a single wheel carrying a quarter mass *m* of the vehicle and at any given time t, the vehicle is moving with a longitudinal velocity v(t).before brakes are applied, the wheel moves with an angular velocity of w(t), driven by the mass m in the direction of the longitudinal motion. Due to the friction between the tyre and road surface, a tractive force F_x is generated. When the driver applies the braking torque it will cause the wheel to decelerate

Until it comes to a stop [11]. A two degree of freedom quarter car model shown in Fig. 2.

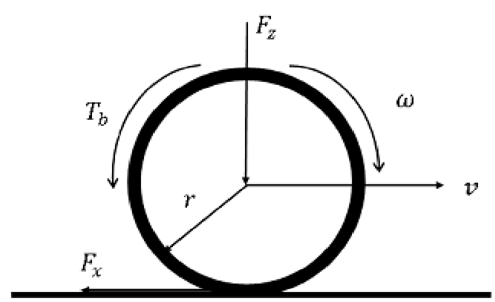


Fig.2.Quarter car model

From Newton's second law of motion, the equations describing the vehicle, tyre and road interaction dynamics during braking are [13]:

$$\dot{v}_x = -\frac{1}{m}\left(\mu_x(\lambda_x)F_z + C{v_x}^2\right) \quad (2)$$

The equation describing the wheel rotational dynamics is given by:

$$\dot{\omega} = \frac{1}{J}(r\mu(\lambda)F_z - B\omega - T_b(sign(\omega)) \quad (3)$$

The hydraulic brake actuator dynamics is modelled as a first-order system given by:

$$\dot{T}_b = \frac{1}{\tau}(-T_b + K_b P_b) \quad (4)$$

Where,

v_x= Longitudinal velocity of the vehicle
C = Vehicle's aerodynamic friction coefficient
μ_x= Longitudinal friction coefficient between the tyre and road surface
λ_x= Longitudinal tyre slip
F_z = Normal force exerted on the wheel
ω = Angular velocity of the wheel
J = Rotational inertia of the wheel
R = Radius of the tyre
B = Viscous friction coefficient of the wheel bearings
T_b = Effective braking torque, which is dependent on the angular velocity
K_b = Braking gain
P_b= Braking pressure from the action of the brake pedal which is converted to torque by the gain K_b
τ = Hydraulic time constant accounts for the brake cylinder's filling and dumping of the brake fluid

B. Controller Block Diagram

In present work first step is to design PID controller for wheel slip control of ABS but major challenge in controlling the wheel slip is that the tyre and road interaction is highly non-linear [12]. Therefore a more robust non-linear control technique is required so an intelligent control technique is used for the control of ABS. Fuzzy logic based controller is designed for the purpose.

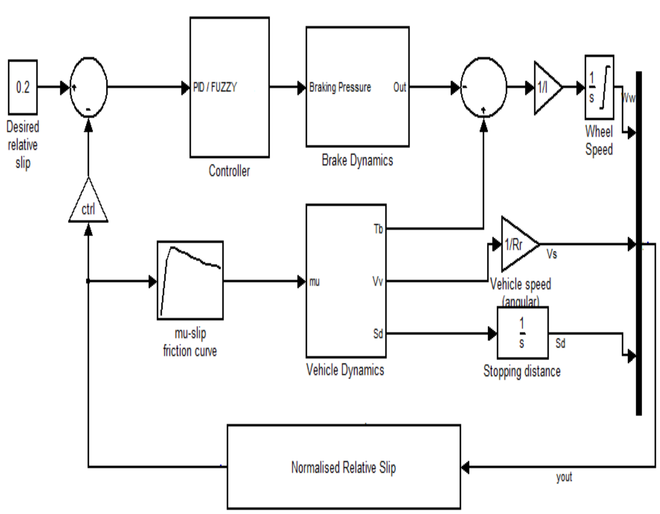


Fig.3. Block diagram of Antilock Braking system

Fig.3 shows that the friction coefficient between the tire and the road surface mu, is an empirical function of slip, known as the mu-slip curve. We created mu-slip curves by passing MATLAB variables into the block diagram using a Simulink lookup table. The model multiplies the friction coefficient mu, by the weight on the wheel, W to yield the frictional force F_f acting on the circumference of the tire. F_f is divided by the vehicle mass to produce the vehicle deceleration, which the model integrates to obtain vehicle velocity. To control the rate of change of brake pressure, the model subtracts actual slip from the desired slip and feeds this signal into a controller and it is designed in such a way so that error can be reduced. Thus by manipulating the braking pressure (p_b) it is possible to maintain the wheel slip near the desired (λ_d) slip value and reducing the vehicle stopping distance.

3. CONTROLLER DESIGN TECHNIQUES

PID (proportional integral derivative) control is one of the earlier control strategies, namely classical linear controller. The error signal e(t) is used to generate the proportional, integral, and derivative action, with the resulting signals weighted and summed to form the control Signal u(t) applied to the plant model. A mathematical description of the PID controller is [19]

$$u(t) = k_p[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\,\frac{de(t)}{dt}] \quad (5)$$

where u(t)is the input signal to the plant model, the error signal e(t)is defined as e(t) = r(t) – y(t), and r(t)is the reference input signal. The behaviour of the PID controller is determined by k_p,T_i, T_d values. That can be tuned by Ziegler-Nichols tuning formula that obtained when the plant model is given the step input [18].Antilock braking system have time varying parameters and high nonlinear characteristics [12].In such situations conventional controllers fails to outperform. Moreover, exact mathematical modelling of the system is required in conventional controllers.

Fuzzy Logic Controller

Fuzzy logic controller has become an important tool in control engineering. The main advantages of fuzzy as compared to other controllers like PI, PID and adaptive controllers are they didn't require any mathematical modelling and have superior non-linear handling capability. A fuzzy logic controller consists of three main operations: Fuzzification, Inference Engine and Defuzzification [8]. The input sensory (crisp or numerical) data are fed into fuzzifier, where physical quantities are represented into linguistic variables with appropriate membership functions. These linguistic variables are then used in the antecedents (IF-Part)of a set of fuzzy ―IF-THEN rules within an inference engine to result in a new set of fuzzy linguistic variables or consequent (THEN-Part) in the inference engine. Using defuzzifier convert the fuzzy variables to crisp values. Fuzzy logic tries to implement human understanding and thinking in control algorithms.

Fuzzy-Mamdani Model: The Mamdani rule base is a crisp model of a system, i.e. it can take a crisp value as input and produces corresponding crisp outputs. This model performs user-defined fuzzy rules on user-defined fuzzy variables. The idea behind using a Mamdani's decision making capability is similar to human. And hence we can effectively model a complex non-linear system, with common-sense rules on fuzzy variables [4]. Modelling a Mamdani rule base requires three steps:

1) The input domain and output range has to been determined for appropriate fuzzy sets.

2) Determine a set of rules between the fuzzy inputs and the fuzzy outputs that model system behavior.

3) A framework is created to map crisp inputs to crisp outputs.

4. PROPOSED METHODOLOGY

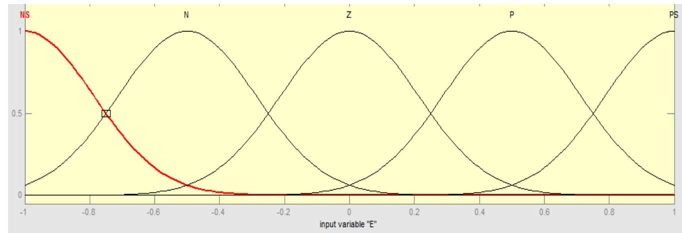
In this paper a proposed controller FLC is designed in such a way to produce a brake torque so that the actual wheel slip traces the reference slip. So the current research is based on slip control and this controller designed with three control objectives consist of reduce stopping distance, limit slip ratio and improve the performance of controlling system(reducing rise time and overshoot on the ABS brake). Mamdani method is applied for designing a fuzzy controller. The input variable to the controller are wheel slip error (e) and rate of change of error (ė) where the wheel slip error is the difference between the modified desired wheel slip and the actual wheel slip which varies with the different road conditions and the output obtained is the error that is corrected by the controller based on the rules provided in Table (II).

$$e = \lambda_d(k) - \lambda(k) \qquad (6)$$

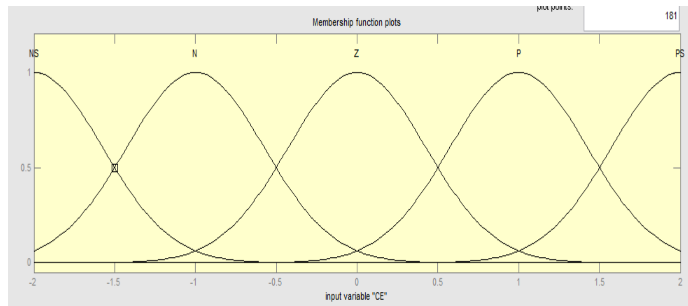
It consists of 25 fuzzy rules and the Gaussian membership function is employed shown in fig.4. First, the input and output variables are altered to the scale [-1, +1] and [-2, +2] respectively and then input is divided into five discussed scale {NS, N, ZE, P, PS}.The fuzzifiacation of the output is divided into nine fuzzy set {NB, N, NS, NVS, ZE, PVS, PS, P, PB}.

Table .II Rule Base

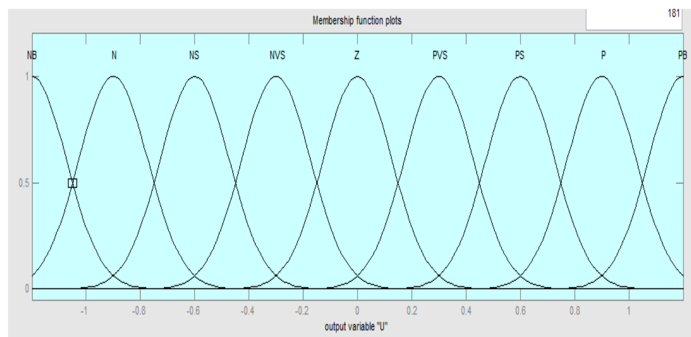
ė / e	NS	N	ZE	P	PS
NS	NVS	N	NS	PS	Z
N	N	NB	N	ZE	NS
ZE	NS	N	ZE	P	PS
P	PS	ZE	P	PB	P
PS	ZE	NS	PS	P	PVS



(a)



(b)



(c)

Fig.4. (a) Membership functions of error (E) (b) Membership function of change in error (CE) (c) Membership function of manipulated variable (U)

The error between the desired and actual slip and rate of change of error is first computed and fed to the FLC. The FLC evaluates the fuzzified output which is further defuzzified using centroid method. The crisp output obtained is then used to change the brake pressure in order to reduce the error. Thus by manipulating the braking pressure (P_b) it is possible to maintain the wheel slip near the desired (λ_d) slip value and reducing the vehicle stopping distance

Once the conditions of each rule have been established, the rules for the developed fuzzy control and the surface that the inference system generates are shown in Fig. 5. The surface has been obtained using MATLAB's Fuzzy Logic Toolbox and Mamdani's fuzzy inference system.

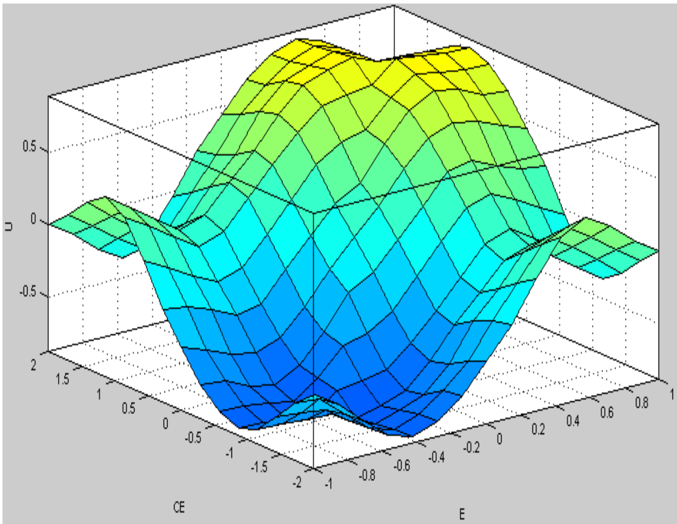


Fig. 5.Surface view

5. RESULTS AND DISCUSSION

The discussed model is simulated on a PC having 64-bit operating system Intel® core^{TM} i5 processor with 2.60 GHz frequency and with 4GB RAM and MATLAB version 7.13.0.564 (R2011b).

The control objective is to reduce stopping distance, limit slip ratio and improve the performance of controlled system. The wheel slip and speed behavior for an ideal ABS with bang-bang controller is shown in Fig.6 and Fig. 7. The slip should be maitained at 0.2 without oscillations whereas the results show that slip is highly oscillatory and goes to 1 which is an undesirable condition. It is also observed from the speed variations that vehicle speed and wheel speed are not same thus due to the reduction in wheel speed it gets locked and skidding occurs.

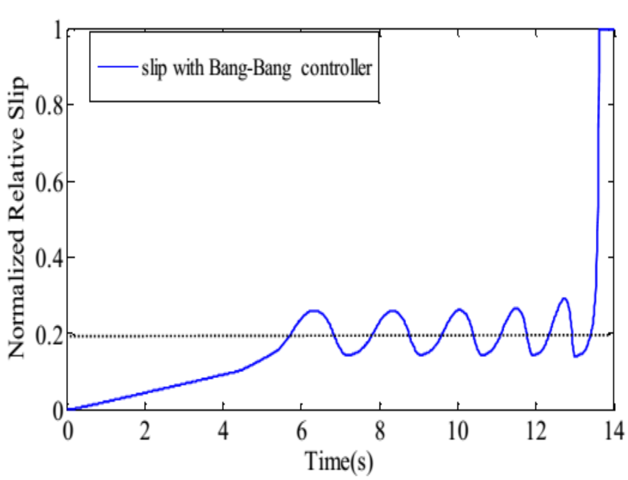


Fig. 6. Relative wheel slip Vs Time for ideal ABS

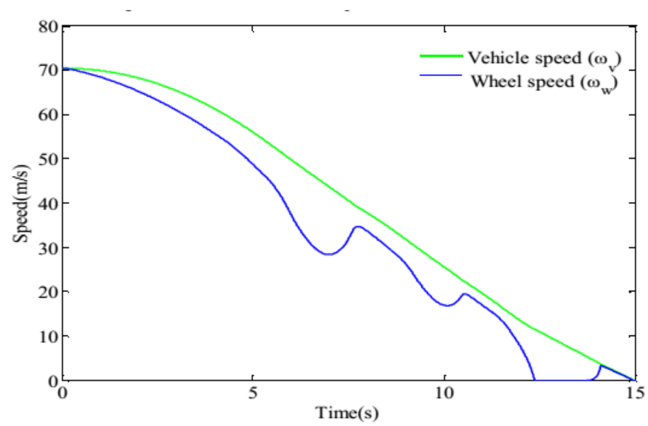


Fig.7. Vehicle and Wheel Speed Vs Time

As we have observed above that if ABS is used with bang-bang controller the output is not at all satisfactory so in order to have satisfactory response from the nonlinear plant i.e. to maintain the wheel slip as close as possible to the desired slip ratio, thereby making the velocity of vehicle to converge to zero by preventing the wheel lock condition so an efficient controller is required. In order to control nonlinear dynamics of the plant a conventional PID controller is designed.

PID parameters obtained using Ziegler Nichols tuning method are K_p =150, Ki =8, K_d =12.

Fig.8 and Fig.9 shows the result of nonlinear ABS after controlling through PID.

Further, the fuzzy logic controller is simulated and its efficiency compared to the classical PID controller in terms of the vehicle speed, stopping distance, wheel slip ratio and braking torque. . It is observed from the results that the fuzzy controller eliminated Overshoot that was present in PID response and response time is also significantly less than that of PID. It is clear from the Fig.10 that there is significant amount of improvement in response in terms of overshoot and rise time.

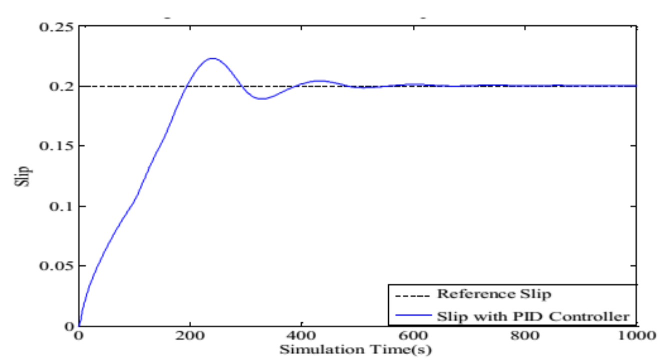


Fig.8. Slip Vs Simulation time with PID

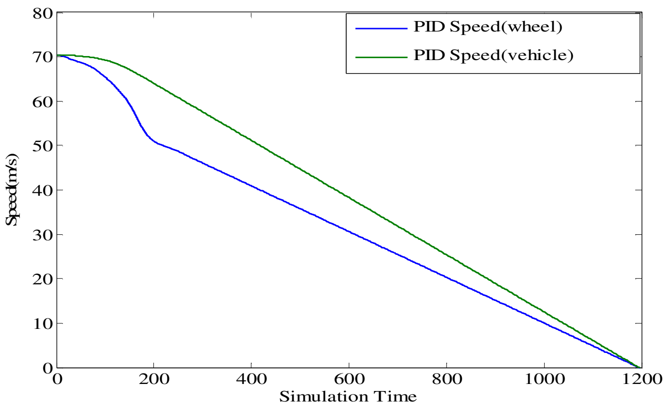


Fig. 9 . Speed Vs Simulation time

It can be observed that, for wheel slip ratio, the proposed Fuzzy logic controller has a very good response to track the desired slip ratio which leads to good stability and steerability of the vehicle considering a straight line motion as depicted in Fig.11. It is also shown that the wheel tends to approach the desired slip after starting the braking process for the PID-based controller after a short period of time but in the case of the self-tuning fuzzy controller they produce a much faster response to reach the slip reference with good rising time compared to the conventional PID.

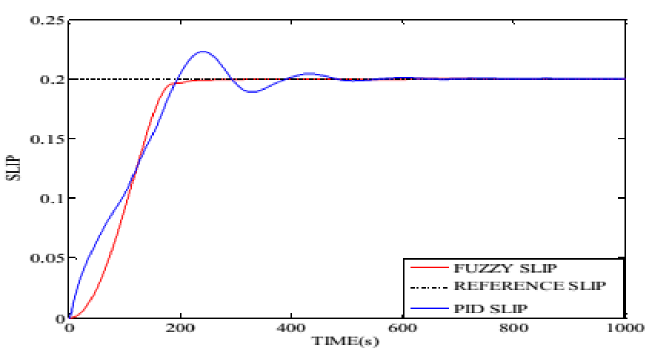


Fig.10. Slip Vs Simulation time

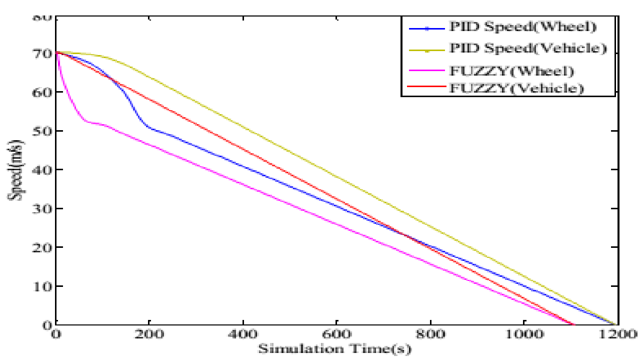


Fig.11. Speed Vs Simulation time

Fig. 12 shows the stopping distance curves for all the controllers considered. It is obvious that the minimum stopping distance is achieved by FLC having a distance of 524.4m implying that it is the best ABS controller compared to the rest of the control schemes.

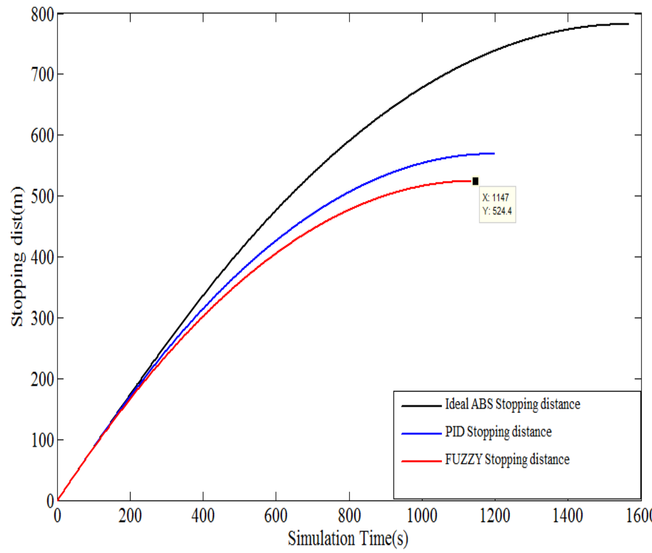


Fig.12.Comparison of Stopping distance Vs Time

6. CONCLUSION

In this paper intelligent controllers are designed for an Anti-lock Braking System (ABS) using MATLAB/SIMULINK. A PID controller is designed and simulated in order to acheive the desired targets i.e. maintaining the slip ratio at 0.2 and reducing the stopping distance. The results show that the transient as well as and steady state performance of the PID controller is not upto the mark and therefore it is inefficient to handle non-linear characteristics of the system. Therefore in order to achieve the desired objective intelligent control schemes are required. Hence a fuzzy controller is designed for the control purpose. The performance analysis of the designed controllers depicts that FLC controller provides lesser rise time and setteling time as comared to the other designed controllers. FLC controller also achieves the minimum stopping distance for ABS. The quantitative performance of the different controllers is given in table III, which again verifies the superiority of FLC controller.

Table III. Performance parameters of designed controllers

Controller	Rise time	%Overshoot	Stopping Distance(m)
Ideal ABS	225	19	782
PID	128	11	568
FLC	56	0	524

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