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# Study on Performance of Vehicle Anti-lock Braking System with Fuzzy Logic controller in Matlab/Simulink

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## Abstract:

A mathematical model of Antilock braking system (ABS) components was developed with fuzzy logic (FL) control algorithm and response was simulated by MATLAB/Simulink. The different parameters like optimal slip and brake pedal force were controlled by FL controllers on the basis of slip, road conditions, coefficient of friction and wheel acceleration as input parameters. The proposed control system was compared with bang bang controllers. The simulation results revealed that the developed ABS control system with FL controller had better braking performance in various road conditions in comparison to the ABS with bang bang controller and ABS without FL controller.

*Keywords* **—ABS, bang bang, fuzzy logic, Matlab/ Simulink, slip.**

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## I. INTRODUCTION

Over the last few decades, the development of fuzzy logic has advanced at a significant speed and has been using as an alternative ways to solve automatic control problems. FL is a well-recognized perception in mathematics and engineering, offers unique capabilities to capture nonlinearities and uncertainties, which cannot be depicted by particular mathematical model [1]. Thus, the FL controller not only illustrates black and white like conventional digital logic, it also explains the immeasurable gray region in between black and white as well. Based on this fundamental thought, researchers predicted FL controllers which illustrate human control in linguistic shape and generates results in the same [2]. In spite of having such extra power in data processing, FL took longer period to obtain high attention in the field of fuzzy control. An analysis of the previous studies showed that, after the successful applications in Japanese consumer products, such as washing machine and camcorders, it has found a great variety of application areas, such as, control engineering, machine intelligence, pattern recognition, signal processing, information processing, management, medicine, motor industry, robotics, industrial processes and so on [3-7]. In terms of usages, automotive application of FL is getting more general, such as, Antilock Braking System (ABS), Traction Control System (TCS), Active Front Steering (AFS), Automotive Air Conditioning System, Automotive Energy Management System, to improve comfort, safety and driving quality [8].

A number of published research articles have noticeably recognized that the main cause of vehicle accident is due to the skidding of the tires during cornering and braking input. To overcome this problem, active braking system along with conventional braking system has been developed with electrical and electronic components, such as, Electronic Brake Distribution, Electronic Stability Control, Automatic Braking System and [9-14].

  

However, among these technologies, researchers have given more concentration on ABS with the aim of improving steering stability and lateral stability of the vehicle on different road conditions to keep the vehicle within lane during braking. Moreover, past studies revealed that the ABS also used to reduce the stopping distance during braking for minimizing skidding effects, especially on low adherence surface [15]. Normally, in an emergency braking situation, wheels of a vehicle tend to lock quickly, diminishing the vehicle steering control and stability, and increasing the stopping distance. Achieving the goal of braking control system is very difficult, because the applied braking pressure varies with different parameters, such as, slip angle, vertical load, inflation pressure, adherence condition between roads and wheels, wheel circumferential velocity, vehicle velocity and so on [16]. When the wheel circumferential velocity will be less than vehicle speed then rolling wheel commences to slip. The wheel slip and wheel acceleration will increase after applying sufficient braking force, then the wheel will lock up. Thus, the goal of braking control system is to maintain the diverse slip ratio for different road conditions to obtain maximum adherence coefficient. However, to achieve appropriate slip ratio as per road conditions, vehicle speeds and tire types, is very complicated task. The previous published research articles revealed, different types of controller has been using to maintain the slip ratio within the values which get maximum adherence coefficient for various road conditions, such as, Proportional Derivatives (PD), Proportional Integral Derivatives (PID), Bang Bang controller, Sliding Mode Controller (SMC), FL Controller and so on.

The different control methods differ in their theoretical basis and performance under the changes of road conditions. Oniz Y et.al. proposed a SMC and grey SMC for tracking a reference wheel sleep in which grey predictor estimates the forthcoming value of wheel slip and SMC takes the necessary action to maintain wheel slip at the desired value [17]. Jiang F et.al. showed that nonlinear PID controller has sorter stopping distance and better velocity performance than the conventional PID controller [18]. Likewise, Ali H. et.al. showed the robust stability and better performance for the ABS, and shorter stopping distance with minimum braking torque has been achieved for different types of surface using PI-PD controller [19]. Aly A. proposed a multi stage fuzzy system for immediate finding of optimal wheel slip for the new surface and forces the actual wheel slip to track the optimal reference wheel slip [20]. Consequently, Mokarram M. et al optimised FL controller by using CMOS circuit. They asserted that the optimised FL controller offers better lateral staility and steerability of a vehicle by keeping slip at minimum value and lessening the oscillations than that of fuzzy logic and PI controller [21]. Ebrahimirad H et. al. compared and analysed the control performance between bang bang and sliding mode controller, and they concluded that the proposed sliding mode controller has better braking performance [22]. Moaaz A. et.al. modeled ABS system using Bang Bang, PD and PID controllers, and they concluded that the controllers controlled the wheel speed and the vehicle speed at the same time and in order to avoid the vehicle skidding during the panic rake. Moreover, they also revealed that the PID controlled have better braking performance compared to Bang Bang and PD controllers [23]. Thus, as reported in literature, we found that the limited research have been done on ABS system using FL controllers. Therefore, we were motivated to develop mathematical and MATLAB/Simulink model of components of ABS with FL controllers and compared the braking performance of it to the ABS with bang bang controller.

## II. MODELLING OF ABS

Mathematical modeling is the initial step to develop a control algorithm for ABS. In the analysis, the mathematical modeling is simplified to a quarter car model. Here, different mathematical equations and expressions are used for the modeling of different components, starting from vehicle dynamics to wheel slip, tire, brake actuator and controller for ABS.

### A. Vehicle Dynamics

In the analysis, the mathematical modeling is simplified to a quarter car model to build the simulation system. To further simplify, secondary factors are neglected and also formulate some assumptions as follows:

The tires are rigid,

The system ignores the influence of lateral wing

Aerodynamics drag is ignored

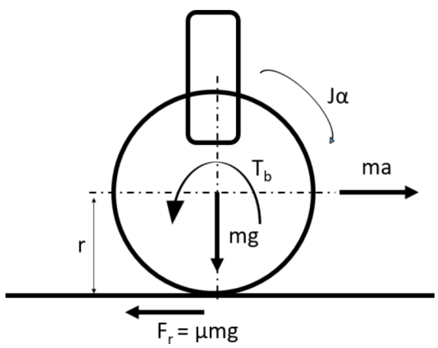


Fig.1Vehicle Dynamics of Quarter Car Model

The free body diagram of the quarter car model is shown in the Figure 1. The force balance equations in the longitudinal direction are;

$$ma = -\mu(\lambda)mg \quad (1)$$

$$j\alpha = r\mu(\lambda)mg - T_b \quad (2)$$

Where,
m = 1/4 × vehicle mass,
a = linear acceleration of vehicle,
μ(λ) = coefficient of friction between road and tire which is nonlinear function of slip ratio and road dynamics,
J = moment of inertia of the wheel,
ω = the angular velocity of the wheel,
α = the angular acceleration of the wheel, r = the radius of the wheel,
Tb = the braking torque acting on the wheel, and
λ = wheel slip ratio that is ratio of difference of wheel and vehicle velocity to maximum velocity among the two.

### B. Wheel Slip

The crucial assumption in most friction models is that the percentage μ principally is a function of the slip ratio λ. The slip is the standardized difference between the wheel speed and the vehicle speed at the contact point [24]. When v >ωr, it is defined as:

$$\lambda = \frac{v - \omega r}{v} \quad (3)$$

Where,
υ = vehicle velocity,
r = effective radius driven wheel and
ω = angular velocity of the wheel

Above figure and mathematical expressions revealed that, if the slip increased, the tractive force between the tire and road surface would increase by virtue of an increase in μ. However, once μ is achieved its peak value, traction will reduce in further increment of slip ratio and accordingly, unbalanced acceleration of the wheel is induced until the drive torque is reduced.

### C. Tire Modeling

Burckhardt tire modeling has been used to calculate the friction forces or the force of the wheel transferred at the road. The normal force of the tire, torque of the axle shaft and vehicle speed have been found at the input of this models, whereas, angular speed of the tire, the force and torque applied on the road have been found at the output. In comparison to the other models, Burckhardt models has been using widely due to its better accuracy in the explanation of the friction coefficient [14, 25]. The equation governing this tire model is given as,

$$\mu(\lambda) = C_1\left(1 - e^{-C_2\lambda}\right) - C_3\lambda \quad (4)$$

Where,

C1, C2, C3 are constants which depend upon road conditions as shown in table 1.

  

TABLE I
COEFFICIENTS OF BURCKHARDT EQUATION

| ***Road surface condition*** | ***C1*** | ***C2*** | ***C3*** |
|---|---|---|---|
| ***Dry Asphalt*** | 1.2801 | 23.990 | 0.52 |
| ***Dry Concrete*** | 1.1973 | 25.186 | 0.5373 |
| ***Wet Asphalt*** | 0.86 | 33.82 | 0.35 |
| ***Cobblestone*** | 1.37 | 6.46 | 0.67 |
| ***Snow*** | 0.1946 | 94.129 | 0.0646 |
| ***Ice*** | 0.05 | 306.39 | 0 |

Similarly, relation between friction coefficient and slip ratio for different road condition is as shown in figure 2.

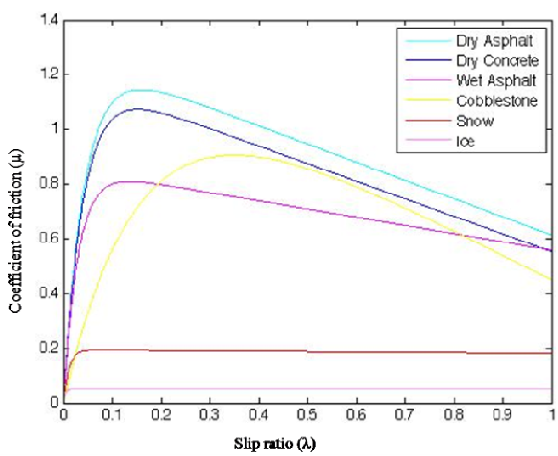


Fig.2 Slip ratio and friction coefficient for different road condition

Figure shows that coefficient of friction achieves the highest value around 0.2 slip ratio for all road conditions, called optimal slip.

### *D. Brake actuator model*

The function of brake actuator is to pass the hydraulic pressure through the ABS circuit as per the command signal received from the brake controller. The brake pressure depends on amount of brake fluid passing through the control valve. The regenerative braking using electric actuator gives better performance than friction brake. However, switching off the electric actuator at deceleration disables the regenerating braking and as a result, the ABS will rely on the friction brake. During opening and closing, different actuators have difference response time. The response time and other parameters of electro-hydraulic actuator are better in comparison to other actuators. Figure 4 shows the brake actuator model used in Simulink.

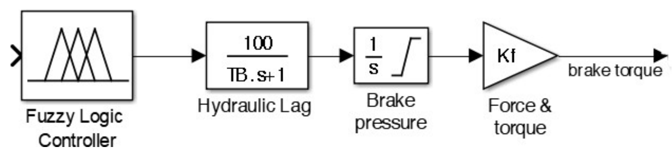


Fig.3 Brake actuator model

## III. MATLAB/SIMULINK MODELLING

Figure 4 shows the simulink model for control of ABS using bang bang controllers. A bang bang controller that takes slip error signal as input is used to determine the required brake force that needs to be applied to minimize excessive slip and avoid locking of the wheels. These controllers switch between minimum and maximum value when a certain set point is reached. The brake actuator subsystem is set up according to its mathematical model which gives angular acceleration of the wheels at the output node. Similarly, vehicle speed and stopping distance is calculated using blocks that serve the purpose to apply the mathematical equations discussed in the earlier sections. The vehicle speed and wheel speed is then used to determine the relative slip of the vehicle which is then fed as feedback to the summation block where and error signal is generated by comparing the existing slip with the optimal slip. Further decision for brake force is calculated based on the positive or negative value of the error slip signal. The feedback slip signal is also fed to the mu-slip conversion block where the slip is converted into coefficient of friction using Burchardt's mathematical model. Different signals are logged before running the simulation to obtain required curves for wheel velocity and slip.

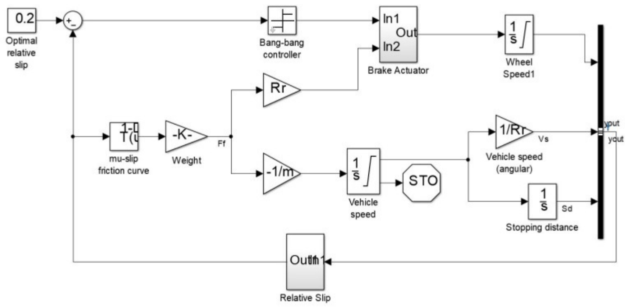


Fig.4 Block diagram of ABS Control System with Bang Bang Controller

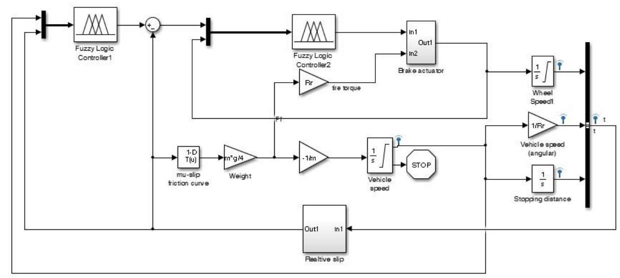


Fig.5 Block diagram of ABS Control System with Fuzzy Logic Controller

Figure 5 shows the Simulink model for control of ABS using FL controllers. Two FL controllers (FLC) have been used for control of ABS. Fuzzy logic controller 1 uses vehicle speed and wheel slip as input to determine optimal slip based on the present road condition. FL Controller 2 uses slip error and wheel acceleration as input to determine the required brake force that needs to be applied to minimize excessive slip and avoid locking of the wheels. The brake actuator subsystem is set up according to its mathematical model which gives angular acceleration of the wheels at the output node. Similarly, vehicle speed and stopping distance is calculated using blocks that serve the purpose to apply the mathematical equations discussed in the earlier sections. The vehicle speed and wheel speed is then used to determine the relative slip of the vehicle which is then fed as feedback to the summation block where and error signal is generated by comparing the existing slip with the optimal slip. Further decision for brake force is calculated based on the positive or negative value of the error slip signal. The feedback slip signal is also fed to the mu-slip conversion block where the slip is converted into coefficient of friction using Burkhardt's mathematical model. Different signals are logged before running the simulation to obtain required curves for wheel velocity and slip.

The use of two controllers provides better control over slip and steerability of the vehicle. The FL 1 which determines the optimal slip has two inputs: Vehicle speed and wheel slip as shown in Figure 6.

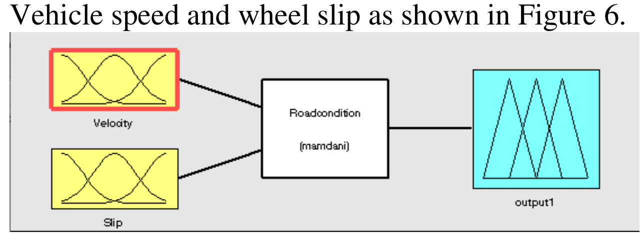


Fig.6 Fuzzy inputs for Fuzzy Controller 1

Velocity and wheel slip are divided into five range of values:

VL (Very Low) L (Low) M (Medium)
H (High) VH (Very High)

FL Controller 2 which is used to determine required brake force has two inputs: Slip error and wheel acceleration as shown in Figure 7.

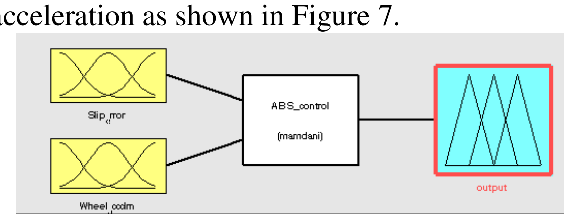


Fig.7 Fuzzy inputs for Fuzzy Controller 2

Slip error and Wheel acceleration are divided into five ranges of values:

NL (Negative Large) NS (Negative Small) Z (Zero)
PS (Positive Small) PL (Positive Large)

  

## IV. SIMULATION RESULTS

The simulation results from the model with FL controllers was obtained and then compared with the simulation result of a model that uses a simple bang-bang controller. The use of FL controllers provided better control over slip and stopping distance of the vehicle. Figure 8 shows the velocity v/s time curve for the model that uses a bang-bang controller. The curve for wheel velocity and vehicle velocity converge to zero after 12 seconds. Figure 9 shows the fluctuation of relative slip once the brake is applied in a system that doesn't use fuzzy logic controllers.

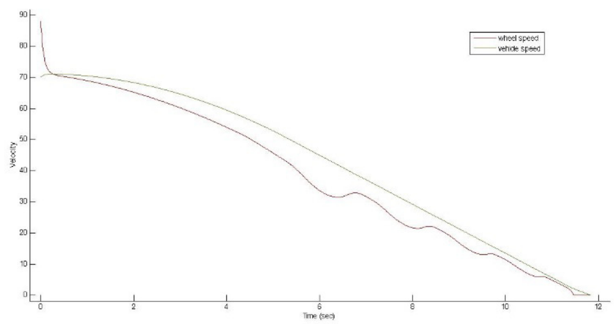


Fig.8 Velocity vs time curve for model without fuzzy controller

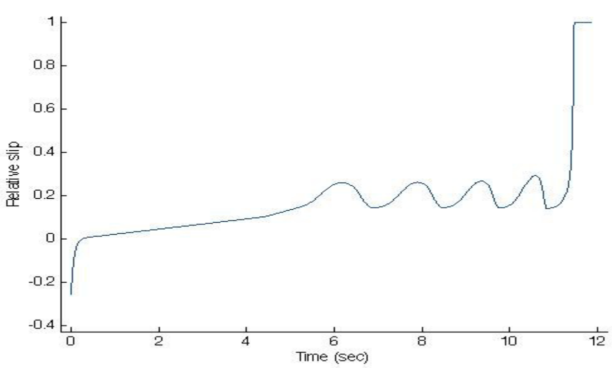


Fig.9 Slip variation in the model without fuzzy controllers

The model that used two FL controllers show improved results in bringing the vehicle to stop with better steerability and control. Figure 10 shows the velocity v/s time curve for the model that uses FL controller.

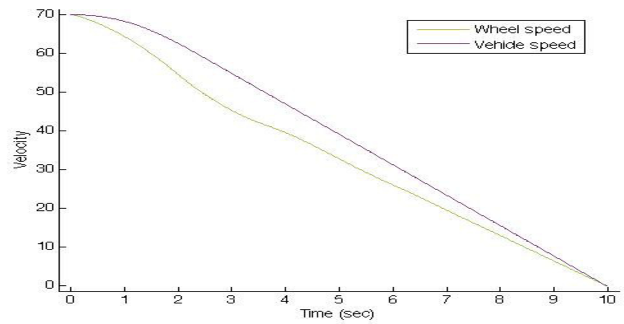


Fig.10 Velocity vs time curve for model with fuzzy controller

The vehicle comes to stop in reduced time and the fluctuation in wheel velocity is also minimized in this model. The vehicle speed and wheel speed converge to zero after 12 seconds. Figure 11 shows the comparison of slip in the model with and without FL controllers. It can be clearly seen that the model using FL controllers provides much better control over slip. The curve smoothly rises to the optimal value and stays there until the vehicle comes to stop. Better slip brings better control and steerability to the vehicle.

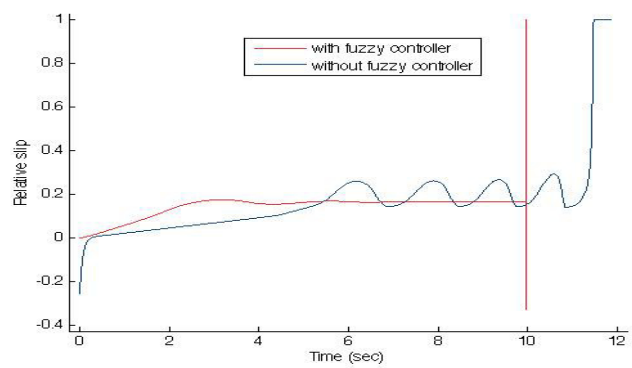


Fig.11 Comparison of relative slip

## V. CONCLUSION AND RECOMMENDATION

An ABS with FL controllers has been created in MATLAB/Simulink and the simulation results compared with an ABS system that uses a simple bang-bang controller. The use of FL controller provides better results in the slip control, steerability and stopping distance of the vehicle. The system without FL controllers brings the

  

vehicle to stop after 12 seconds with fluctuations in slip whereas the system with FL controllers brings the vehicle to stop after 10 seconds with stable wheel slip and better steerability. Hence, FL controllers provide better wheel slip control, better steerability and better stopping distance in comparison to ABS with bang-bang controllers.
The model can be further modified by adding more inputs to the FL controller. Slope of the road can be added as an input parameter while controlling the brake force applied to the vehicle.

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