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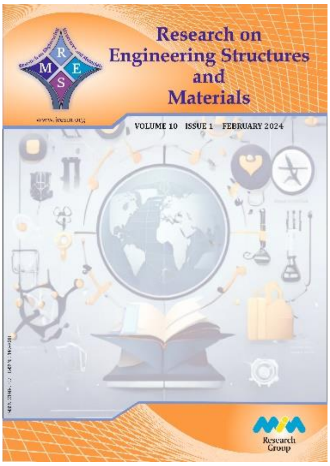

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Adugna Fikadu Geleta, Mahesh Gopal, Muleta Tiki Lemi

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Research Article

Vehicle anti-lock brake system - dynamic modeling and simulation based on MATLAB Simulink and CarSim

Adugna Fikadu Geleta[a], Mahesh Gopal[*, b], Muleta Tiki Lemi[c]

Dept. of Mechanical Engg, College of Eng. and Technology, Wollega University, Nekemte, Ethiopia

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Abstract

The anti-lock brake system (ABS) is a safety feature for automobiles that regulates brake pressure and delivers predictable braking in the majority of circumstances by monitoring wheel lock-up. It necessitates the creation of a robust control system due to the unknown uncertainties on the braking system induced by altering the vehicle model dynamics and road conditions. To progressively decrease the automobile accidents caused by abrupt braking and will achieve the best brake performance. The mathematical model was developed considering vehicle speed, and slip ratio between the tire and the road conditions and simulation was done for Super Urban Vehicle of the ABS using Fuzzy logic controller and CarSim software in MATLAB/Simulink are the main objectives of this study. With the assistance of the fuzzy logic control approach and the MATLAB/Simulink software, a quarter-vehicle dynamic model was developed to simulate under a variety of road circumstances, such as wet and dry conditions, and at different speeds. Finally, it was determined that the braking distance was decreased and the vehicle stability was maintained during the simulation process by comparing the results of the simulation performed using the CarSim software connected to MATLAB/Simulink and the performance of the built controller.

1. Introduction

A road vehicle must constantly alter its velocity and distance following shifting traffic circumstances to be used safely and reliably. This is accomplished by designing a system that utilizes the limited amount of traction between the tire and the road as effectively as possible under all of the expected operating situations that the vehicle would experience during regular operation. The most crucial accident-avoidance systems on a car that must consistently function in a variety of situations are without a doubt the brakes, steering, and tires. Any braking system's effectiveness is thus constrained by the degree of traction present at the tire-road contact.

The authors [1], [2] discussed the ABS and its components. The simulation model was developed using ADAMS; this model was used to determine the performance of the brakes in different situations, such as when the vehicle is turning and when the brakes are applied. The researchers [3]developed a predictive control algorithm (PCA) for an ABS. The algorithm is designed to minimize the braking distance under any given road conditions and to stabilize automobile behavior. The suggested algorithm is verified, tested and compared with conventional ABS and the results show that it can significantly reduce the wheel slip and improve vehicle stability. For modeling the dynamic behavior of pneumatic heavy vehicle brakes with incorporated ABS, [4] suggested a novel model. The model is used to assess the effectiveness of incorporated ABS and examine the impact of different

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[*]Corresponding author: adugnaf@wollegauniversity.edu.et
[a] orcid.org/0009-0004-4322-7683; [b] orcid.org/0000-0001-7672-5399; [c] orcid.org/0000-0002-2179-2882
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settings on braking performance. The outcomes demonstrate that the model is capable of faithfully simulating the dynamic behavior of the integrated anti-lock braking system. The authors [5] discussed and developed a Hardware-in-the-Loop Simulations (HILS) system for active brake control systems. The author includes the verification method and outcomes of the HILS system in addition to describing the development and execution of the system, which comprises a controller approach, a brake system of control model, and a vehicle model. An ABS-focused sliding mode control strategy was introduced by [6] and the simulations and trials on a real-time ABS system show the efficacy of the suggested approach. Results reveal that in terms of system stability, robustness, and speed response, the suggested technique performs better than the state-of-the-art conventional control methods. The authors [7] present a controller algorithm for an automobile ABS using MATLAB/Simulink environment and also provide valuable insight into the performance of the controller system and its components. Mathematical modeling was developed by [8] based on the dynamic behavior of the ABS and simulation was done using Simulink under different operational conditions and also discusses the possibilities of further improvements in the system such as active control, improved component design, and sensor technology. The most effective architecture for an ABS employing a linear time-varying (LTV) model and a stability requirement was suggested. The outcomes demonstrate that the suggested non-linear controller performs better than the conventional one [9]. To create an accurate tire model that is appropriate for ABS simulations, [10] developed a discrete tire modeling approach for ABS simulations. This algorithm provides a complete examination of tire-road interaction. To obtain the required braking reaction, [11] introduced a linear control approach for an ABS that utilizes fuzzy logic and employs a proportional-derivative (PD) controller. The findings demonstrate that the suggested controller may deliver a smooth and precise braking response with minimal overshoot.

The authors [12] conducted a simulation model using Simulink, to and discuss the implications of ABS performance. The researcher [13] proposed an electric car with an axle motor that offered a linear parameter variable system to improve the observer and enhance robustness against parameter uncertainty and external disturbances using simulation. The MATLAB / Simulink software was used for modeling and simulation. The fuzzy control door limit control strategy was used to get results very accurate. The researcher suggested that the fuzzy logic controller is an effective means of modeling and simulating an ABS [14]. To increase the vehicle's stability and safety, the author [15] built an ABS control system employing CarSim, MATLAB/Simulink, and LabVIEW as the communication tool for an integrated electro-hydraulic braking system. The researcher [16] explained the operation of ABS and the MATLAB ABS mathematical models used to simulate the system. The Carsim simulation software is used and the results of both the simulation software are compared. The design of a regenerative anti-lock braking system (RABS) controller for an electric vehicle has been demonstrated by [17]. The authors additionally navigate through how to use the results of simulations to verify the system's performance using the fuzzy logic controller technique. The authors suggested that the controller can deliver a safe and dependable regenerative braking system for an electric vehicle.To study the dynamic characteristics of ABS system, the MATLAB was used to simulate the model of the ABS system. The simulation findings demonstrate that the wheel slip ratio may be decreased by adjusting the wheel braking pressure through the ABS control system, preventing the wheel from locking and enhancing vehicle stability [18]. A simulation model was designed by [19] to visualize the system behavior and optimum brake performance of ABS. To increase the safety of electric vehicles, an integrated electronic hydraulic brake system (IEHBS) was developed in two representative scenarios of the regenerative and ABS processes using simulation software such as MATLAB/Simulink, AMESim, and CarSim [20]. MATLAB Simulink was used to run the simulation, to obtain the desired level of wheel slip, [21] developed a mathematical model using the Lugre Friction and Burckhardt Friction models of the ABS. To enhance braking performance and prevent wheel locking, [22] suggested a sliding-mode control (SMC) method based on MATLAB and CARCISM. The outcomes demonstrate that the suggested method outperforms the traditional ABS in terms of stability and braking distance. A fixed-time slip control method for ABS in electric vehicles was described by [23] based on an extended-state observer (ESO). The outcomes demonstrate that the suggested technique outperforms the other controllers in terms of wheel slip, braking torque, and vehicle speed deviation. Using MATLAB/Simulink, [24] carried out the modelling and simulation of the ABS. The simulation results demonstrate the suggested ABS's capacity to produce stable and good dynamic performance. The researcher [25] suggested a control strategy based on a model predictive control (MPC) approach, which uses a linear state-space model of the system and also discussed the design of an output feedback adaptive controller and the execution of a processor-in-the-loop (PIL) validation test. The co-simulation platform that combines CarSim and Simulink to mimic an automobile ABS was created by [26]. The platform was used to evaluate the anti-lock braking system's performance at various vehicle speeds and road surface conditions. The outcomes demonstrated that the co-simulation platform could successfully analyze the behavior of the anti-lock braking system and recreate it with accuracy.

Researchers have conducted numerous experiments in ABS technology, developed a wide range of models, algorithms, and methods to improve braking performance, including linear and nonlinear parameter varying methods, generalised predictive control method, PID controller HILS method, longitudinal wheel model, Car tyre model, Lugre Friction Model, Burckhardt Friction Model, Bang-Bang control algorithm, adaptive fuzzy fractional order sliding mode control, fuzzy sliding mode control, CAE methods and also used different advanced software such as ADAMS, Fuzzy, MATLAB, Simlink. Despite the extensive assessment of the literature, there is minimal research available considering vehicle speed, tyre slip ratio, and road conditions. This study aims to address the gap by providing an in-depth investigation of the SUV of ABS technology using a Fuzzy logic controller and the CarSim software and contributes to the field by addressing gaps in the literature. This work describes a dynamic mathematical model developed using a fuzzy logic control approach and the MATLAB/Simulink software to simulate under a wide range of road conditions and to solve critical issues for industry specialists to manage brake pressure to provide predictable braking.

2. Modeling of the Vehicle Dynamics System

2.1. Longitudinal Vehicle Dynamics Model

A quarter-vehicle model with three degrees of freedom is modeled to mimic a vehicle's longitudinal dynamics, taking into consideration straight-line emergency braking up until stopping. A single sprung mass (the automobile body) is coupled to an unsprung mass (the wheel) for the vehicle's longitudinal dynamics modeling, and Fig. 1 depicts the vertical dynamics influence of the vehicle on traction. As indicated that the tire is modeled as a linear spring and damping element, whereas the suspensions within the sprung mass and unsprung mass are modeled as linear viscous damper and spring elements.

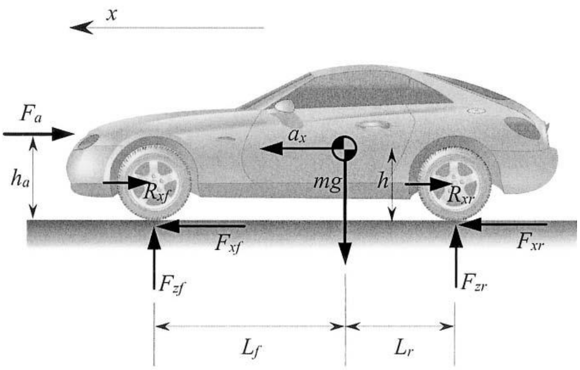


Fig. 1. Vehicle longitudinal dynamics

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

$$\sum F = m_v * a \Longrightarrow F_x - F_a - F_r \;= m_v * a \tag{1}$$

Since the vehicle's acceleration is the derivative of speed, this expression may be rewritten as

$$m_v * \dot{v} \;= F_x - F_a - F_r \Longrightarrow \dot{v} \;= \frac{F_x - F_a + F_r}{m_v} \tag{2}$$

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

$$m_v = m_w + \frac{1}{4} m_s \tag{3}$$

Drag force is created by aerodynamic resistance force (F_a) and rolling resistance force (F_r), two force components that act parallel to and in opposition to the vehicle's motion.

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

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

For passenger automobiles with mass in the range of 800-2000 kg, [27] claim that the frontal area A_f the following connection between vehicle mass and the frontal area may be used: $A_f = 1.6 + 0.00056(m - 765)$

The energy that a vehicle must transfer to its tires to drive across a surface at a constant speed is known as the rolling resistance force (F_r), and it may be calculated as follows:

$$F_r = C_r * m_v * g \tag{5}$$

Therefore, the following formula may be used to get the net force or overall Vehicle longitudinal force (F_x) :

$$\begin{aligned} F_x &= m_v * a - F_a - F_r \\ &= m_v * a - \frac{1}{2}(\rho * C_d * A_f * V^2) - \frac{1}{4} * C_r * m_v * g \end{aligned} \tag{6}$$

2.2. Tire Dynamics Model

Braking forces are produced at the intersection of the tire and the road surface when braking torque is applied to a wheel, according to [28]. As illustrated in Fig. 2, the longitudinal force generated at each tire is known to be influenced by the longitudinal slip ratio, the tire-road friction coefficient, and the applied normal force.

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

$$F_x = \mu(\lambda) * F_z \tag{7}$$

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

$$F_z = m * \frac{g}{4} + F_l \tag{8}$$

As a result of braking, the longitudinal weight transfer load, F_l, is represented as follows:

$$F_l = \frac{1}{2L}(m_v * h_{cg} * \dot{v}) \tag{9}$$

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

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

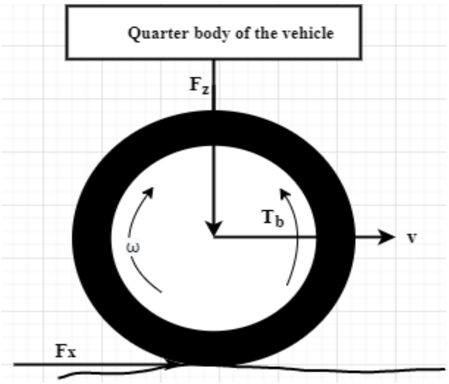


Fig. 2. Free body diagram of single wheel

The direct reduction in the wheel angular velocity (ω) is caused by the rotational acceleration of a body, decelerating the vehicle at the quantity owing to braking torque (T_b) applied to the wheel radius(R), and moment of inertia(I). This equation may be used to model the rotational dynamics of a wheel:

$$\sum T_y = I * a = I * \dot{\omega} \tag{10}$$

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

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

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

$$I * \dot{\omega} = F_{net} * R - T_b \Rightarrow \dot{\omega} = \frac{1}{I}(F_{net}) * R - T_b \tag{11}$$

$$T_t = I_w * \alpha$$

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

$$I = \frac{1}{2} m_w * r_w^2 \tag{12}$$

The braking torque T_b and the brake force F_b, which act at the point where a single wheel meets the ground, are connected as follows:

$$T_b = F_b * r \tag{13}$$

Where, r is the wheel cylinder radius. The area of the wheel cylinder and the hydraulic pressure in the braking system both influence the force that the pads apply to the rotor. The following equation may be used to determine the maximum braking torque:

$$T_{b,max} = P * A * r_e \tag{14}$$

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

2.3. Tire-Road Friction Coefficient Characteristics and Estimation

The complicated friction dynamics between the tire and the varied road conditions are discussed in this section using an empirical model. The real-time estimate of the tire-road friction coefficient has been proposed using a variety of various methodologies in the literature. As stated by [29], the tractive forces generated by a tire during braking or acceleration are proportional to the normal forces of the road acting on the tire.

The road coefficient of adhesion (also known as the friction coefficient), which is symbolized by the symbol(μ), varies based on the road surface.

Since the goal of an ABS is to control the torque given to the driven wheels to reduce tire slide, it can only function within the stable zone of the $\mu - \lambda$ characteristic, shown in Fig. 8.

The slip ratio is the point obtained during emergency braking scenarios, at which the tangential velocity of the tire surface (wheel speed) and the longitudinal speed of the vehicle are not the same. So, the wheel longitudinal slip ratio λ (from Fig. 8) is defined by the normalized difference between the vehicle speed v and the speed of the wheel perimeter($R.\omega$).

$$\lambda = \frac{v - \omega * R}{v} \equiv 1 - \frac{\omega * R}{v} \tag{15}$$

Differentiating the equation mentioned equation by time (t):

$$\dot{\lambda} = \frac{\dot{v}(1-\lambda) - R * \dot{\omega}}{v} \tag{16}$$

Substituting equations (2) and (8) into the previous equation gives the following result in equation (14):

$$\dot{\lambda} = -\frac{1}{v} \left(\frac{\mu * F_z}{M}(1-\lambda) - \left[\frac{\mu * R * F_z - T_b}{I}\right] R\right) = -\frac{\mu .*}{v}\left[\frac{(1-\lambda)}{M} + \frac{R^2}{I}\right] + \frac{R}{I * v} * T_b \tag{17}$$

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

$$\mu(\lambda) = \left[C_1\left(1 - e^{C_2 * \lambda}\right) - C_3 * \lambda\right] \tag{18}$$

The Formula cannot be directly applied for the detection of tire-road friction coefficient efficiently due to the enormous amount of factors involved. For purposes of identifying the tire-road friction coefficient, MATLAB/Simulink uses a look-up table in place of the Formula.

Table 1. Surface friction parameters of different road conditions [30]

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

As shown in Fig. 3, the road coefficient of friction is a nonlinear function of wheel slip (λ) and the coefficient of friction reduces from the dry to ice road conditions. This shows how the friction coefficient μ(λ) increases with slip λ up to a valueλ_0, where it attains its maximum value μ_0. For higher slip values, the friction coefficient will decrease until the wheel is locked. As the plots indicate, increasing slip can increase the tractive force between the tire and road surface by an increase in μ.

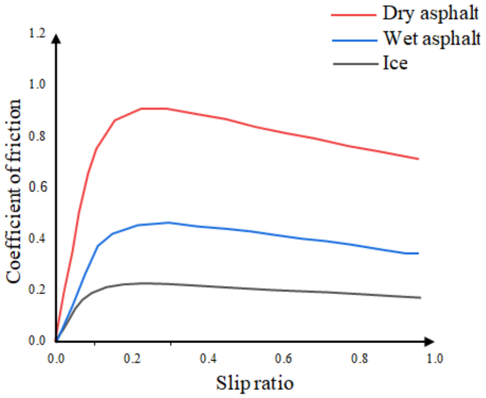


Fig. 3. Slip ratio vs. friction coefficient for various road conditions

On wet surfaces or roads contaminated by dirt, the brake force coefficient typically spans the range of 0.2 to 0.65 which is summarized in Table 2 [29]. Consider the tire force characteristics in Fig. 4 to comprehend that the longitudinal slip ratio affects braking forces. It demonstrates that, until it reaches a maximum (peak) value, the tire longitudinal force normally grows linearly with the slip ratio. Beyond this point, the tire force's strength diminishes and stabilizes at a fixed amount. As a result, the road surface adhesion coefficient curve divides the whole wheel slip range into two regions: the stable zone and the unstable region [29].

The wheel speed falls, the slip ratio rises, and the ground brake force progressively reduces until the vehicle wheel is locked if the wheel slip is caused by brake torque that is greater than ground brake torque. As a result, the goal of the suggested control strategy based on a look-up table is to keep the wheel slip ratio within the stable range during the braking process of the vehicle.

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

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

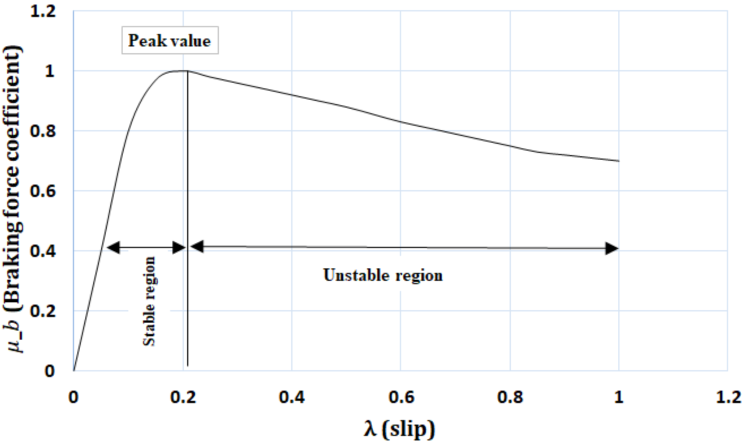


Fig. 4. Characteristics function of tire-road friction

2.4. Fuzzy Logic Rules

Fuzzy approaches are used in intricate and imprecise processes when there is no mathematical model or the mathematical model is significantly nonlinear. Fuzzy logic controllers are capable of representing knowledge in the form of linguistic rules and encompassing a high level of complexity with a small number of rules.

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

- Fuzzification is the process of converting a crisp (actual integer) input into a fuzzy set and determining an input's percentage membership in overlapping sets.
- The inference mechanism converts the fuzzy input into a fuzzy output,
- Rules: Mamdani's technique uses rules to determine outputs depending on inputs and rules.
- Defuzzification is needed to transform the fuzzy output into a numerical number. It integrates all fuzzy actions into a single fuzzy action and converts that single fuzzy action into a clear, executable system output.

In complex and imprecise systems for which either no mathematical model exists or the model is significantly nonlinear, fuzzy approaches are used [31]. According to [32] fuzzy logic controllers may express information comparatively simply in the form of language rules and can handle a considerable deal of complexity with a small number of rules. Both the inputs and output are crucial in the Fuzzy logic control approach. For the inputs and outputs, Gaussian membership functions (MFs) are used. Gaussian MFs are chosen as the best choice for obtaining adequate parameter values for a more robust control system. The MF range for the input and output is [-1, 1]. The controller's output is brake pressure, which regulates vehicle slippage and maintains safety.

Table 3. The fuzzy logic base rule

No.	Error	Error rate	ΔP
1	Zero (ZE)	Negative Big (NB)	Big Pressure Increase (BPI)
2	Negative Big (NB)	Zero (ZE)	Big Pressure Increase (BPI)
3	Negative Big (NB)	Positive Small (PS)	Medium Pressure Increase (MPI)
4	Positive Small (PS)	Negative Big (NB)	Medium Pressure Increase (MPI)
5	Zero (ZE)	Negative medium (NM)	Medium Pressure Increase (MPI)
6	Negative medium (NM)	Zero (ZE)	Medium Pressure Increase (MPI)
7	Zero (ZE)	Negative Small (NS)	Small Pressure Increase (SPI)
8	Negative Small (NS)	Zero (ZE)	Small Pressure Increase (SPI)
9	Positive Small (PS)	Negative Small (NS)	Pressure Hold (PH)
10	Negative Small (NS)	Positive Small (PS)	Pressure Hold (PH)
11	Positive Big (PB)	Negative Small (NS)	Medium Pressure Decrease (MPD)
12	Negative small (NS)	Positive Big (PB)	Medium Pressure Decrease (MPD)
13	Zero (ZE)	Zero (ZE)	Pressure Hold (PH)
14	Positive Small (PS)	Zero (ZE)	Small Pressure Decrease (SPD)
15	Zero (ZE)	Positive Small (PS)	Small Pressure Decrease (SPD)
16	Positive medium (PM)	Zero (ZE)	Medium Pressure Decrease (MPD)
17	Zero (ZE)	Positive medium (PM)	Medium Pressure Decrease (MPD)
18	Positive Big (PB)	Zero (ZE)	High Pressure Decrease (HPD)
19	Zero (ZE)	Positive Big (PB)	High Pressure Decrease (HPD)

The output of the Fuzzy logic controller (FLC) is the brake torque or change in pressure and the fuzzy member-ship languages used are: big pressure decrease (BPD), medium pressure decrease (MPD), small pressure decrease (SPD), pressure hold (PH), small pressure increase (SPI), medium pressure increase (MPI), and big pressure increase (BPI) as shown in Table 3.

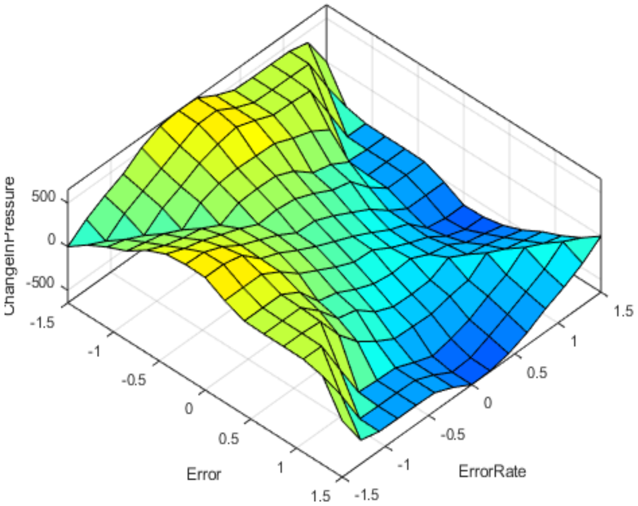


Fig. 5. Fuzzy logic controller surface characteristics

This surface viewer shows the output surface for any system output versus any one (or two) inputs. The control surface of a two-input and single-output system is shown in Fig. 5, where error and error rate represent inputs and change in pressure represents the controller output.

2.5. ABS Simulation in CarSim

The simulation parameters for CarSim are set here as shown in Fig. 6 The full vehicle simulation of ABS model is used in the CarSim software, which is interlinked with MATLAB. Some additional parameter's behavior like pressure can be used as compared to MATLAB ABS model. The simulation time is set to 10 seconds in all.

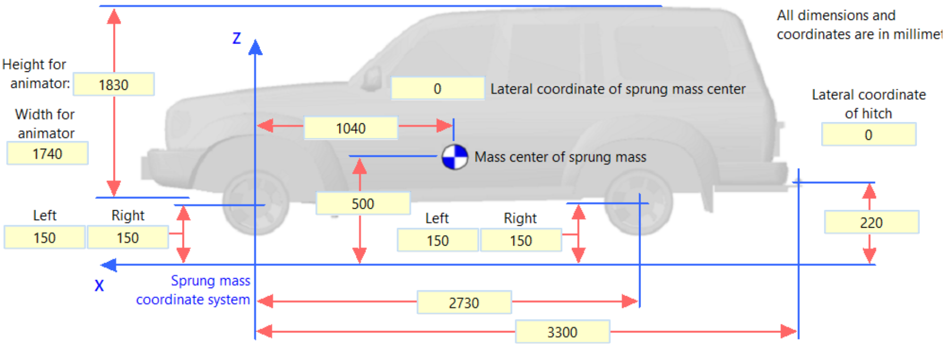


Fig. 6. Vehicle parameters in CarSim

3. Results and Discussion

3.1. MATLAB Simulation Result Using The Fuzzy Logic Controller

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

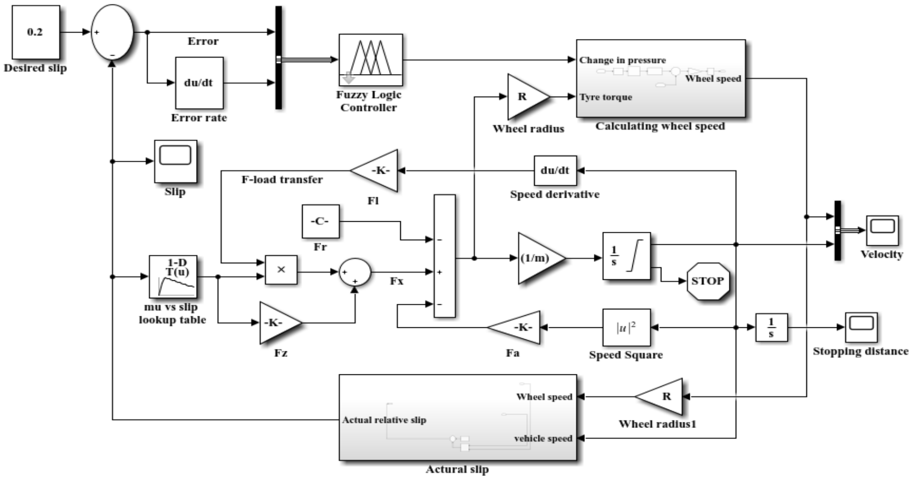
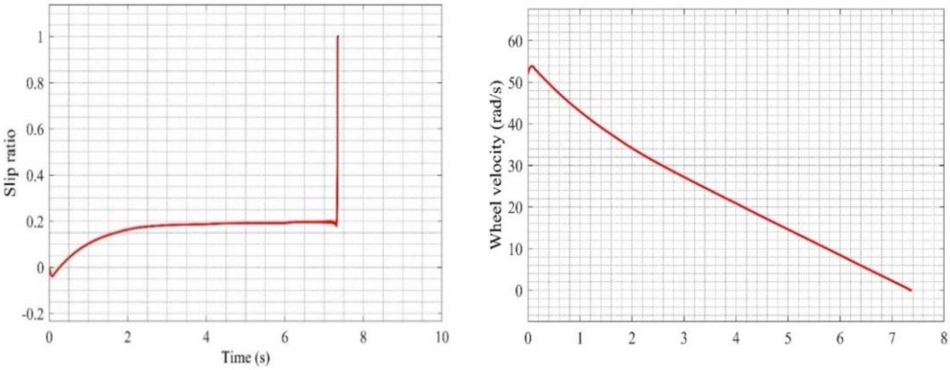


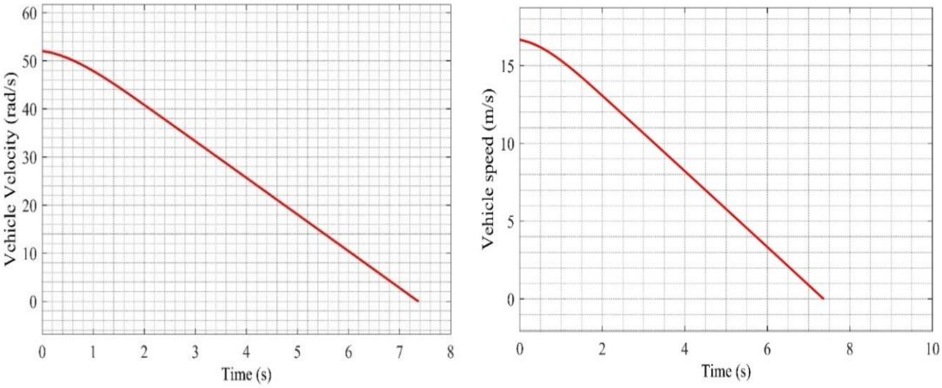
Fig. 7. Quarter vehicle model on MATLAB/Simulink with fuzzy logic controller

As the initial speed of the vehicle increases, the braking time and braking distance increase. Fig. 7 shows the MATLAB/Simulink model of the system with the fuzzy logic controller.



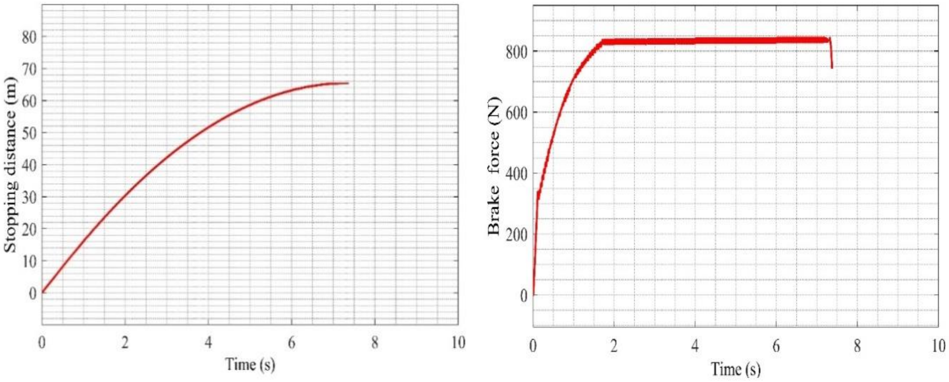
a) Slip ratio

b) Wheel Velocity



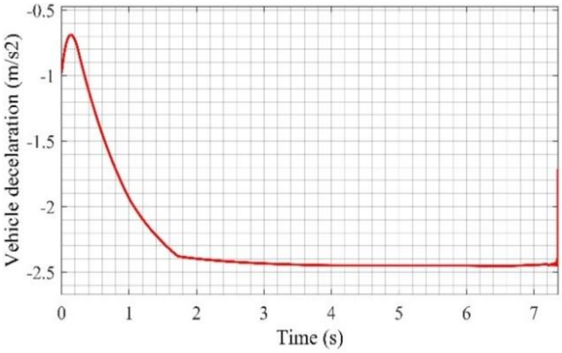
c) Angular vehicle speed

d) Vehicle linear velocity



e) Stopping distance

f) Brake force



g) vehicle deceleration

Fig. 8. Simulation results of ABS with FLC at 60 km/hr

The purpose of the controller is to maintain the vehicle slip as close as possible to the value of 0.2 which was achieved in this work as shown in Fig. 8 (a). Consequently, vehicle stability is maintained with the help of a developed fuzzy logic controller, by which the actual slip is maintained as close as possible to the desired value of the slip.

From the simulation study, it has been seen that the stability of the vehicle is more stable as compared to the other models in which wheel speed suddenly comes to zero at a time of 7 seconds after braking. Braking force as shown in Fig. 8 (f), is the most important parameter of the brake system which is directly related to braking torque and braking distance since it is the amount of force needed to achieve assumed braking parameters for the mechanical vehicle.

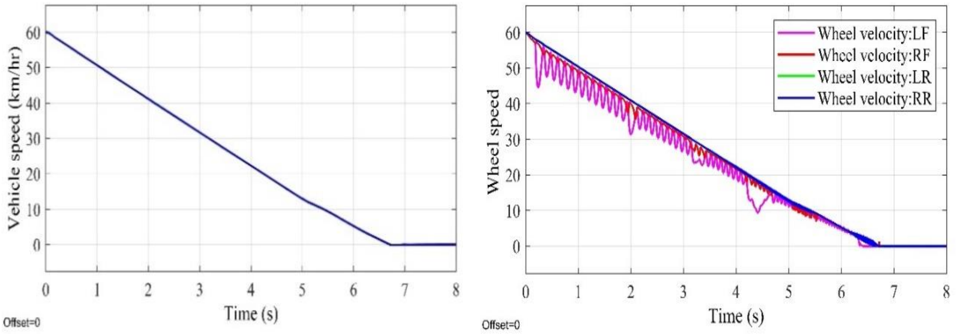
To obtain the maximum braking torque to stop the vehicle within a minimum distance, the location of the peak as the controller has been exhibited. In the case of conventional braking systems or other controlling mechanisms, after the brake is applied to the wheel, it takes 10 to 14 seconds to let it slow down and regain traction, which takes only about 7 seconds in this study.

A velocity graph for both wheels and vehicle has been obtained, and it shows that both the velocity curves converge at a point when the vehicle is stopped, which ensures the vehicle stops without skidding.

3.2. CarSim Simulation

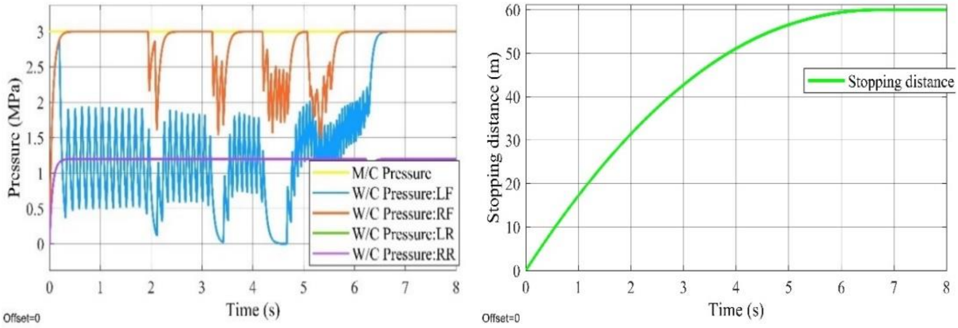
The second simulation is realized by CarSim simulation to confirm the performance of the proposed fuzzy logic controller. Since, the ABS model of the CarSim software represents the full vehicle simulation, and can be taken as a vehicle test under given circumstances, it was interlinked with MATLAB/Simulink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

The wheel cylinder pressure variation is one of the additional parameters used in the CarSim ABS model for hatchback SUV vehicles. The braking pressure applied to the brake pedal is about 3 MPa, which was kept constant. Then, MATLAB/Simulink was integrated with CarSim & the parameters used are the same, in which the achieved result is almost similar to that illustrated in Fig. 9.



a) Vehicle velocity

b) Wheel velocity



c) Wheel and master cylinder pressure

d) Stopping distance

Fig. 9. Simulation results of ABS in CarSim at 60 km/hr

At the end of the simulation, it gives the required wheel cylinder pressure that is to be applied to each wheel of the vehicle and the wheel control pressure increases quickly back to system or master cylinder pressure as the vehicle velocity drops below the velocity threshold and comes to rest, as shown in Fig. 9 (c). From the simulation results, the wheel cylinder pressure variation has been obtained for each wheel.

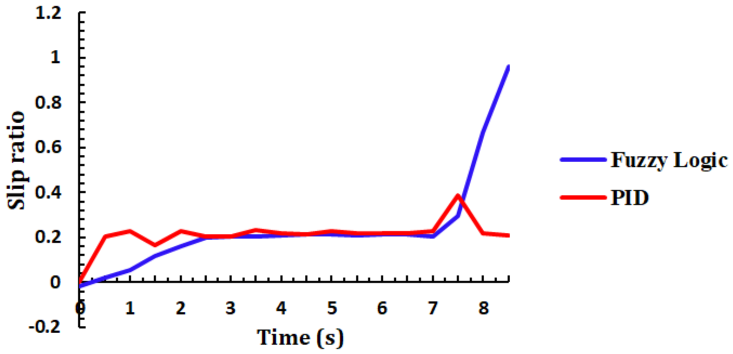


Fig. 10. Comparsion of Fuzzy and PID slip ratio

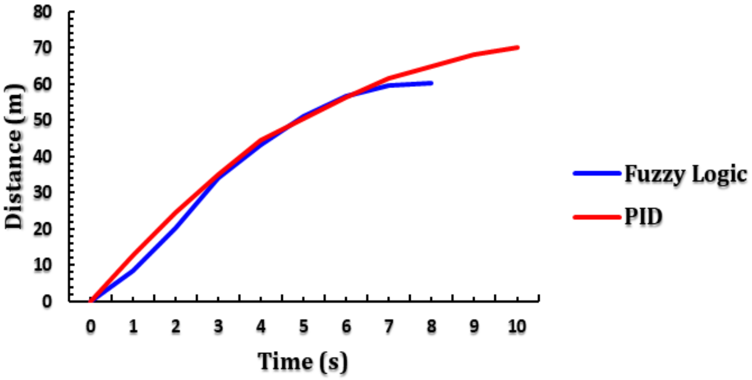


Fig. 11. Comparsion of Fuzzy and PID Braking distance

The front and rear brake system pressure has their proportion and the front brake pressure is more compared to the rear. The authors compared fuzzy logic to a MATLAB/Simulink PID controller. The slip control by the fuzzy logic controller system has an excellent convergent rate, but the PID has a relatively sluggish convergence rate, as shown in Fig. 10. The ABS response employing a fuzzy logic controller performs better by regulating longitudinal slip about 0.2 during braking till the vehicle stops. This enables the vehicle to stop without skidding after the 7th second.

The fuzzy logic with PID controllers' braking distances are also compared, and the findings demonstrate that the fuzzy logic controller achieves a lower brake distance, as shown in Fig. 11. After 7 seconds, the fuzzy logic brake distance is 63 meters, whereas the PID distance is 670 meters in 14 seconds. Based on these results, the fuzzy logic controller is to be more effective for the ABS than the PID controller.

The results demonstrate that the suggested fuzzy logic controller is successful in regulating the vehicle longitudinal model and achieves better performance than PID controllers.

From the results of the two model, it was observed that the model created in the CarSim program produces results that are more exact, detailed, and accurate than the model created in the MATLAB software. This occurs when a full-vehicle system model is utilized in CarSim whereas the MATLAB/Simulink model is developed using the quarter model of a car. In light of this, it can be said that the created controller for a quarter-car model performs well and converges quickly.

Conclusion

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

- The vehicle stability and braking performance have been improved by contributing additional braking with the help of a fuzzy logic controller strategy to the standard EBD and conventional braking systems. The proposed controller shows better performance to minimize the slip error as compared to the conventional controller, and hence, it maintains the stability of the vehicle and reduces the stopping distance of the vehicle.
- For validation purposes and to address a few limitations of the ABS model, the simulation was also conducted in CarSim software linked with MATLAB/Simulink. The outcome demonstrates that the wheel cylinder pressure is properly controlled and the braking stability is enhanced during the simulation process.
- The results of slip ratio and braking performance are compared utilizing fuzzy logic to a MATLAB/Simulink PID controller. The fuzzy logic controller successfully regulates the vehicle longitudinal model and achieves enhanced performance than PID controllers

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