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Performance of Anti-Lock Braking Systems Based on Adaptive and Intelligent Control Methodologies

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ABSTRACT

Automobiles of today must constantly change their speeds in reaction to changing road and traffic circumstances as the pace and density of road traffic increases. In sophisticated automobiles, the Anti-lock Braking System (ABS) is a vehicle safety system that enhances the vehicle's stability and steering capabilities by varying the torque to maintain the slip ratio at a safe level. This paper analyzes the performance of classical control, model reference adaptive control (MRAC), and intelligent control for controlling the (ABS). The ABS controller's goal is to keep the wheel slip ratio, which includes nonlinearities, parametric uncertainties, and disturbances as close to an optimal slip value as possible. This will decrease the stopping distance and guarantee safe vehicle operation during braking. A Bang-bang controller, PID, PID based Model Reference Adaptive Control (PID-MRAD), Fuzzy Logic Control (FLC), and Adaptive Neuro-Fuzzy Inference System (ANFIS) controller are used to control the vehicle model. The car was tested on a dry asphalt and ice road with only straight-line braking. Based on slip ratio, vehicle speed, angular velocity, and stopping time, comparisons are performed between all control strategies. To analyze braking characteristics, the simulation changes the road surface condition, vehicle weight, and control methods. The simulation results revealed that our objectives were met. The simulation results clearly show that the ANFIS provides more flexibility and improves system-tracking precision in control action compared to the Bang-bang, PID, PID-MRAC, and FLC.

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1. INTRODUCTION

Automobile reliability is one of the most essential challenges in the automobile manufacturing industry. The importance of braking systems in achieving reliability cannot be overstated. When braking on a road surface, locking the wheels is harmful. This results in longer stopping distances and less steering, both of which are undesirable. The application of ABS is the most important barrier to good braking performance in an automobile. This technique was first implemented in 1970 by the Benz plant, and it quickly gained widespread support among automotive manufacturers and drivers [1]. The following are the shortcomings of basic mechanical brakes: Their efficiency is low, resulting in a higher risk of accidents. It takes a long time to come to a halt. The vehicle loses its stability and begins to slide when doing emergency braking. As a result, it was required to create an ABS safety mechanism that operates automatically and is more efficient. When a vehicle is equipped with ABS, the tires are not locked when emergency braking is applied, which improves safety. The ABS uses a closed-loop system to modulate the braking force in responsiveness to retardation of the wheel and rotational speed to ensure that the controlled wheel does not lock. Due to the fact that braking causes wheel slip and frequently causes the wheel to lock, the amount of friction between the wheel and the road is decreasing. After a long-distance, the automobile will come to a halt. The only external large force acting on an automobile is friction between the road and the tire. The amount of force is determined by how much the wheels are slipping. ABS adjusts wheel slip by altering braking oil pressure, and the goals of ABS are met. ABS helps to overcome this problem by reducing braking force and preventing wheel locking. The tire and the road friction forces are kept at its maximum, and the distance between the tire and the road is reduced, resulting in increased reliability. ABS keeps the wheels from locking, allowing them to travel freely. This indicates that the car can be controlled by the driver [2].

Antilock brake systems have three goals: minimize stopping lengths, enhance steerability during braking as shown in Figure 1, and increase stability. In recent years, numerous researches have been undertaken on the application of various control theories to the ABS, such as neural networks and adaptive controls.

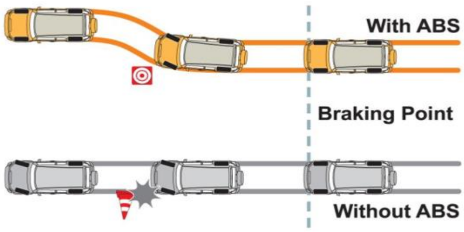


Figure 1. Effect of ABS

This work employs a simulation of an anti-lock braking system to verify the system's behavior under several controller methodologies, including classical and intelligent controllers. In addition, the optimal controller's performance will be evaluated under various road conditions in order to validate the efficiency. Several publications discussed the ABS or slip control system simulation methodology. The non-linear control of wheel slip in ABS is presented by [3] and Robust control for ABS is proposed by [4]. Adaptive Neuro-Fuzzy Self-tuning PID Controller is presented in [5]. The authors in [6] studied Maximize performance and ride quality with continuous control.

Sliding mode controllers have been developed and studied in [7]. A conventional controller, such as PID, cannot fulfill the needs of the ABS system because it can’t find the parameters of the controller dynamically and can’t reduce the effect of disturbance of the system. In this paper, the controller of the ABS braking system's primary goal is to provide the controlled torque needed to achieve the optimal wheel slip rate in the quickest time possible for different road surfaces and the presence of the disturbance.

The following is a breakdown of the paper's structure: The dynamics of the ABS model and the mathematical forms are explained in Section 2. Section 3 presents the control design methodology. Numerical simulations are demonstrated in section 4 and the conclusion will be presented in 5.

2. MATERIALS AND METHODS

2.1. Structure and operation of ABS

The ABS as shown in Figure 2 is made up of the following parts: speed sensor, tooth wheel, master cylinder, hydraulic unit (actuator) and electronic control unit. The ABS regulates brake line pressure independently of pedal effort in order to get the wheel speed back within the slip range required for the best braking outcomes.

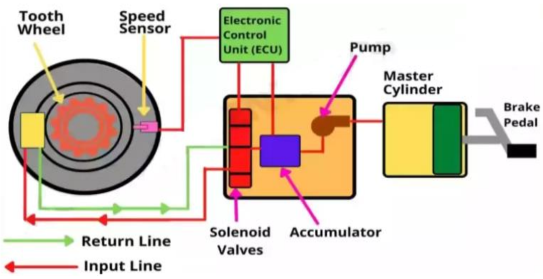


Figure 2. Structure of ABS [8]

Anti-lock Braking System works in the following steps [8]:

Step 1: When the brake pedal is depressed, the piston compresses the brake fluid, and the ECU sends a signal to the solenoid valve and pump.

Step 2: When the wheel comes to a halt due to braking, the Speed Sensor transmits a signal to the ECU. The ECU sends a signal to the pump and solenoid valve to stop the flow of brake fluid and release the pressure on the wheel (by returning the brake fluid through the return line).

Step 3: The speed sensor delivers another wheel speed signal to the ECU. Again, the ECU sends a signal to the solenoid valve and pump to start the flow, causing the brake fluid to flow rapidly until the vehicle speed drops or the vehicle stops without skidding. ECU is the central control unit of ABS, and collects sensor information to construct a plan of action and regulates the braking pressure by turning the hydraulic adjustment module on and off. The actuator collects control signals from the ECU and automatically regulates the brake pressure of the brake wheel cylinder [9].

2.2. Dynamic Model of ABS

Due to the obvious simpler design and greater real-time control needs, this paper chooses to develop the simulation system using a single-wheel model. Using the physics law, a mathematical form of quarter vehicle dynamic motion was created. The resistance of the wheel and air resistance will be ignored at the same time. Figure 3 depicts the quarter vehicle model. Table 1 displays the parameters and variables that will appear in the modeling equations of ABS.

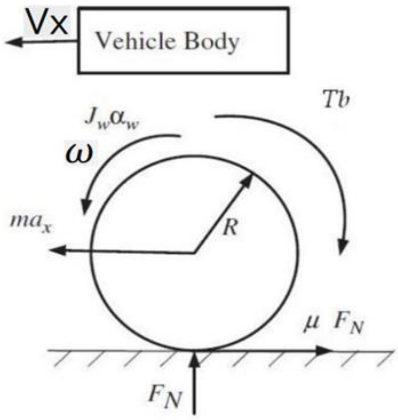


Figure 3. Single wheel model [10]

Table 1. Parameters and variables of single wheel model

Vehicle parameters	Description
ω	Angular velocity of rotational wheel
a_x	Linear acceleration
αω	Angular acceleration
T_w	Wheel torque
J_ω	Moment of Inertia
R	Radius of tire
V_x	Linear velocity of vehicle
F_n	Vertical force from tire to road
T_b	Braking torque
μ	Frictional coefficient
λ	Wheel slip
m	Mass of the model

For this model, the degrees of freedom are determined by the rotational speed of the wheel ω, and the vehicle's longitudinal velocity Vx. The system's non-linear dynamics equations are illustrated as follows:
In the longitudinal direction, the force balance is calculated using the following equation:

$$m\, a_x = m.\frac{dV_x}{dt} = -\mu. F_n. \tag{1}$$

The wheel torque T_W can be negative or positive or, depending on whether the motor or the brakes create the torque.

$$T_w = \begin{cases} T_d \quad if\ T_w > 0 \qquad (T_d: Driving\ Torque) \\ T_b \quad if\ T_w < 0 \qquad (T_b: Braking\ Torque) \end{cases} \tag{2}$$

The formula for summing torques around the wheel center is

$$J_\omega\, \alpha_\omega = \text{wheel torque} - \text{brake torque} = T_w - T_b,$$
$$J_\omega\, \alpha_\omega = J_\omega \dot{\omega} = (\mu. F_n. R) - T_b. \tag{3}$$

The slip ratio (λ) is calculated as

$$\lambda = \frac{V_x - \omega.R}{V_x}. \tag{4}$$

Differentiating the two sides with respect to time, we get the following

$$\dot{\lambda} = \frac{\dot{V_x}\,(1-\lambda) - \dot{\omega}.R}{V_x}. \tag{5}$$

In pure rolling, V_x= ω. r, λ = 0, and in pure sliding, ω = 0, slip rate λ = 1.

Typical properties of μ-λ (friction coefficient in relation to slip ratio) are present in Figure 4, where increased slip increases the tractive force between the tire and the road surface due to an increase in μ. To find a constant value for optimal slip, we must look for the best compromise between the frictional coefficient of the tire and the frictional coefficient of the road. The desirable slip ratio value is the value at which μ-λ characteristics offers the highest value, which is the value that achieves the shortest stopping distance [10]. It clearly shows that the optimal value of slip is close to 0.2 for virtually all road surfaces. To optimize the frictional coefficient, we want the ABS controller wheel to slide as near to this desired value as possible. The ABS' ability to maintain and sustain vehicle steering while reducing stopping distances is demonstrated by properties of μ-λ. The friction coefficient is calculated as a function of the vehicle's speed and slip rate as the following formula [11].

$$\mu(\lambda, V_x) = \left[c_1\left(1 - e^{-\lambda c_2}\right) - c_3\right] e^{-c_4 V_x}. \tag{6}$$

The ABS system model is made in the following way:

$$\dot{x} = f(x, u), \tag{7}$$

$$y = \lambda. \tag{8}$$

The system state variables are $x_1 = D_x$ represents the stopping distance, $x_2 = V_x$ and $x_3 = \lambda$.
The state space equations are

$$\dot{x_1} = x_2, \tag{9}$$

$$\dot{x_2} = \frac{-F_n}{m}\left[c_1(1 - e^{-c_2 x_3}) - c_3 x_3\right] e^{-c_4 x_2}, \tag{10}$$

$$\dot{x_3} = \frac{-F_n}{x_2}\left(\frac{1-x_3}{m} + \frac{R^2}{J_\omega}\right)\left[c_1(1 - e^{-c_2 x_3}) - c_3 x_3\right] e^{-c_4 x_2} + \frac{R}{J_\omega . x_2} T_b, \tag{11}$$

where c_1 represents the maximum value of the friction curve, c_2 is the friction curve shape, c_3 is the friction curve difference between the maximum value and the value at λ = 1, and c_4 is the wetness characteristic value. Various different tire-road friction conditions can be approximated by varying the values of the parameters c_1 through c_4.

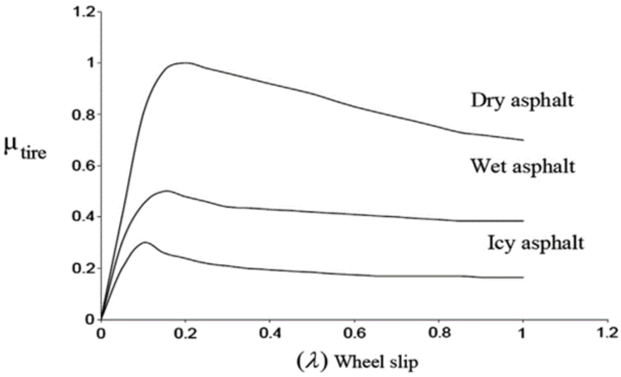
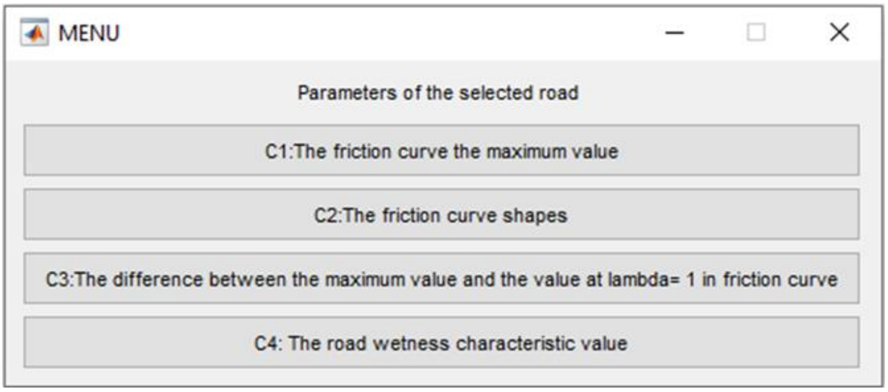
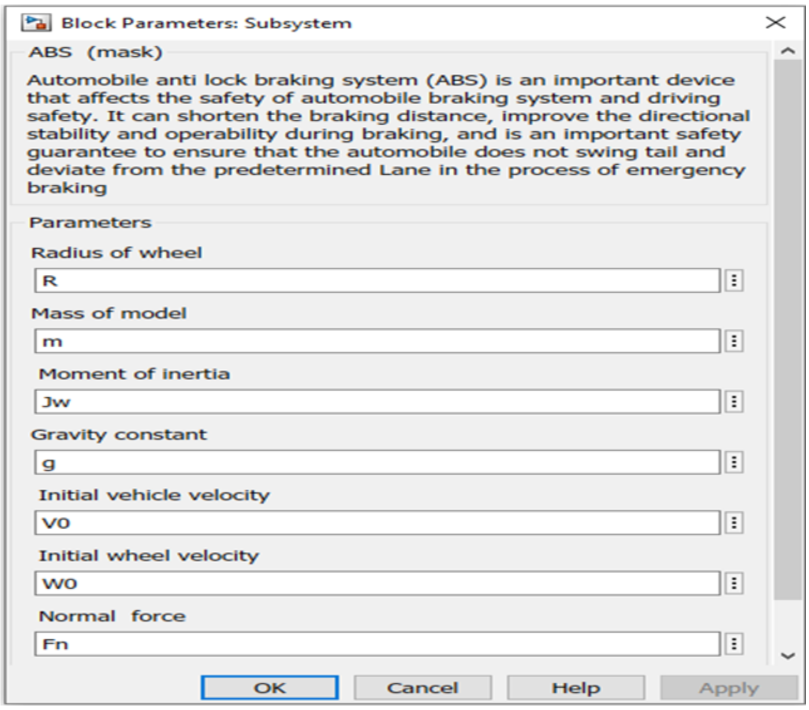


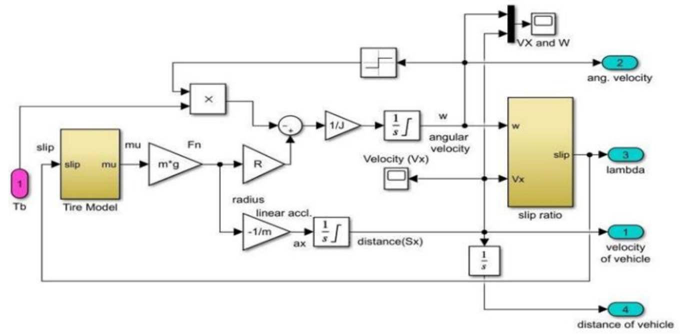
Figure 4. Frictional coefficient of road surfaces vs slip ratio [9]



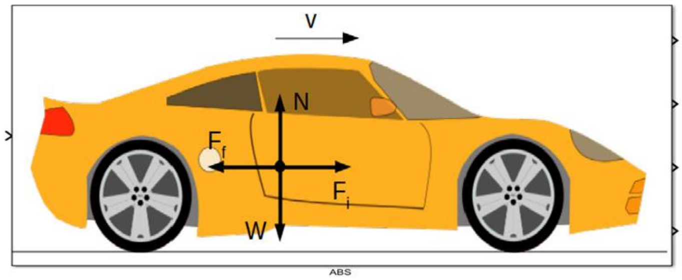
a. Menu of The Road Type and Parameters



b. Block Parameters of ABS



c. Simulink Model of ABS



d. Mask Model of ABS

Figure 5. Simulink and mask model of ABS with road parameters

To check that the mask and Simulink model in Figure 5 are designed correctly, we plot the variation of the friction coefficient function of slip for various road conditions as shown in Figure 6. For a road covered in snow or ice, the maximum value of the friction coefficient drops dramatically. Table 2 lists the specifications for various road surfaces.

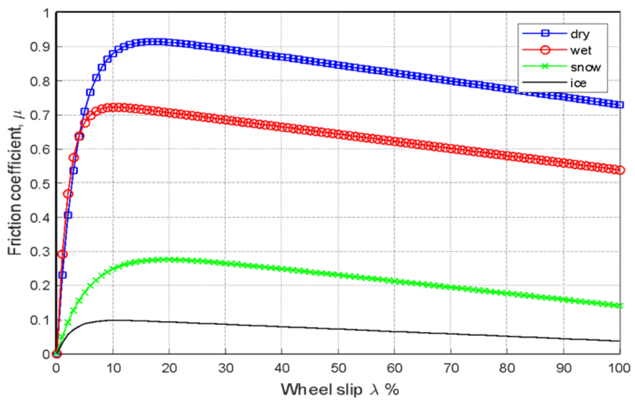


Figure 6. Check the relationship between the coefficient of friction and the coefficient of slip

Table 2. Tire-road friction parameters

Surface conditions	c_1	c_2	c_3	c_4
Dry asphalt	1.029	17.16	0.523	0.03
Dry concrete	1.1973	25.168	0.5373	0.03
Snow	0.1946	94.129	0.0646	0.03
Ice	0.05	306.39	0	0.03

The brake lines are the most active elements in a conventional brake system. Fluid viscosity, cross-sectional flow area, and brake line length all affect the flow of braking fluid from the master cylinder to the wheel cylinder. The time delay between the application of force to the brake pedal and the functioning of the wheel brake increases as fluid viscosity increases, which can compromise ABS performance. Dynamic behavior is added in the Simulink model by a first-order transfer function with unitary gain and time constant considered for this hydraulic lag [13].

3. CONTROL DESIGN METHODOLOGY

The goal of an ABS feedback control system is to maintain each tire on the vehicle operating at the top of its μ- λ characteristics and as near to the constant value (0.2) as possible to ensure optimal tire-road-surface friction under variable road conditions. Figure 7 depicts the ABS control framework, where the sensor continuously monitors the controlled variable (slip ratio) and provides data to a controller, which changes brake pressure modulator as needed to keep up with the intended output match to the reference values of the slip ratio.

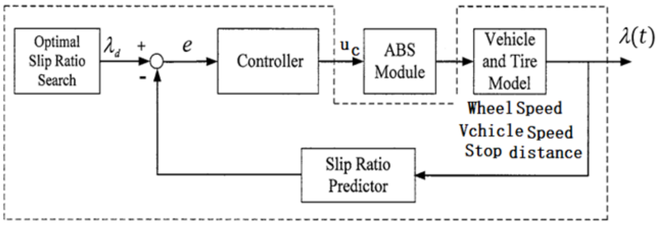


Figure 7. ABS control Structure

3.1. Bang–Bang Controller (ON-OFF)

A bang-bang (ON-OFF) controller has two fixed settings, which it abruptly flips between as shown in Figure 8. This controller is commonly used to control a system with only two settings: ON or OFF. The benefit of implementing the ON-OFF controller is that it is a simple system.

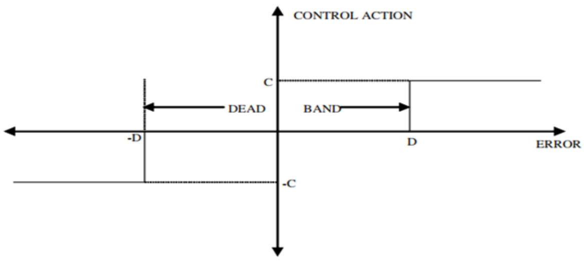


Figure 8. Bang-Bang (On-Off) controller

The ON-OFF algorithm is defined as follows:

$$u_c(t) = \begin{cases} -C & for\ error < -D, \\ 0 & for\ |error| < D, \\ +C & for\ error > D. \end{cases} \quad (12)$$

The error variable e(t) represents the difference between the desired $\lambda_d(t)$ and actual slip $\lambda(t)$values.

$$e(t) = \lambda_d(t) - \lambda(t). \quad (13)$$

The controller output is $u_c(t)$, where D is half the width of the dead-band region and C is the controller output magnitude. When the error is within the dead-band zone, the control activity is interrupted, otherwise the output is +C or -C depending on whether the error is positive or negative [14].

3.2. PID Controller

The Proportional-Integral-Derivative (PID) method is now the most widely utilized control algorithm in automated systems. The conventional PID control remains an important control method for three reasons: its track record of efficacy, wide availability, and ease of use. PID controllers are utilized in this work to manage wheel longitudinal slip and vehicle braking distance by adjusting brake torque. The tracking error e(t) is represented in Eq. 13. The ideal version of the PID controller output u(t) is given by the formula:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}\,, \tag{14}$$

where K_p is the proportional gain, K_i integral gain, and K_d is the derivative gain. These gains are tuned by trial and error to get the optimal wheel longitudinal slip [15,16].

3.3. Fuzzy Logic Control (FLC)

The FLC was created as a replacement for traditional model-based control systems. It may be applied to both linear and nonlinear systems and does not require a mathematical model of the plant. Fuzzy systems have gotten a lot of attention in fields including automated control, data characterization, expert systems, and computer vision. In classical logic, variables can take on true or false values and in fuzzy logic, the validity of any proposition is a question of degree, ranging from totally true to completely false by a value between 1 and 0. The fuzzy Inference System (FIS) as presented in Figure 9 are composed of the following four elements [17]:

Fuzzification: is the process of converting a numerical variable into a fuzzy number.
Fuzzy inference: The truth value for each rule's premise is computed and applied to the conclusion section of each rule under inference.
Rule base: The rules are written in an "If-Then" style, with a fuzzy logic quantification of the expert's language explanation of how to attain excellent control.
Defuzzification: is the process of converting the fuzzy output to the crisp number.

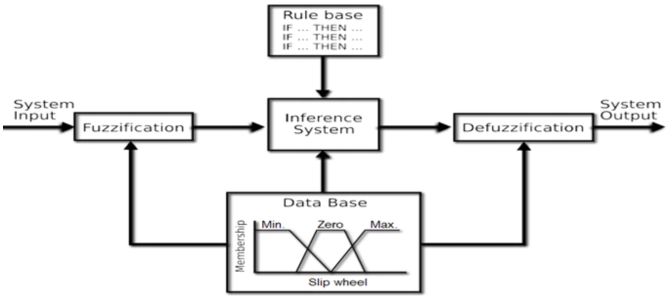


Figure 9. Fuzzy inference system diagram [17]

A fuzzy logic toolbox is an easy-to-use software for specifying the forms of each variable's membership functions, as well as changing the list of rules that govern the system's behavior. Then using the surface viewer, describe which rules are active and how the membership function shapes impact the outcomes. The ABS fuzzy controller has two inputs, error of the slip rate and the rate of change of this slip which is the deceleration of the vehicle. Figure 10 shows the fuzzy inference system for the ABS controller. For the "Error" input, Gaussian membership functions are used with a range of [-10 to 10] to cover the input range. The input "Error" is split into two membership functions, Positive (P) and Negative (N), as illustrated in Figure 11. The same scenario can be repeated in the case of the second input, which is the rate of change of error.

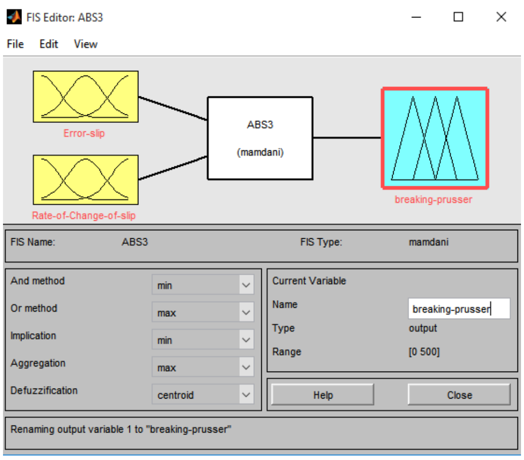


Figure 10. Inputs and Output of FLC

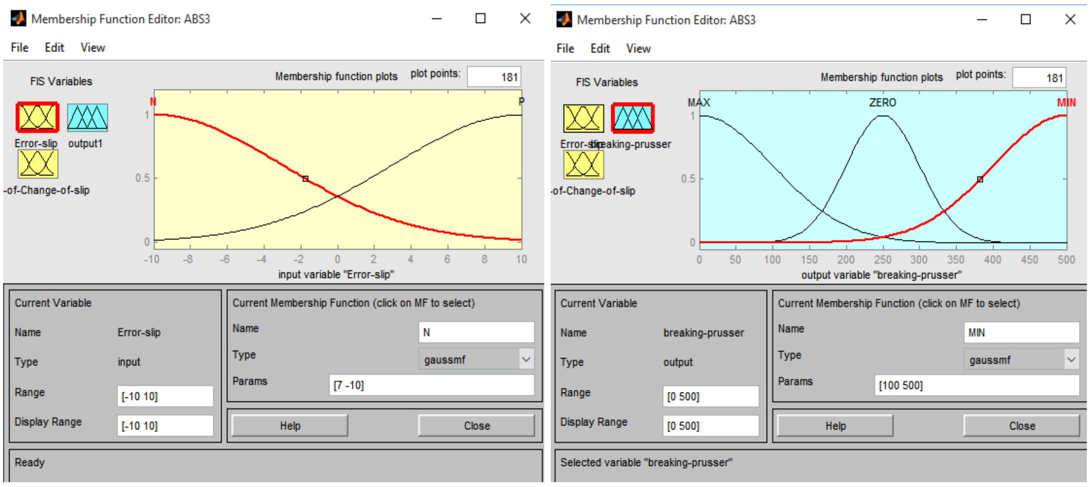


Figure 11 Membership Functions of the slip wheel and output

The braking pressure is FLC's output signal. Set the range [0 to 500] to cover the output range of this signal, which regulates the vehicle's slippage and guarantees its stability. As illustrated in Figure 11, when creating the rule basis, the output is split into three membership functions. Three states are considered: maximum (Max), no change (Zero), and minimum (Min). When braking, a set of fuzzy rules were created to get the car to operate in the stable range. Figure 12 shows the rule viewer, where the fuzzy controller rules are designed as follows:

1. If (Error-slip is N) and (Rate-of-Change-of-slip is N) then (breaking-pressure is MIN)
2. If (Error-slip is N) and (Rate-of-Change-of-slip is P) then (breaking- pressure is ZERO)
3. If (Error-slip is P) and (Rate-of-Change-of-slip is N) then (breaking- pressure is ZERO)
4. If (Error-slip is P) and (Rate-of-Change-of-slip is P) then (breaking- pressure is MAX)

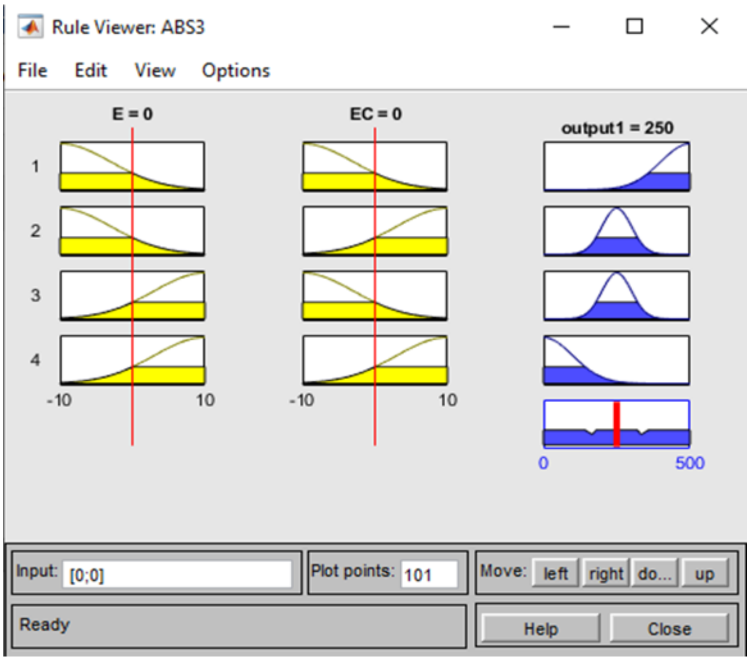


Figure 12. Rule Viewer of FLC

3.4. PID based Model Reference Adaptive Control (PID-MRAC)

The reference model, the adjustment mechanism, and the controller are the three basic components of an MRAC system as shown in Figure 13. The closed-loop system's transfer function is the reference model. This model captures the closed-loop system's desired behavior [18].

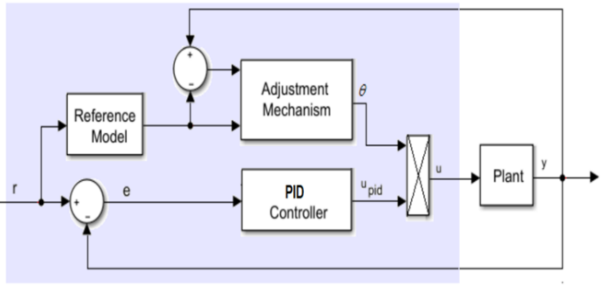


Figure 13. Structure of MRAC

Figure 14 shows the Simulink model of PID-MRAC. For the model reference, the continuous transfer function was utilized to implement the standard form of the second-order system [19,20].

$$G_m(s) = \frac{K\omega_n^2}{S^2+2\xi\omega_n S+\omega_n^2}\ . \tag{15}$$

To get a quick time response, we choose the damping ratio ξ = 0.707 and the natural frequency ω_n=2 rad/sec, and therefore the transfer function of the reference model is as follows.

$$G_m(s) = \frac{\lambda}{\lambda_d} = \frac{0.8}{S^2+2.83S+4}. \tag{16}$$

The control action is adjusted by the adaptation mechanism depending on the difference between the plant output and the reference model output. The adaptation parameter (θ) is

$$\theta = (y - y_m)y_m.\frac{-\gamma}{s} = e\ .y_m.\frac{-\gamma}{s}. \tag{17}$$

where e is the error signal, y is the plant output, y_m is the reference model output and γ is the learning rate. Increasing the value of γ causes plants to respond to changes more quickly. The adjusted control signal, u(t), is

$$u = u_{PID}(t)\theta(t), \tag{18}$$

where $u_{PID}(t) = K_p\, e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}$.

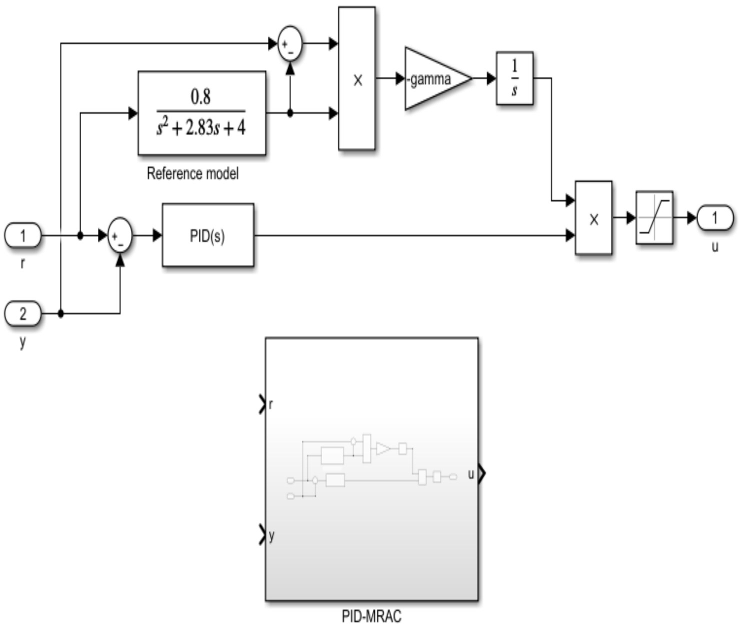


Figure 14. Simulink Model of PID-MRAC

3.5. Adaptive Neuro Fuzzy Inference System

An ANFIS is a hybrid system that may be used to create intelligent control algorithms and is employed in a variety of fields for complex nonlinear systems. ANFIS has invented a novel hybrid technology called Neuro-fuzzy networks by combining the learning power of NNs with the expert systems of FL. Principally, Neural network are functionally the same as the fuzzy [19]. Combining these technologies allows leveraging their strengths while avoiding their flaws. Adaptive approaches construct membership functions and rules automatically, which can be utilized to produce the optimal outcome from training data. The training was carried out using a hybrid learning technique that combines back-propagation with the least square method [18]. Figure 15 shows the ANFIS block diagram, this structure has the same components as the FIS except for the ANN block. The neural network is linked to the rule base block and trained using the backpropagation approach to find the appropriate collection of rule bases. The control signal required to get the optimal outputs is generated once the right rules have been selected and fired. Figure 16 shows the steps of the flowchart for programming ANFIS using Matlab built-in functions [20].

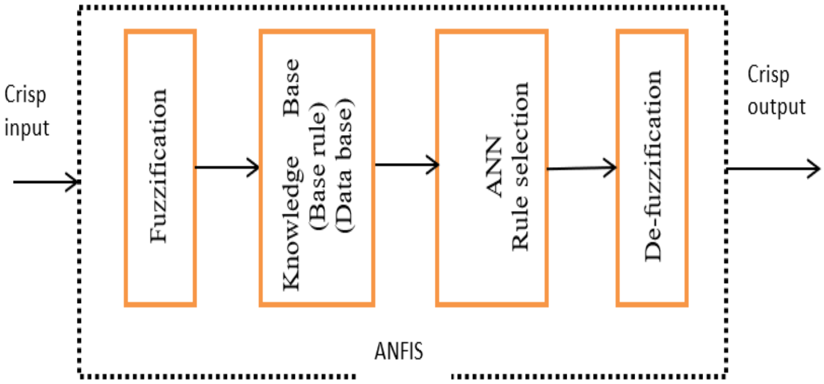


Figure 15. Block Diagram of the ANFIS Scheme

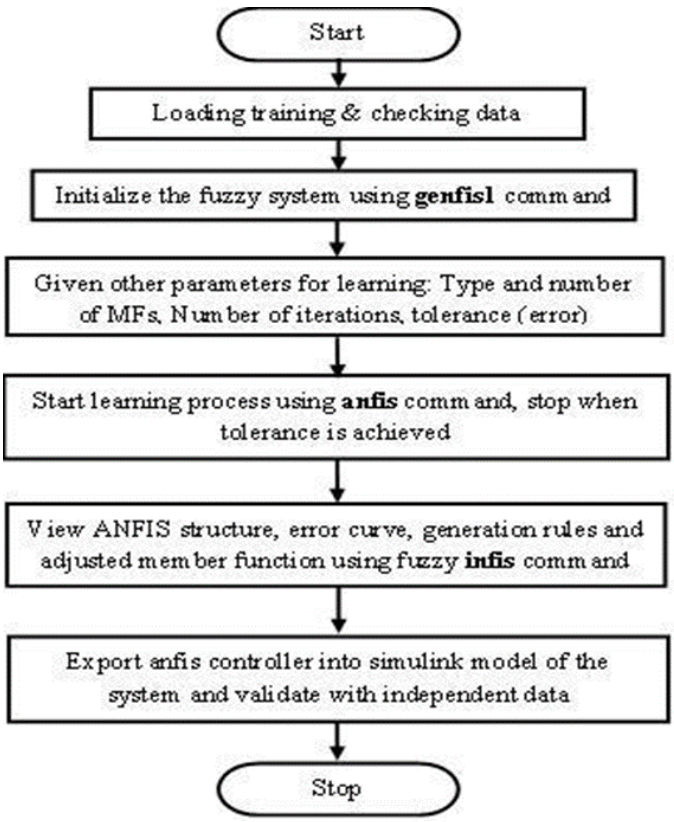


Figure 16. Programming Environment of ANFIS

The Sugeno-type ANFIS is developed by training the input-output data set of the ABS based on a pre-designed PID-MRAC controller. A total of 2000 datasets were obtained, which were then separated into training and testing data sets. We can export the ANFIS model to a Simulink file or workspace when the training is completed and use it to control the system directly. The difference between the training data output value and the ANFIS output corresponding to the identical training data input value is the training error. As shown in Figure 17, the training error diminishes as the number of epochs grows. As the number of epochs increases, the inaccuracy eventually gets saturated. In addition, training and ANFIS outputs data are shown in Figure 18. The basic structure of the type of ANFIS controller is presented in Figure 19 [21,22].

Figure 17. Error Signal of Training ANFIS

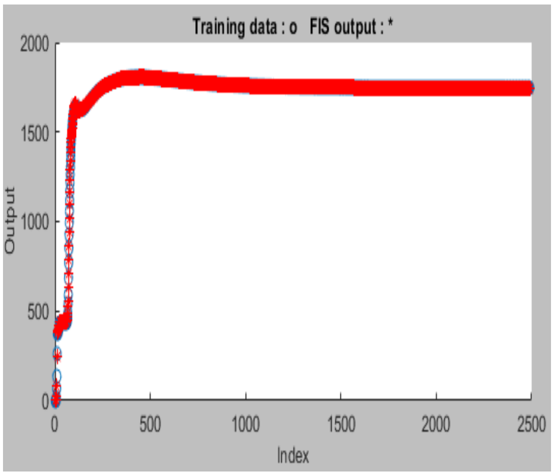


Figure 18. Training Data and ANFIS Output

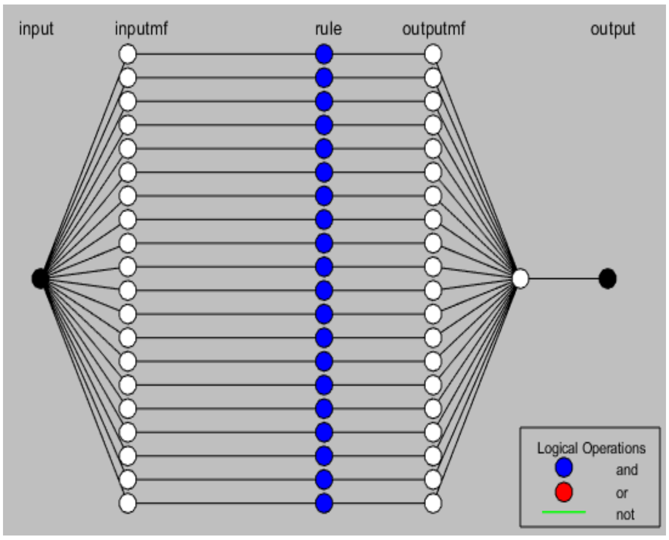


Figure 19: Structure of ANFIS Model Structure

4. RESULTS AND DISCUSSION

The input parameters that have been used are given as the following: m =450 kg, R=0.33 m, g=9.8 m/s^2, and J=1.13 KNm. First, we will notice the effect of the different controllers as shown in Figure 20 in the case of dry roads. The best controller will be applied in the case of wet and snowy roads. The parameters of dry asphalt road, C_1= 1.2, C_2=23.99, C_3= 0.52 and C_4=0.03. Figure 21. displays the open loop response of vehicle and wheel speed, stopping distance and slip ratio, where the desired slip is 0.2 with initial vehicle speed being 80 Km/h. We can see that the car comes to a complete stop after 5.6 seconds of braking and the stopping distance is 225 m. The output slip never reaches the set point. According to the open loop response, the controller must be designed to reduce error and enhance transient responsiveness.

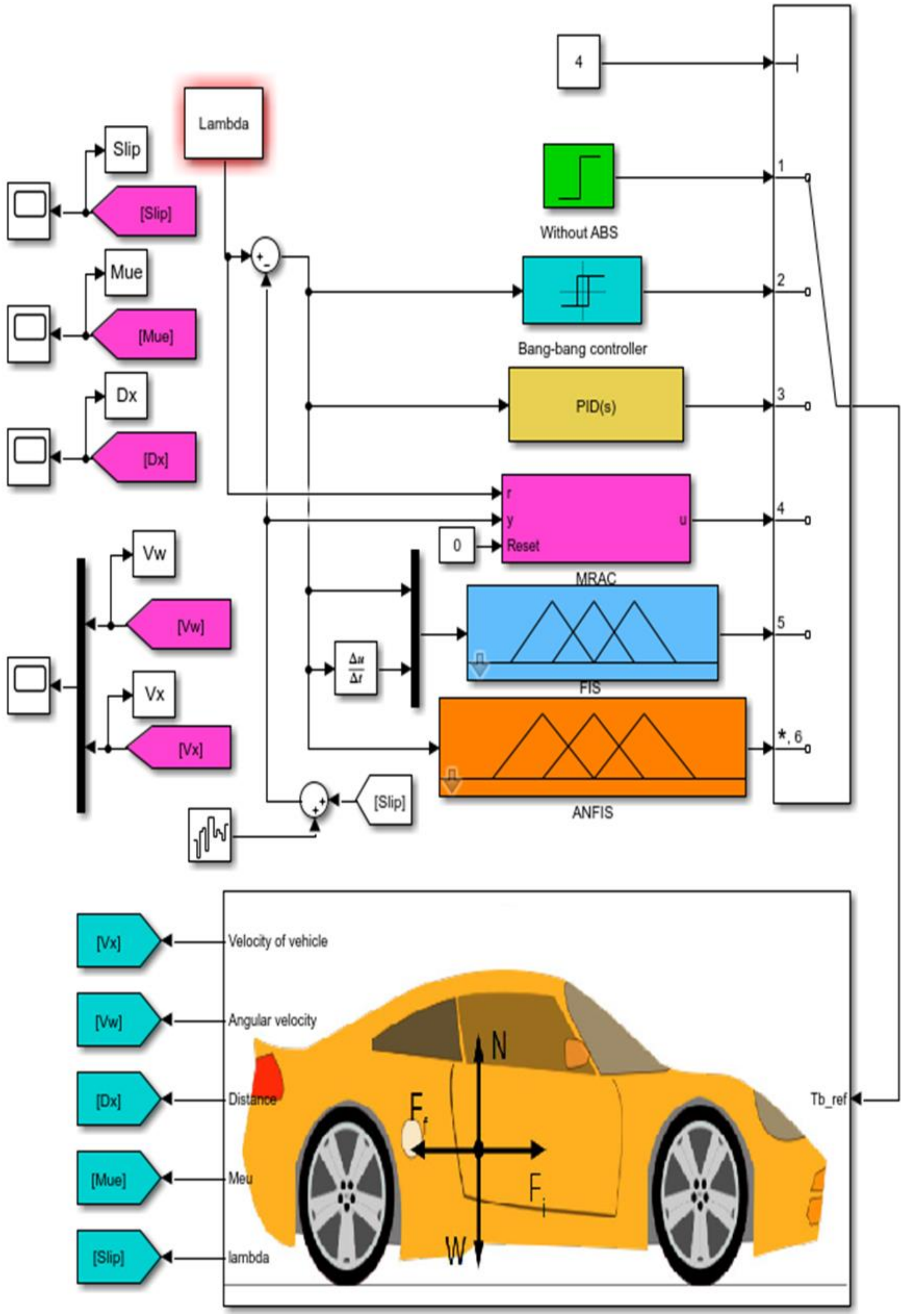


Figure 20. ABS with Different Controllers

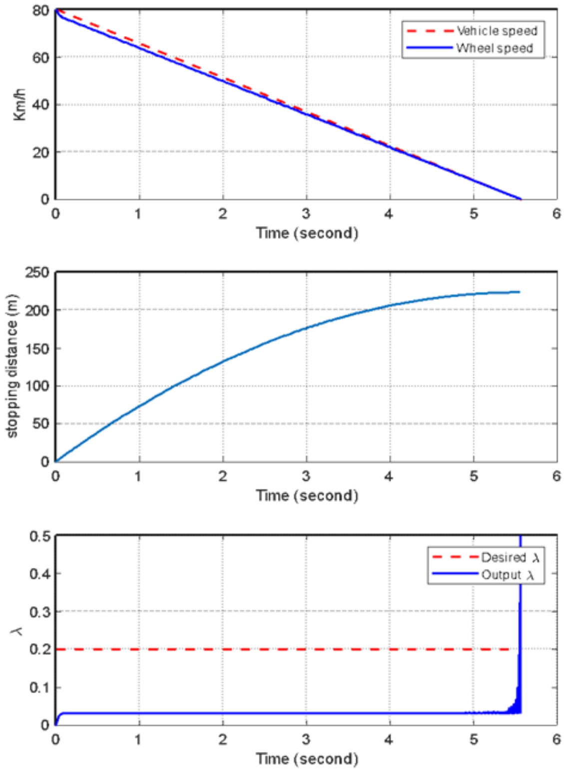


Figure 21. Open loop system without ABS

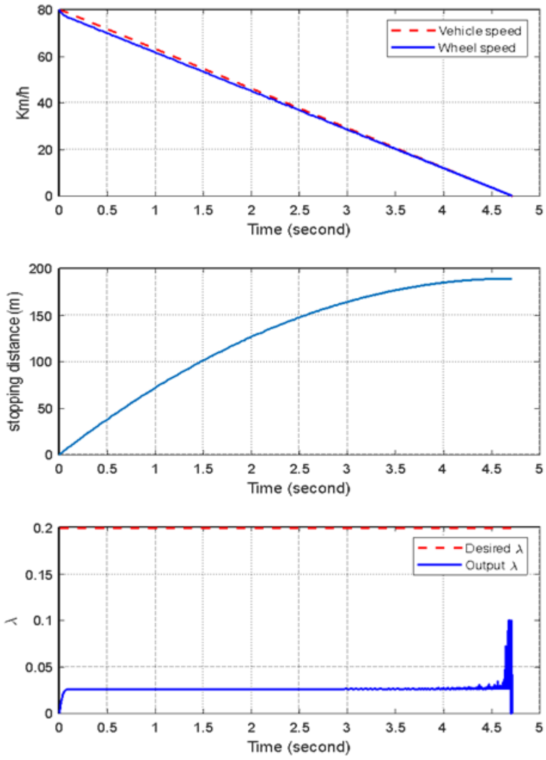


Figure 22. ABS with Bang-bang controller

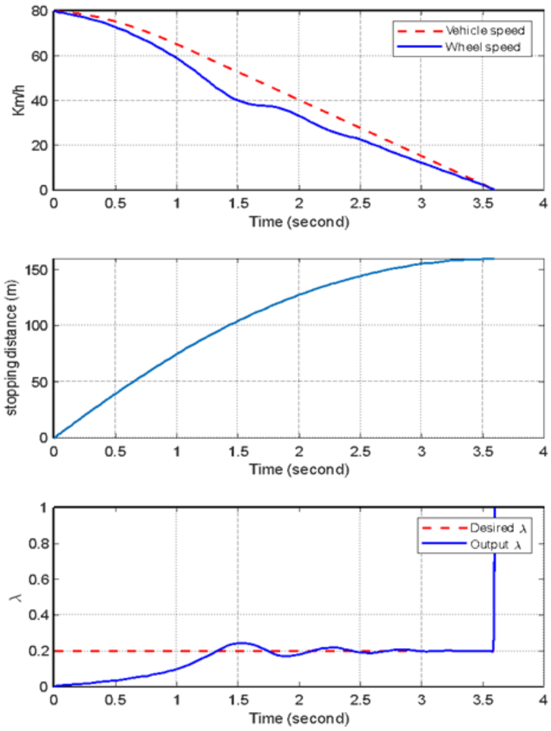


Figure 23. ABS with PID

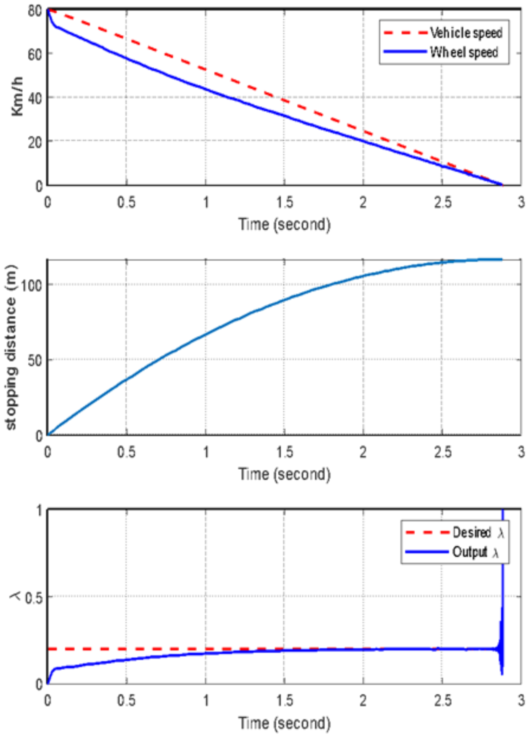


Figure 24. ABS with FLC

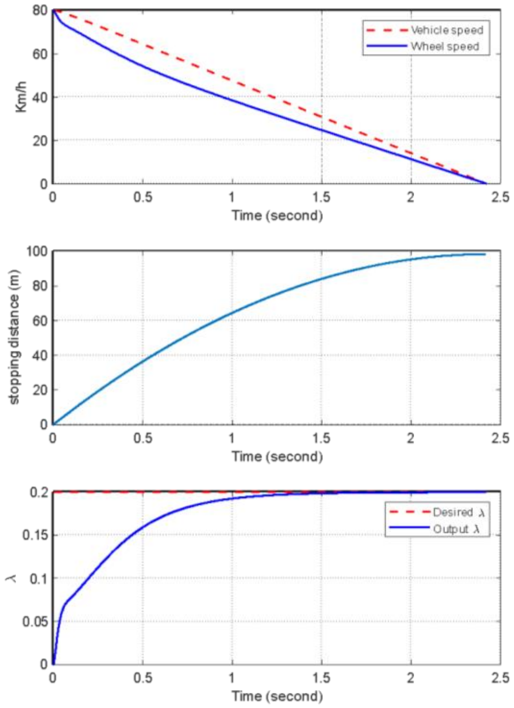


Figure 25. ABS with PID-MRAC

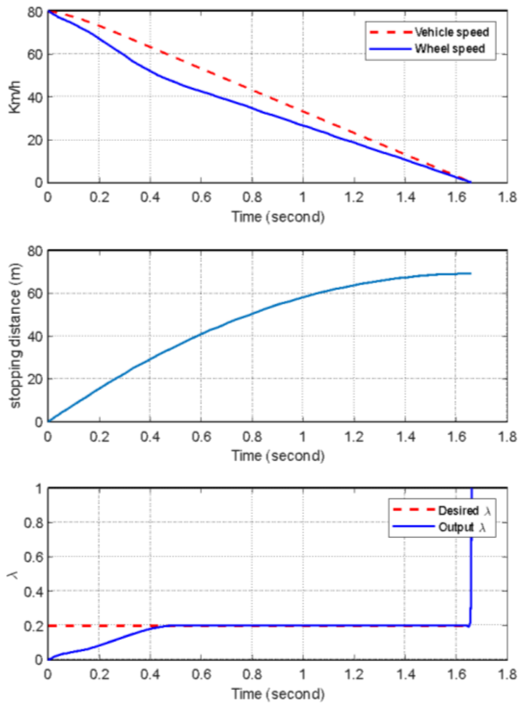


Figure 26. ABS with ANFIS

Figure 22 depicts the vehicle's performance when braking in a straight line with the Bang-Bang controller. This diagram depicts and plots the vehicle velocity and wheel rotational speed, as well as the stopping distance and slip rate as the time proceeds. The stopping distance is lowered to 190 m in 4.7 seconds, but the slide wheel ratio response is not adequate. Figure 23 shows the response of the ABS with PID controller. From the simulation results, the actual slip takes about 1.3 to 3 seconds to settle with the vehicle's required fixed slip. As a result, in the case of a PID controller, the settling time for wheel slip is close to 3 seconds. The automobile comes to a complete stop in 3.6 seconds of braking, with 160 meter stopping distance. Figure 24 shows the response of the ABS with FLC. It is found that by using the FLC controller breaking, the stopping distance is reduced to 110 m at 2.8 s, Also, the specification of the slip response time was within the acceptable range. Figure 25 depicts the ABS's response to the PID-MRAC. With a 100-meter braking distance, the vehicle comes to a complete stop in 2.4 seconds. The response of the ABS with ANFIS is shown in Figure 26. The vehicle comes to a complete stop in 1.6 seconds with a stopping distance 70 meters. The simulation results show that the ANFIS controllers outperform all other designed controllers in terms of slip rate performance. Table 3 presents the comparison of stopping time and distance performance. As a result of the comparisons, we can infer that the ANFIS controller is more resilient and effective than the PID-MRAC, FLC, standard PID control and Bang-bang controller schemes.

Table 3. Braking Time and Distance

ABS Controller	Braking time (Sec.)	Braking distance (m)
Open Loop	5.6	225
Bang-bang	4.7	190
PID	3.6	160
FLC	2.8	110
PID-MRAC	2.4	100
ANFIS	1.6	70

Table 4 present the transient performance of slip wheel for Bang-bang, PID, FLC and ANFIS. As a result, the ANFIS controller was found to be a superior control technique than the standard Bang-bang, PID and FLC.

Table 4. Performance of Slip Rate Wheel

Transient response specification	Bang-Bang	PID	FLC	PID -MRAC	ANFIS
Rise time (Sec.)	-	1.25	1.1	1	0.4
Peak time (Sec.)	-	1.6	1.5	1.3	0.6
Settling time (Sec.)	-	2.5	2.5	2	0.75
Overshoot %	-	10	0	0	0

The parameters of wet asphalt road, c_1= 0.857, c_2=33.822, c_3= 0.347 and c_4=0.04. The parameters of snow-covered road, c_1= 0.1946, c_2=94.129, c_3= 0.06 and c_4=0.04. According to the simulation results of Figure 27 and Figure 28, even if the road state is changed, the ANFIS controller of the ABS designed in this work can accurately judge the road state when the brake is applied and identify the ideal slip to control the car. As a result, it can be used to break in a variety of road conditions and provide outstanding braking performance. Furthermore, the ANFIS controller achieves the most stability for a vehicle, particularly, when the vehicle is under adverse road conditions and the braking distance of the vehicle is reduced. The ANFIS controller is a smart control which can reduce the overshoot system response and accelerate the time response faster to reach a stable condition with zero steady state error. The learning algorithm that is used is backpropagation. It will work by feedforward to get the actual output and work by feedback to get the error value with the target output. Also, the designed neuro-fuzzy controller can work when the implementation for forward wheel speed is between 2500 and 3000 rpm. The slip value that is generated is still within an acceptable range in some road conditions.

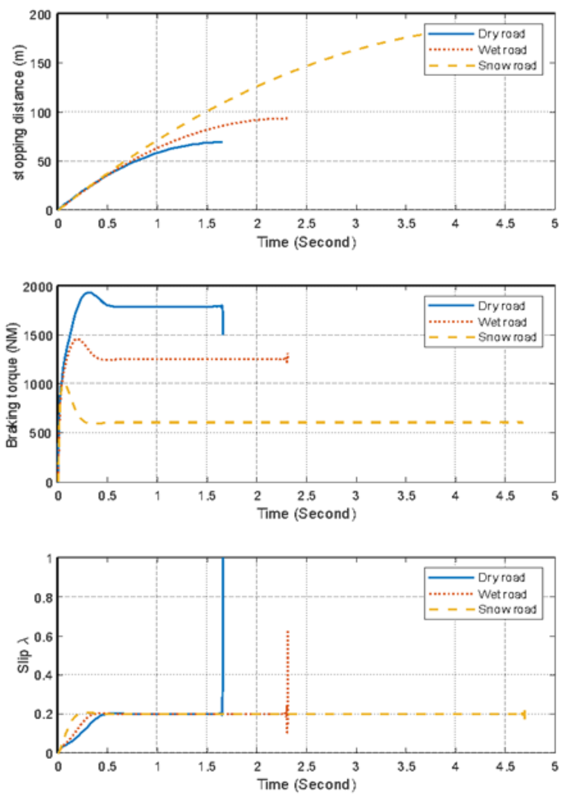


Figure 27. Result of ANFIS controller for different road surface

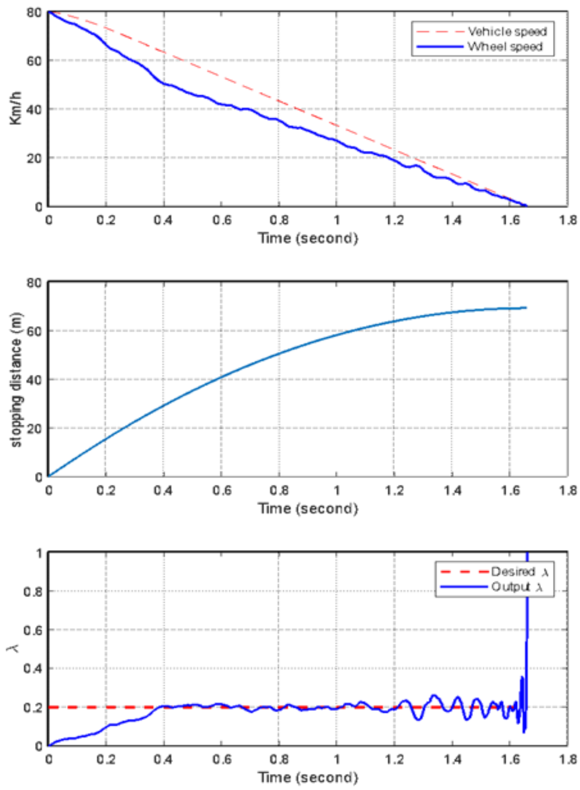


Figure 28. Result of ANFIS controller with increase vehicle wight and presence the disturbance

From the data in Table 5, which is represented in the 3D bar graph in Figure 29, the control design in this paper improves the automobile braking performance compared to the different papers. The stopping time is 1.5 seconds, the stopping distance is 23 m, and the settling time of the optimal slip ratio is 0.4 seconds. Moreover, unlike the other studies, the proposed method was tested in the presence of the disturbance.

Table 5. Breaking performance results for different related studies.

Reference	Mass of the model (Kg)	Settling time of Slip ratio (Sec)	Stopping distance (m)	Stopping time (Sec)	Presence the disturbance
The Proposed Method	300	0.4	23	1.5	Yes
Moaaz 2020 [10]	300	1.6	25	2.4	No
Abd El-Fatah [23]	300	3.5	50	4.5	No
Shah 2020 [24]	300	5	80	10	No
Shewale 2017 [25]	300	14	200	17	No

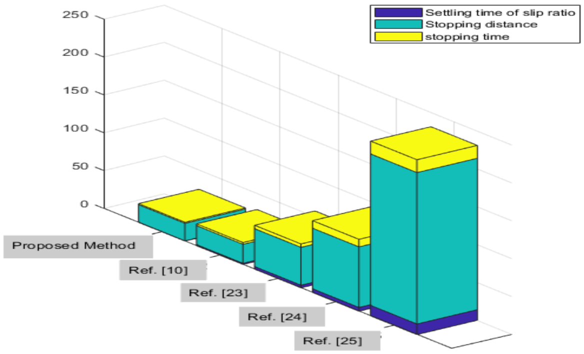


Figure 29. Breaking performance results for different related studies

5. CONCLUSION

The ABS controls and modulates the amount of pressure supplied to the wheels to keep them within the vehicle's stability range. The ABS can minimize vehicle braking distance and improve tire efficiency. A rigorous modeling and simulation study was carried out on a simplified quarter car brake model in straight-line braking, taking the applicable control methods into account. In this work, various control techniques are used to develop an anti-lock braking system (ABS). A comparison study was also carried out amongst all controllers to show the differences in terms of slide rate, stopping time, and stopping distance. Weight, road friction coefficient, road incline, and other nonlinear dynamics can all have a significant impact on antilock braking system efficacy (ABS). Classical control methods may not be able to control this nonlinear system. The Bang-Bang control is not sensitive and has the drawbacks of a weak controller and a limited on/off range. When the slip ratio is large, the conventional PID controller is inefficient since it is a linear controller but the interaction between the tire and the road is highly nonlinear. It also has a significant performance constraint. The PID-MRAC, FLC, and ANFIS are designed to adjust the desired slip ratio value with changes in the road circumstances to maintain a consistent predetermined slip ratio while adapting to the road conditions. The simulation results revealed that the ANFIS method outperformed the Bang-Bang, PID, PID-MRAC, and FLC strategies in managing the ABS. The study also showed that the ANFIS scheme is robust even in the face of disruption. The three control objectives of ANFIS are to improve the performance controlling system on the ABS brake, minimize stopping time, and restrict slip ratio. The simulation results showed that our objectives were met.

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