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Anti-Lock Braking Systems: A Comparative Study of Control Strategies and Their Impact on Vehicle Safety

[1]Gehad Ali Abdulrahman Qasem, [2]Mohammed Fadhl Abdullah

[1]Faculty of Engineering and Computing, University of Science & Technology, Aden, Yemen
[2]Faculty of Engineering, Aden University, Aden, Yemen
Authors E-mail: [1]j.alabadi@ust.edu, [2]al_badwi@hotmail.com

***Abstract* - This study presents a comparative analysis of control strategies designed to enhance the performance of Anti-Lock Braking Systems (ABS) and improve vehicle safety. The research explores three key approaches: First, it evaluates Fuzzy Logic-Controlled ABS, comparing five defuzzification algorithms using MATLAB's Fuzzy Logic Toolbox. Second, it investigates a Neural Network-Based Fault-Tolerant Control strategy, emphasizing improved fault tolerance during braking. Third, it assesses the performance of three ABS controllers—fuzzy logic, bang-bang, and PID controllers. The findings reveal that Fuzzy Logic-Controlled ABS significantly enhances braking performance and directional stability, while Neural Networks demonstrate rapid response and accuracy in generating real-time substitute signals, thereby boosting system reliability. Among the controllers, the PID controller excels in reducing stopping distance and time, though the Fuzzy Logic Controller shows superior control over relative slip, enhancing steerability despite longer stopping distances and times. This comparative analysis provides valuable insights into ABS control strategies and their implications for vehicle safety. Future research should focus on refining ABS algorithms, developing robust fault detection mechanisms, and optimizing controller designs to further advance automotive safety and ABS efficiency.**

Keywords: Anti-lock Braking Systems (ABS), Fuzzy logic, PID, Fault-tolerant control, Braking performance, Neural networks, ABS controllers, Comparative analysis, MATLAB/Simulink.

I. Introduction

In recent years, substantial improvements have been made in automotive technology, particularly in the areas of vehicle stability and passenger safety. Consequently, the integration of multiple safety systems has become vital to prevent driver injuries during normal driving or unexpected braking circumstances [1]. During complete braking, especially in rapid or panic braking conditions, a large braking force is exerted to the wheel's brake cylinder, resulting in wheel lock-up [2]. When a wheel is locked, it loses traction with the road surface, significantly restricting maneuverability and driver control over the wheel's direction [3]. Moreover, the braking distance increases dramatically, greatly increasing the danger of accidents [4]. To overcome this issue, automotive technology designers have concentrated on building efficient braking systems that include numerous components, such as electric, electrical, mechanical, and hydraulic systems. An outstanding device in this arena is the Anti-lock Braking System (ABS), which successfully regulates brake torque to prevent wheel lock-up during braking maneuvers [5]. The development of motor-driven vehicles dates back to 1769, with the occurrence of the first recorded accident in 1770 [6]. Consequently, engineers began working on boosting vehicle safety and lowering driving accidents. Braking system design plays a key part in reaching these goals.

The ABS system is initially designed and produced for the aerospace industry in 1930. Subsequently, ABS implementation expanded to airplanes in the 1950s and to high-end automobiles in the 1960s. In 1972, the first application of ABS in cars was introduced in England [7]. The 1980s witnessed widespread use and implementation of ABS, which is now commonly found in most late-model vehicles and even selected motorcycles [6]. Currently, Anti-Lock Braking System (ABS) technology has become widely established in both cars and motorcycles. It has been mandatory for cars in Europe since 2004 and for motorcycles since 2016. In the automotive sector, the ABS technology can be categorized into two main approaches: switching control logics based on wheel deceleration and wheel slip control [8], which represents the state-of-the-art in ABS technology.

ABS system also known as anti-skid braking system (ABS)is an automobile safety system that allows the wheels on a motor vehicle to maintain tractive contact with the road surface according to driver inputs while braking, preventing the wheels from locking up and avoiding uncontrolled skidding [9]. ABS systems employ numerous control mechanisms to regulate brake pressure and distribute force across the wheels to achieve optimal performance, reduce braking distance, and enhance response time. The modern abs system allows steering during braking which gives more control over the vehicle in case of sudden braking. ABS is designed to ensure that braking pressure is not instantly applied to rotating wheels as this could result to locking and skidding of wheels [10]. Where, the primary advantages of employing ABS system in vehicle are that it provides better control over the vehicle and minimizes stopping distance on dry and slippery conditions. Since with ABS fitted car the chance of skidding is very minimal and consequently it provides a superior steering control during braking. Without ABS technology, even a professional driver can fail to prevent the skidding of the vehicle on dry and slick roads during rapid braking. But with ABS technology, a typical person can easily prevent the skidding of the vehicle and acquire superior steering control during braking [11].

The main motivation for conducting this study is to understand and evaluate the various control methods employed in the ABS system of vehicles, share their benefits, and analyze their performance and effectiveness in a comparative manner. By exploring and analyzing the comparative aspects of the control methods used in ABS, the study can shed light on the advantages, limitations, and constraints associated with each control technique. This understanding can contribute to the improvement of future ABS system design and development, as well as enhance vehicle performance and safety.

II. Research Methodology

In this study, a general review of the anti-lock braking system (ABS) for vehicles is undertaken. Additionally, it will apply a comparative analysis research approach to examine and evaluate various control systems employed in ABS system. The comparative study would comprise the systematic comparison of different control approaches to measure their performance and efficacy in achieving optimal braking performance and enhancing vehicle safety. Based on three research papers that utilized different techniques for control units applied to the ABS system, these control units include Bang-Bang control, PID control, fuzzy logic control, and neural networks. The remainder of this paper is structured as follows:

- Provide a detailed explanation of the anti-closure brake system (ABS).
- Verification of various control units applicable to ABS.
- It provides a quantitative and qualitative comparison of these ABS control units.
- It gives an analysis of ABS controls in quantitative and qualitative terms.
- Finally, it presents the most important results reached by these studies.

III. The Forces Acting on a Vehicle

There are two types of brakes used in cars: drum brakes and disk brakes. Drum brakes generate braking force on the inner surface of a brake drum. While disk brakes generate braking force on the surface of a rotating brake disk. Both types generate braking force by pressing brake pads or shoes against a rotating surface (drum or disk) connected to the wheels. The demands placed on the brakes are extremely exacting and include short braking distance, fast response time, precise control, resistance to dirt and corrosion, high reliability and durability, resistance to wear, and ease of maintenance. Forces are necessary for the motion and direction change of a body. When a vehicle is in motion, various forces act upon it. Tires play a crucial role as any change in speed or direction involves forces acting on them. In braking situations, the brake force is considered the primary force for deceleration. Other forces also contribute to partial deceleration.

The forces acting on a vehicle include [5]:

- **Theory of inertia:** Bodies tend to maintain their state of rest or motion.
- **Turning forces:** Rotating bodies are influenced by turning forces, such as the rotation of the wheels.
- **Distribution of forces:** Various types of forces act on the vehicle regardless of its motion state.
- **Tire forces:** Tire forces are the forces that affect the wheel's performance, including circumferential force, vertical tire force, and lateral force. These forces are influenced by factors such as braking torque, friction force, and sideways forces. The lateral-force coefficient is the relationship between the lateral force acting through the wheel's center and the wheel contact force.

These include forces along the longitudinal axis (e.g., motive force, aerodynamic drag, rolling friction) and forces laterally (e.g., steering force, centrifugal force during cornering or crosswinds). These forces are transmitted to the tires and then to the road through the chassis, steering, engine and transmission, and braking system.

IV. Anti-Lock Braking System (ABS)

The anti-lock braking system controls the longitudinal slip of the wheels to generate the maximum braking and prevents the wheels from becoming locked [12].

4.1 Objectives of Antilock braking systems

As mentioned earlier, the antilock braking system (ABS) is specifically designed to prevent the wheels of a vehicle from locking up during braking, thus ensuring better control and stability [9].The benefits of ABS implementation are reducing the stopping distances, improving stability, and enhancing steer-ability during braking [9].

4.2 Principles of operation of the anti-lock braking system (ABS)

The principles of operation of the Anti-Lock Braking System (ABS) are as follows:

- **Wheel speed sensors:** The speed sensors are responsible for measuring the rotational speed of each wheel and operate based on the principle of electromagnetic induction [13].
- **Electronic control unit (ECU):** The ECU is that receives, filters, and amplifies sensor signals in order to calculate the rotational speed and acceleration of the wheels. The electronic control unit receives signals from the sensors in the ABS system and adjusts the brake pressure based on the received information [14].
- **The Hydraulic Control Unit (HCU):** The HCU is a control unit that operates based on signals received from the Electronic Control Unit (ECU). Its main function is to apply or release the brakes in order to prevent the wheels from locking up during braking. The HCU is composed of various components, including solenoid valves, an accumulator, and a pump.
- **Monitoring and Feedback:** ABS continuously monitors the wheel speed and brake pressure to ensure effective operation. It provides feedback to the driver through the brake pedal pulsation or by activating a warning light on the instrument panel if a fault is detected [13, 14].

4.3 Working of ABS

ABS work by monitoring the rotational speed and acceleration of each wheel using sensors. When a wheel lock-up is detected, the Electronic Control Unit (ECU) sends a signal to the hydraulic unit, which releases brake pressure to prevent the wheel from locking up. Once the wheel speed increases, the brake pressure is reapplied to maintain optimal control. The Hydraulic Control Unit (HCU) controls the hydraulic brake pressure to each wheel based on sensor inputs, ensuring proper wheel speed control.

4.4 Mathematical modeling

Developing a control algorithm for the antilock braking system begins with the crucial task of mathematical modeling [15]. This modeling, along with simulation, offers valuable insights into braking phenomena and the influence of various parameters on a vehicle's braking performance. The primary purpose of Anti-lock braking systems (ABS) is to regulate wheel slip and maintain the friction coefficient at an optimal level. Wheel slip refers to the relative motion between a wheel (tire) and the road surface while the vehicle is in motion. It happens when the angular speed of the wheel (tire) deviates from its free-rolling speed, either exceeding or falling below it, [16]. Commonly used vehicle models include the general vehicle model, four-wheel vehicle model, two-wheel vehicle model, and single-wheel vehicle model. The vehicle dynamic model is inherently complex and challenging to derive directly from the fundamental physical model, especially considering the highly nonlinear and time-varying nature of ABS dynamics. To streamline the simulation of vehicle braking dynamics, the single-wheel dynamic model is often employed for simulating vehicle braking dynamics [15], [17]. In this work, we will utilize simplified mathematical models, specifically the quarter-car model, for both the vehicle and the wheel. This model effectively describes the braking performance and facilitates the analysis of automobile ABS braking performance while also simplifying certain issues [15]. A comprehensive mathematical model of ABS comprises four components: vehicle dynamics, tire, brake system, and control system.

4.4.1 Dynamic Model

To understand the braking system, one can analyze the vehicle dynamics, including lateral, longitudinal, and vertical aspects, as well as the associated power train systems. However, because longitudinal dynamics are the predominant direction of braking movement, this article concentrates primarily on them. As a result, the suspension system, weight transfer between wheels, and lateral forces are not considered in this research. It is assumed that the wheels are dynamically decoupled, that all wheels are on the same road, and that the vehicle brakes in a straight line to a complete stop. Aerodynamic forces have little influence, and the connection between the wheel and the road is rigid. Throughout the braking process, the wheel radius remains consistent, ensuring that the vehicle's braking system is well-understood and effective.

4.4.2 Vehicle Dynamics Model

The free body diagram of a quarter vehicle model, depicted in Figure1, describes the vehicle's longitudinal motion and the wheel's angular motion during braking. Although the model is general, it adequately captures the fundamental characteristics of the actual vehicle system [18], [19].

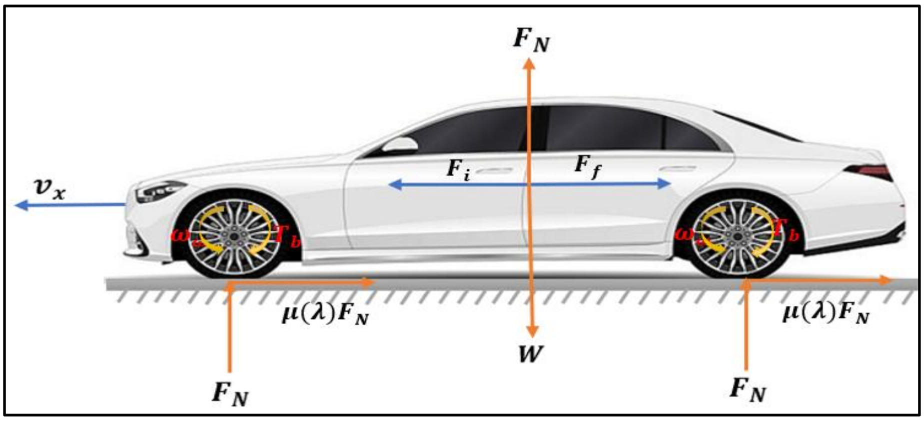

Figure 1: Acting forces during vehicle braking

According to Newton's second law, equation of motion of the simplified vehicle can be expressed by,

$$m_v \times \dot{v}_x = -F_f - F_a \qquad (1)$$

Where; v is vehicle velocity, $\mathbf{F_f}$ is the friction force between wheel and ground, $\mathbf{F_a}$ is aerodynamic force acting on the vehicle, $\mathbf{m_v}$ is total mass of the quarter vehicle. If we consider a vehicle moving in a straight direction under braking conditions, we can write the equations of equilibrium:

- From translational motion:

$$\sum ʃ_x = 0 \Rightarrow F_f - F_i = 0 \Rightarrow F_f = F_i \Rightarrow ʃ_x = m_v \times \dot{v}_x = \mu \times F_N \qquad (2)$$

$$\dot{v}_x = -\mu \frac{F_N}{m_v} \qquad (3)$$

Where, $\mathbf{F_i}$ is the inertial force of the vehicle.

- From rotational motion:

$$\sum f_y = 0 \Rightarrow F_N - W = 0 \Rightarrow F_N = W \qquad (4)$$

The road friction force is given by Coulomb law:

$$F_f = -\square \times F_N \qquad (5)$$

Where; F_N is normal force (total normal load), and μ is the coefficient of friction.

The vehicle's weight is:

$$W = m_v \times g \qquad (6)$$

Then,

$$\mathrm{F_f} = -\square \times m_v \times g \qquad (7)$$

Where, **g** is the gravitational acceleration.

The inertia force is the product between the vehicle mass $\mathbf{m_v}$ and vehicle acceleration a_x:

$$F_i = m_v \times \dot{v}_x = m_v \times a_x \qquad (8)$$

To extract the expression of the vehicle acceleration, the equation above can be rewritten in the next form by substitute in equation no.

$$\dot{v}_x = \frac{1}{m_v}(-\square \times m_v \times g) = -\square . g \qquad (9)$$

$$\text{If} \qquad \mu = a.\left(1 - c\mu - e^{-\lambda b}\right) \qquad (10)$$

$$\text{Then,} \quad \dot{v}_x = -g \times a\left(1 - c\mu - e^{-\lambda b}\right) \qquad (11)$$

To find the equation of vehicle speed, we integrate of previous equation.

4.4.3 Wheel Dynamics Model

In order to acquire a deeper comprehension of the issue of wheel slip control, we can analyze a quarter vehicle model that exclusively drives in the longitudinal direction, as depicted in Figure2, [20]. This model depicts a solitary wheel supporting one-fourth of the total mass (m_v) of the vehicle. Although it does not encompass all the dynamic elements such as nonlinearity and unknown parameters, it accurately depicts the underlying physical traits and dynamics of the braking system, offering valuable insights into its core behavior.

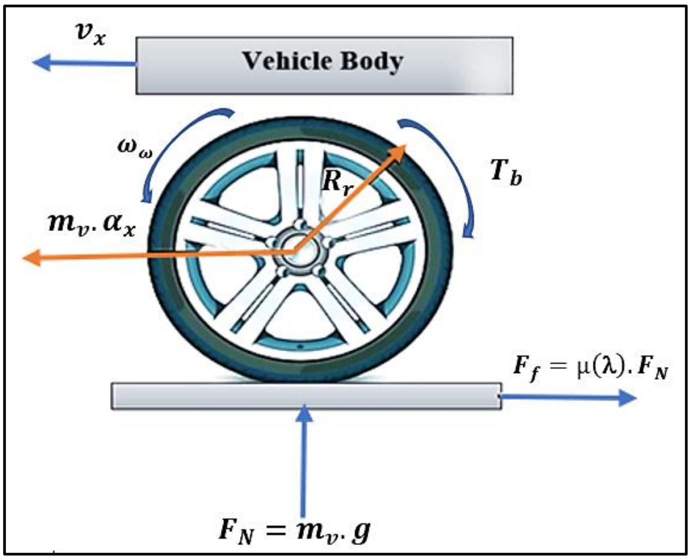

Figure 2: Quarter vehicle dynamics

The tire-wheel system is modeled by analyzing the wheel's movement, as shown in Figure 2. During braking, the driver applies a braking torque (T_b) through the braking system, with a radius (r) and moment of inertia (J_w), resulting in a direct reduction in the wheel's angular velocity (ω_w). The friction force (F_t) between the wheel and the road generates an opposing torque with a radius (R_r). For simplicity, we assume that the wheel is rigid, and the normal force (road reaction) passes through the wheel hub, thus not contributing an additional torque. Applying Newton's laws to the free body diagram depicted in Fig. 3, so, equilibrium equation can be drive as:

$$\sum M = \omega_w = J_w \times \alpha_x = R_r \times \mu \times F_N - T_b \qquad (12)$$

$$\dot{\omega}_w = \frac{1}{J_w}(R_r \times \mu \times F_N - T_b) \qquad (13)$$

Wheel Slip

The ABS system is responsible for regulating the wheel slip (s) to maintain it around an optimal target. The wheel slip is determined using the following calculation:

$$\delta = 1 - \frac{\omega_w}{v_x} \qquad (14)$$

Where, ω_w is the equivalent angular speed of the vehicle, equal with:

$$\omega_w = \frac{v_x}{R_r} \qquad (15)$$

V. Slip Ratio

The slip ratio is a crucial parameter in vehicle dynamics as it quantifies the slip of each wheel. It plays a fundamental role in understanding the relationship between wheel deformation and longitudinal force. Additionally, it is of significant importance in wheel anti-lock systems [19]. Under normal conditions [20], the vehicle maintains a proportional relationship between its linear velocity and the wheel's angular velocity. However, during braking, this correlation is disrupted as the brake torque reduces the wheel velocity. In some cases, the wheel may lock, resulting in frictional forces between the tire and the road, while the vehicle maintains its linear velocity due to inertia.

The slip ratio (λ) represents the disparity between the vehicle's linear velocity and the wheel's angular velocity and can be calculated as follows:

$$\lambda = \frac{v_x - R_r \times \omega_w}{v_x} = \qquad (16)$$

Differentiating the equation above with respect to time (t), get:

$$\dot{\lambda} = \frac{\dot{v_x} \times (1 - \lambda) - R_r \times \dot{\omega_w}}{v_x} = \qquad (17)$$

5.1 Tire Model

The tire plays a crucial role in introducing nonlinearity to the vehicle dynamics as the forces generated in the tire directly impact its motion. Numerous studies have been conducted to determine the friction coefficient in various dynamic systems [19].

5.2 Friction Force

When braking torque is applied to a wheel, a braking force $\mathbf{F_B}$ is generated between the tire and the road surface that is proportional to the braking torque under stationary conditions (no wheel acceleration). The braking force transmitted to the road (frictional forceF_R) is proportional to the vertical tire force F_N:

$$F_R = \mu_{HF} \times F_N \qquad (18)$$

The factor μ_{HF} is the coefficient of friction.

5.3 Coefficient of Friction

The coefficient of friction determines the maximum braking force that can be transmitted. It can vary significantly across different conditions. Several factors influence the friction coefficient between the wheel and the road, including weather conditions, environmental factors (humidity, temperature), road surface conditions (dry, wet), tire condition, vehicle speed, tire side-slip angle, and the slip ratio between the tire and the road. The coefficient of friction for motor-vehicle tires reaches its peak on clean and dry road surfaces, while it is lowest on icy surfaces. On wet roads, the coefficient of friction is greatly influenced by the vehicle's speed. ABS safety systems aim to maximize available traction [21].

VI. Technologies Applied to the Anti-Lock Braking Systems (ABS)

In recent years, many researchers have applied various techniques to Anti-Lock Braking Systems (ABS) in order to improve control over vehicle brakes and reduce accidents. Among the modern techniques that researchers have used and implemented in ABS systems are Fuzzy Logic systems (FL), Neural Networks (NN), Fault Tolerant Control (FTC) and PID Control.

6.1 Fuzzy logic

Fuzzy logic (FL) is a powerful approach for precise control, incorporating uncertainty and capturing aspects of natural language meaning. It uses fuzzy sets to handle flexible reasoning and accommodate situations beyond binary true or false. The three main components of fuzzy logic are fuzzification (converting crisp inputs into fuzzy sets), inference (applying fuzzy logic rules to produce fuzzy outputs), and defuzzification (converting fuzzy outputs into crisp outputs). Defuzzification methods include the centroid method, weighted average method, maxima method, and area open method. Figure 3 shows a framework for fuzzy logic systems [22, 23].

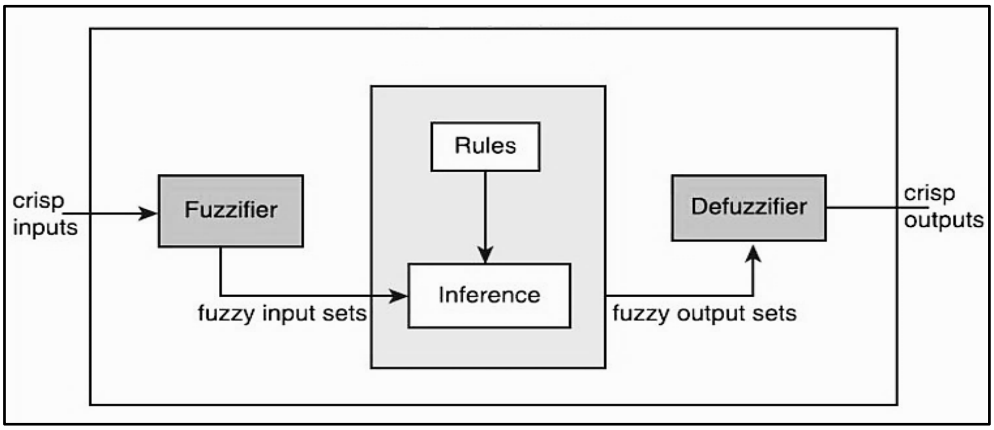

Figure 3: A framework for fuzzy logic systems

The work conducted by [13] investigated the performance of an Anti-lock Braking System (ABS) based on fuzzy logic used and compared different defuzzification methods (centroid, bisector, MoM, LoM, and SoM). The objective is to enhance braking performance and directional stability compared to traditional ABS approaches. The results of comparing the defuzzification methods were calculated and presented in a waveform. Based on these results, the authors reached that the centroid and bisector methods demonstrate similar brake performance in terms of brake values, while the Mean of Maxima (MoM), Largest of Maxima (LoM), and Smallest of Maxima (SoM) methods are less suitable for fuzzy control applications. The LoM method yields the highest results, while the SoM method yields the lowest results. The figure 4 shows the results of defuzzification methods.

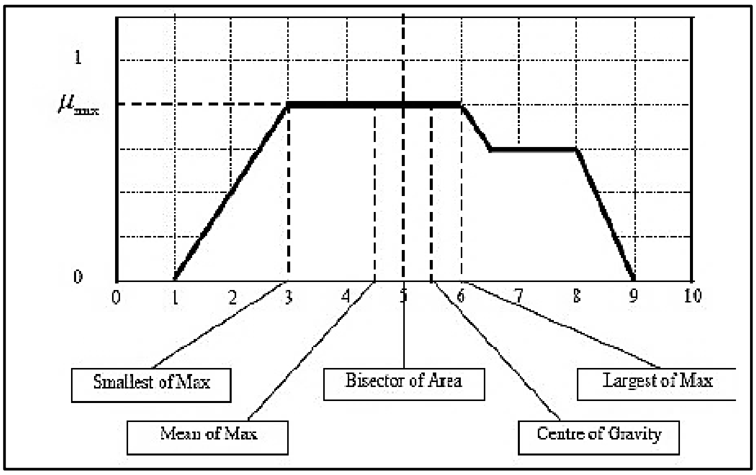

Figure 4: Results of defuzzification methods [13]

6.2 Neural Networks (NNs) and Multi-Layer Perceptron (MLP)

A Neural Network (NN) is a computational model inspired by the human brain, consisting of interconnected artificial neurons organized in layers. These layers include an input layer, one or more hidden layers, and an output layer [24]. The network learns by adjusting the weights of connections between neurons based on training data. During inference, the network processes new input signals and generates an output. Neural networks excel at extracting information and patterns from complex data and can perform tasks like classification, prediction, and data analysis. There are different types of neural networks, including feed-forward, convolutional, recurrent, and radial basis function networks, each with specific applications. In a recent study conducted by[5], an active Fault Detection and Isolation (FDI) and Fault Tolerant Control (FTC) method was employed to identify and mitigate potential faults in an ABS speed sensor. Data constructor models using a Neural Network based on Multilayer Perceptron (MLP) were implemented to generate alternative signals for both ABS speed sensors. The Multi-Layer Perceptron (MLP) is a widely used type of neural network. It consists of nodes, also known as neurons or network units, as depicted in Figure 5. Each unit is represented by a circle, and the connections between them are referred to as weights or links. The MLP can be seen as a mathematical mapping between a set of input variables (x_m, where m ranges from 1 to M) and a set of output variables (y_n, where n ranges from 1 to N).

The relationship between the inputs and outputs is defined by an output equation.

$$y_n(x_1, x_2 \dots x_m) = \sum_{l=1}^{L} \widehat{\omega}_{nl}\, f\left(\sum_{m=1}^{M} \omega_{lm} x_m + \theta_l\right) + \hat{\theta}_n \tag{19}$$

Where; ω is link weight, θ an offset value, and f is a nonlinear transformation function called an activation function.

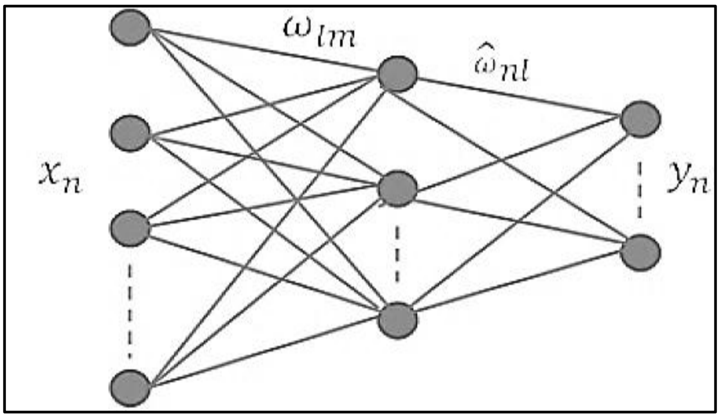

Figure 5 : RFC (M) versus LWS (λ) [5]

Alternative signals served two purposes: generating residual signals for fault detection and substituting isolated faulty signals. Residual signals are derived by computing the discrepancy between alternative constructed signals and their corresponding actual signals. These residual signals serve as indicators of fault occurrence and severity. If a fault is identified and diagnosed in a sensor's signal, the faulty signal is isolated and replaced with the corresponding constructed signal, ensuring the system functions properly despite the fault. This methodology incorporates efficient Curve Fitting (CF) principles facilitated by Neural Networks (NNs) for rapid data processing. Two identical MLP network models, the Wheel Speed Constructor (WSC) and Vehicle Speed Constructor (VSC) models, were constructed and trained to generate wheel speed and vehicle speed data, respectively. As illustrated in Figure 6 and Figure 7. The input layer of (WSC) model is composed of vehicle speed data (Vs) and the rate of change of vehicle speed (dV/dt), while the output layer represents the wheel speed data (ωs). The input layer of (VSC) model is composed of wheel speed data (ωs) and the rate of change of wheel speed ($d\omega/dt$), while the output layer represents the vehicle speed data (Vs) [5].

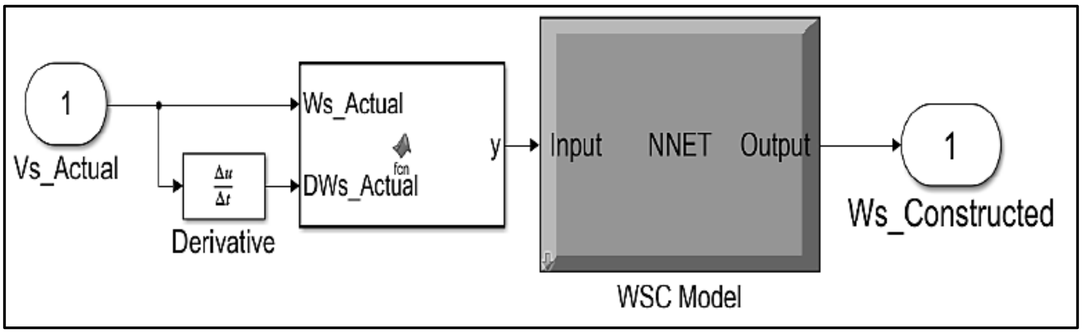

Figure 6: WSC data construction model [5]

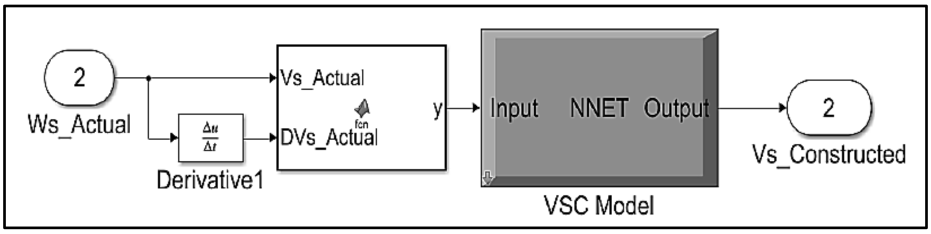

Figure 7: VSC data construction model [5]

Experimental tests were conducted with various initial speeds below the maximum limit of 130 km/h, recording vehicle speed data, the rate of change of vehicle speed, wheel speed data, and the rate of change of wheel speed. The constructed speed signals were compared to the actual speed signals, showing a perfect agreement despite the decrease in actual speed during braking. The performance of the trained models was evaluated in both faulty and fault-free conditions, demonstrating accurate responses and fulfilling their intended purpose, especially in the presence of faults. However, despite the overall advantage, a challenge arises when a fault occurs, as the faulty signal is used to construct the corresponding signal for the other sensor, leading to potential inaccuracies and false fault occurrences. To overcome this issue, an additional method should be implemented to prevent the faulty signal from being used by its associated data constructor, thereby avoiding false fault detection alerts. Resolving this problem is crucial for ensuring the reliability and effectiveness of the fault detection and isolation system. The results demonstrate that these models effectively map the measured data to the desired output using optimal functions. The rapid response of the trained models makes them well-suited for generating real-time alternative signals for fault-tolerant applications in speed sensors, particularly during intense or emergency braking scenarios [5].

6.3 PID Controller

A PID (Proportional-Integral-Derivative) controller is a widely used feedback control mechanism in engineering and industrial applications. It aims to regulate a system's behavior by continuously adjusting an output variable based on the error between the desired set point and the actual measured value. The PID controller combines three control actions: proportional control, which produces an output proportional to the error; integral control, which integrates the error over time to eliminate steady-state errors; and derivative control, which predicts the future error trend based on the rate of change. By dynamically adjusting the weights of these control actions, the PID controller can achieve stability, responsiveness, and improved control performance in various systems, such as temperature, speed, and position control. It is a versatile and widely implemented control technique due to its simplicity, effectiveness, and adaptability to various control scenarios. The figure 8 shows the installation of the PID controller [25, 26].

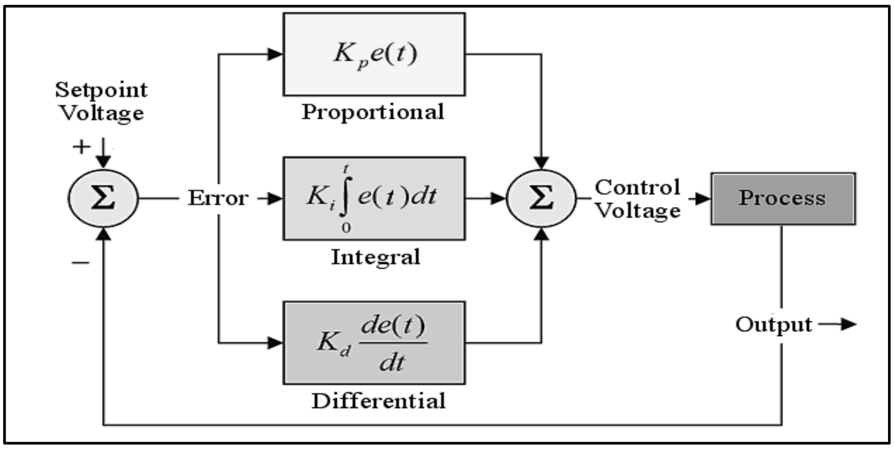

Figure 8: Block diagram of PID

In the study conducted by [21], researchers developed and simulated a mathematical model of an Anti-Lock Braking System (ABS) using bang-bang controllers shown in the figure 9, fuzzy logic controllers shown in the figure 10, and PID controller shown in the figure 11. The objective was to regulate the braking force applied at different time intervals, taking into account parameters such as relative slip, road condition, and coefficient of friction between the road and tire.

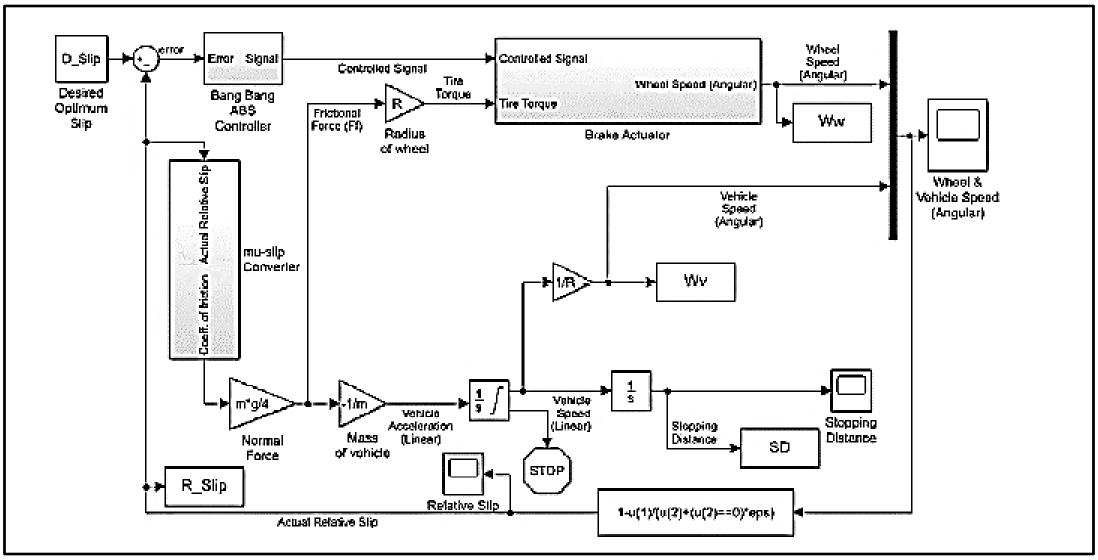

Figure 9: Block diagram of ABS control system using bang-bang controller [21]

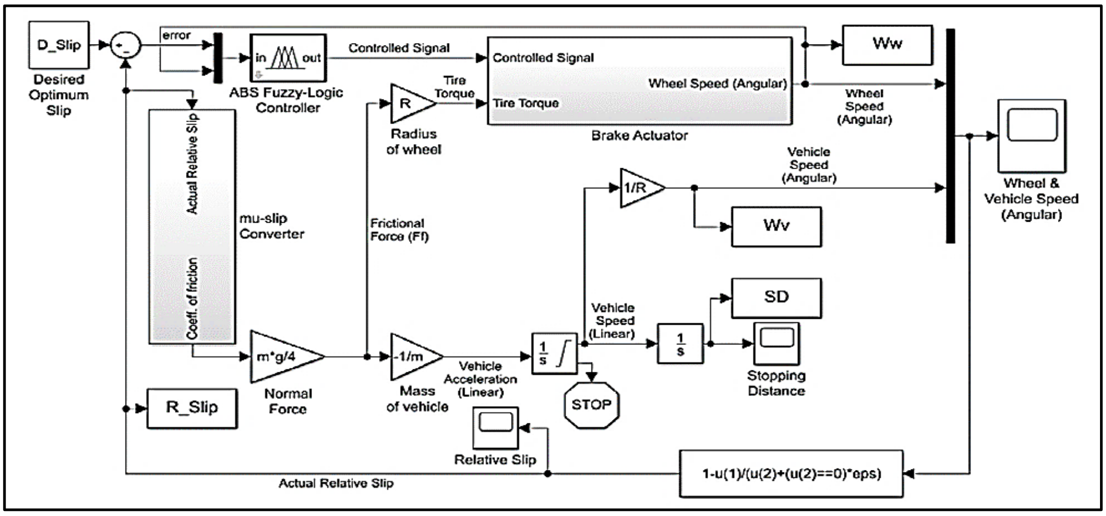

Figure 10: Block diagram of ABS control system using fuzzy logic controller [21]

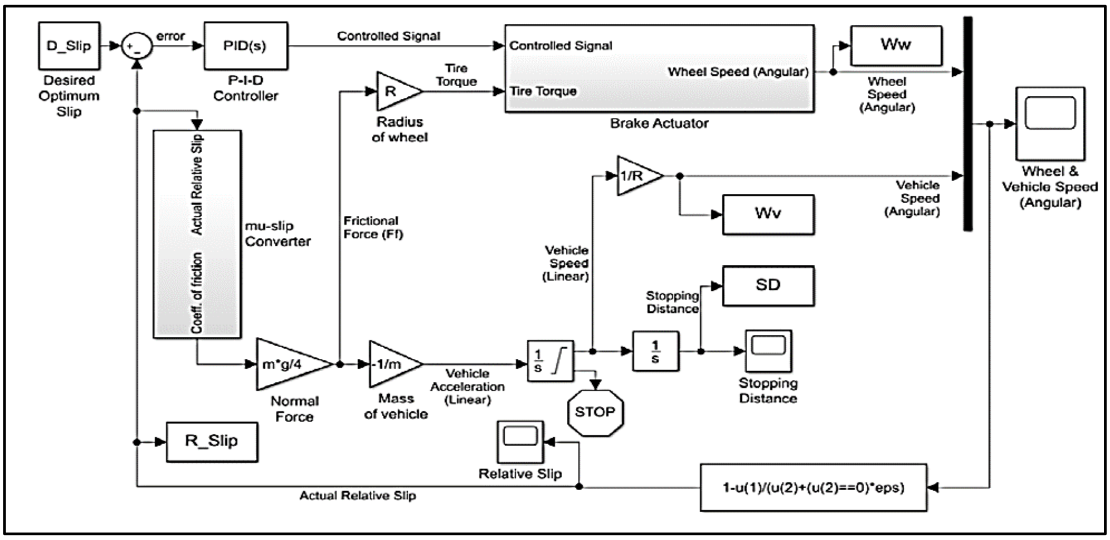

Figure 11: Block diagram of ABS control system using PID controller [21]

The simulations were performed in the MATLAB/Simulink environment. Where, the measurements collected in the study included the stopping distance and stopping time of the vehicle under different controller configurations. A comparative analysis was conducted to evaluate the performance of each controller and determine the most effective one for simulating the Anti-Lock Braking System (ABS). The simulation results were compared between models utilizing fuzzy logic and PID controllers, as well as models using a Bang-Bang controller and no controllers. The presence of controller's yielded superior performance for the Anti-Lock Braking System (ABS) compared to the absence of controllers. When considering the stopping distance and stopping time during braking, the PID controller demonstrated superior performance compared to the fuzzy logic and Bang-Bang controllers for ABS implementation in a vehicle.

The Bang-Bang controller resulted in a shorter stopping time but increased wheel speed fluctuations, indicating repeated locking and releasing of the wheels. However, it still proved more effective than having no controllers for ABS application. While the Fuzzy Logic controller exhibited higher stopping distances and times compared to the PID and Bang-Bang controllers, it showcased improved control over relative slip, leading to enhanced steerability. Fine-tuning input parameters or adjusting membership functions can enhance the performance of the fuzzy logic controller [21,22, 24].

The relative slip curves demonstrated smooth ascending trends for the absence of controllers and the fuzzy logic controller, while they exhibited fluctuations for the Bang-Bang and PID controllers. This suggests that the fuzzy logic controller and the absence of controllers offer superior control over vehicle steerability and stability. Nevertheless, the Bang-Bang and PID controllers still displayed some compromises in these parameters, although not entirely absent [21].

VII. Conclusion

Developing Anti-lock Braking Systems (ABS) involves intricate processes encompassing mathematical modeling, dynamic analysis, and simulation. While theoretical designs may appear straightforward, their practical implementation demands extensive research and effort. This paper has undertaken a comparative analysis of three studies, each focusing on enhancing ABS through distinct methodologies.

In the first study, the evaluation of ABS performance employing fuzzy logic with various defuzzification methods revealed promising results, particularly with centroid and bisector techniques. Future investigations aim to build upon these findings for further improvement. The second study introduced a Fault-Tolerant Control (FTC) mechanism using Neural Networks (NN) for ABS speed sensors, demonstrating effectiveness in fault detection. However, challenges persist in accurately isolating faulty signals to prevent false alerts, necessitating additional methods for refinement. The third study assessed ABS performance with different controllers, with the PID controller emerging as the most effective in terms of stopping distance and time. While the Fuzzy Logic Controller offered improved steer-ability, the PID controller showcased superior performance in braking efficiency.

In conclusion, this comparative analysis sheds light on the multifaceted approaches to ABS optimization, emphasizing the need for continued research and innovation to ensure the utmost safety and efficiency in automotive braking systems.

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AUTHORS BIOGRAPHY

Gehad Ali Abdul Rahman Qasem was born on January 1, 1988, in Halmeen-Lahj. He completed his secondary education at Halmeen Model School. He earned his Bachelor's degree in Electronics – Electro-techniques - Mechanisms from Farhat Abbas University in Algeria in 2014, and later obtained his Master's degree in Embedded Electronic Systems from the same university in 2017. He can be contacted at e-mail: j.alabadi@ust.edu

Mohammed Fadhl Abdullah is currently a Professor of Computer engineering in Faculty of Engineering at Aden University in Yemen. He received his Master and PhD degrees in Computer Engineering from Indian Institute of Technology, Delhi, India, in 1993, and 1998. He was the editor-in-chief of Aden University Journal of Information Technology (AUJIT). He is a founding member of the International Center for Scientific Research and Studies (ICSRS). His main research interests are in the fields of Machine learning, Parallel algorithms, and Cybersecurity. He can be contacted at e-mail: al_badwi@hotmail.com, or m.albadwi@ust.edu

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