International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 1, February 2025, pp. 260~279
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i1.pp260-279

Adaptive control techniques for improving anti-lock braking system performance in diverse friction scenarios

Mohammed Fadhl Abdullah[1], Gehad Ali Abdulrahman Qasem[1], Mazen Farid[2,3,4], Heng Siong Lim[2], Chin Poo Lee[3], Nasr Alsakkaf[1]
[1]Faculty of Engineering and Computing, University of Science and Technology, Aden, Yemen
[2]Faculty of Engineering and Technology, Multimedia University, Melaka, Malaysia
[3]Faculty of Information Science and Technology, Multimedia University, Melaka, Malaysia
[4]Department of Computer Science, Faculty of Education, Lahij University, Lahij, Yemen

Article Info

Article history:

Received May 22, 2024
Revised Sep 6, 2024
Accepted Oct 1, 2024

Keywords:

Anti-lock braking systems
Friction coefficients
Simulation
Stability
Stopping distance
Vehicle dynamics
Wheel slip

ABSTRACT

Anti-lock braking systems (ABS) enhance vehicle safety by preventing wheel lock-up, but their effectiveness depends on tire-road friction. Traditional braking systems struggle to maintain effective performance due to the risk of wheel lock-up on varying road surfaces, affecting vehicle stability and control. This study presents a novel method to improve ABS efficiency across varying friction conditions. The proposed approach employs a feedback control mechanism to dynamically adjust the braking force of each wheel based on the prevailing friction coefficient. Specifically, we incorporate a P-controller in the input signal and two additional P-controllers as output and input parameters for friction. By manipulating the proportional control values, key parameters such as wheel speed, stopping distance, and slip rate can be effectively managed. Notably, our investigation reveals intriguing interactions between the proportional controls, highlighting the complexity of ABS optimization. The method was evaluated through simulations across various friction conditions, comparing it to conventional ABS in terms of brake performance, stability, and stopping distances. The results indicate that the proposed method significantly enhances ABS performance across varying friction coefficients; however, additional research is warranted to address stopping distance and time issues, particularly in snowy and icy conditions.

Corresponding Author:

Heng Siong Lim
Faculty of Engineering and Technology, Multimedia University
Bukit Beruang, 75450 Melaka, Malaysia
Email: hslim@mmu.edu.my

1. INTRODUCTION

Anti-lock braking systems (ABS) systems have improved car safety by preventing wheel lock-up during braking maneuvers. They work to shorten stopping distances and help drivers maintain control of their vehicles on slippery surfaces by adjusting the amount of pressure applied during braking. However, variable friction coefficients can reduce the efficiency of ABS, resulting in decreased braking performance and significant safety risks. Therefore, it is necessary to understand and overcome the challenges posed by changing friction conditions to enhance the safety and overall effectiveness of ABS devices. The efficiency of a vehicle's brakes is greatly affected by friction coefficients, which are important in studying the interaction between the tires and the driving surface. These coefficients represent the force resulting from the wheel's interaction with the road in proportion to the vertical load of the tire.

ABS typically consists of components such as wheel speed sensors, an electronic control unit (ECU), and a brake pressure modulator. However, designing ABS is complex due to measurement noise, uncertainties, and nonlinearities. Road condition variations cause significant changes in braking pressure, wheel slip, and tire-road friction parameters, requiring precise estimation. Therefore, various methods have been developed to control ABS effectively under diverse conditions and enhance its functionality. Most research focuses on wheel slip control as the primary variable affected by different braking scenarios and road conditions. ABS design challenges include vehicle dynamics during braking, tire force saturation uncertainties, and variations in vehicle parameters and tire-road friction. Addressing these challenges necessitates robust controller development, leading to proposed approaches like fuzzy logic controllers and gain scheduling [1]–[3]. Some studies combine these methods to improve performance [4], though they often demand significant memory storage.

Several factors, including tire standards, car size, climate, and road conditions, impact the average friction coefficient. ABS applications are engineered and adjusted to function optimally within a specific range of adhesion coefficients under standard operating conditions. Nevertheless, a broad range of friction coefficients is frequently encountered in real-world situations, which can severely limit the effectiveness of the braking system. Reduced friction coefficients increase the likelihood of wheel lock-up during braking, particularly on wet or icy roads, reducing vehicle control and lengthening stopping distances. Conversely, high friction coefficients, found on dry, well-maintained highways, for example, may induce early wheel lock-up, restricting the vehicle's mobility and potentially causing a loss of control. Thus, it is vital to design solutions that will boost the efficiency of ABS across the full range of friction coefficients encountered in common driving scenarios.

In this work, we propose a novel method to enhance ABS efficiency by employing a feedback control mechanism that dynamically adjusts the braking force based on the prevailing friction coefficient. This approach incorporates a P-controller and additional P-controllers for input and output parameters related to friction. The rest of this article is organized as follows: section 2 reviews related work. Section 3 outlines the motivation and objectives. Section 4 details the method employed. Section 5 describes the ABS. Section 6 presents the simulation results. Section 7 discusses these results. Finally, section 8 concludes the paper.

2. RELATED WORK

Many studies have been conducted to find solutions to problems related to changing friction coefficients and improving ABS performance. These solutions include hardware and software enhancements aimed at improving control techniques and the interaction between braking systems and their components. Technological advancements employ better sensors, actuators, and brake system designs to deliver more accurate readings and faster reaction times. The evaluation of the ABS algorithm's performance will be based on the following metrics. Conversely, advancements in software pertain to the development of intricate control algorithms capable of real-time adjustments to effectively adapt to varying friction conditions [5]–[8]. Ulum and Patriawan [9] have demonstrated the superiority of ABS systems over non-ABS systems in terms of stopping distances by creating and implementing an ABS braking system using Simulink software. In both wet and dry scenarios, the augmented coefficient of friction for the wheels in the ABS system leads to decreased stopping distances [10]. Moreover, the ABS system enhances brake control by enabling dynamic adjustments of the vehicle's dynamics[11].

Savitski *et al*. [12] developed four controller architectures for a continuous wheel slip control system for electric vehicles (EVs) equipped with integrated wheel motion sensors (IWMs). They applied the sliding mode approach for optimal slip searching, overcoming the limitations of previous studies. The controllers, which include variable structure proportional-integral (VSPI), first-order sliding mode (SM), integral SM, and SM with a continuous twisting algorithm (CTA), were developed based on experimental results. The results demonstrated that the VSPI control preserves wheel slip, adjusts for disturbances, and allows for easy adjustment in IWM control [12]. Sullivan *et al*. [13] developed the dual control for exploration and exploitation (DCEE) strategy to address the ABS problem. The Magic Formula tire model enhanced stopping time and distance by up to 15% and 8.5%, respectively, compared to extreme seeking techniques. The DCEE technique is effective across various driving conditions, including low and high speeds, as well as on snow, wet, and dry roads with changing surfaces. Future studies may focus on expanding the prediction horizon to improve stability and transient tire behavior [13]. In their work, Mantripragada and Kumar [14] investigated how various tire properties affect the efficiency of algorithms used to manage ABS. Authors explored all possible combinations of the four primary longitudinal characteristics by using the magic formula 6.1 tire model to create thousands of virtual tires. For comprehensive simulations of vehicle dynamics, they developed and integrated two ABS controllers with IPG carmaker. A sensitivity study, based on conditional variance applied to 211,250 simulation runs, reveals that the ABS stopping distance is heavily influenced by the tire peak friction coefficient and the shape factor.

The simulation findings indicate that tire parameters C and D contribute approximately 80%–93% to stopping distance, regardless of the ABS method used [14]. Advancements in sensors have significantly simplified the measurement of critical vehicle dynamics parameters, such as vehicle speed and friction coefficient. As a result, the ABS system now benefits from enhanced control capabilities. In research conducted by Wei [15], innovative approaches were developed to evaluate adhesion and velocity coefficients within ABS controllers. The efficacy of these approaches was validated through successful application to real-world automobile ABS test data. Consequently, these technologies improve ABS control by enabling precise predictions of the vehicle's travel speed and frictional force coefficients.

Mims *et al*. [16] published a research paper that included two studies focused on developing and evaluating a driving simulator and interactive exercise for an emergency braking task with haptic ABS feedback. The simulator and interactive exercise are designed to provide a safe and repeatable environment. The interactive exercise, Pedals Emergency Stop, uses images of pedals instead of a driving scene to prevent simulator sickness. In the first study, participants were required to press the brake pedal in a manner consistent with emergency braking when ABS activated. 85% of participants successfully completed the task within the first four trials, with an average of three trials. The second study explored refinements to the interactive exercise, requiring participants to pass three out of four trials. The results suggest that the pedals emergency stop interactive exercise can be an effective tool for drivers to gain experience with emergency braking and haptic ABS feedback [16].

To enhance user safety and implement ABS technology, Wu *et al*. [17] utilized adjustable wheelchairs. They employed flexible fuzzy-neural reasoning systems, which are techniques for predicting the friction coefficient. The objective of Uzunov *et al*. [10] was to evaluate the adhesion properties of tires on road surfaces in automobiles equipped with ABS. The researchers found that, across various surfaces, an increase in the initial velocity led to a reduction in the coefficient of friction. El-Bakkouri *et al*. [18] proposed an output-feedback adaptive controller for ABS. This controller is designed to precisely track the ideal slip coefficient while adapting to new road conditions. Its validation, conducted using a processor-in-the-loop setup, demonstrated exceptional performance in terms of stability, tracking accuracy, robustness, and practical applicability [18]. Yang *et al*. [7] employed logic threshold control and phase plane theory to investigate the relationship between slip rate and braking torque during ABS braking. They proposed a control technique for coordinating regenerative braking systems (RBS) and ABS, thereby improving brake energy recovery efficiency. A comparative simulation assessed the braking capability of electric cars with varying adhesion coefficients. The proposed coordinated control technique enhanced braking energy recovery efficiency by 23.08% to 38.54% compared to standard systems, leading to improved braking performance, reduced braking distance, and shorter braking time [7].

3. MOTIVATION AND OBJECTIVES

This research addresses the urgent need to enhance the safety and effectiveness of automotive braking systems. ABS systems have significantly reduced accident rates and improved vehicle control during braking. However, variations in the coefficient of friction between the road surface and the wheels can impact the performance of the ABS system. The main objectives are to refine control algorithms to handle different friction coefficients and to use simulation tools to optimize braking effort distribution. The effectiveness of the proposed improvements will be assessed using a high-fidelity vehicle performance model, focusing on critical parameters such as stopping distance, vehicle stability, and brake efficiency. The optimized ABS system will be further refined using simulation-based approaches to achieve optimal performance.

4. METHOD

The proposed study will use simulation to investigate the effectiveness of specific ABS technology under various friction conditions. The vehicle dynamics models that will form the basis of the simulation will include the following features:

a. Vehicle: A quarter-car model will be used in our research;
b. Wheels: Considering the effects of various friction coefficients on the road, we shall model the wheels. The state of the road surface frequently affects the tire friction coefficient;
c. ABS technology: This mechanism will serve as the control unit, calculating the braking force to be applied to each wheel.

The simulation can be used to evaluate the performance of ABS technology in various scenarios, including:

a. Wet roads: The friction rate on the surface will be reduced to simulate wet conditions;

b. Gravel: The friction coefficient of the pavement can be decreased to simulate gravel conditions;
c. Turns: To replicate turning results, the vehicle will brake while driving.

The following measures should be used to assess the success of acquisition and benefit-sharing methods:
a. Braking distance: The amount of time it takes for the vehicle to come to a complete stop;
b. Stop time: The duration required for the vehicle to come to a complete stop;
c. Wheel lock-up: The amount of time each wheel is locked when coming to a stop.

The following is a list of the techniques that were employed to finish this research:
a. Related work: The pertinent literature will be thoroughly examined in order to compile information on ABS, friction coefficients, and how these factors affect braking effectiveness;
b. Data collection and analysis: The study aims to assess ABS performance by analyzing vehicle characteristics, regulated friction coefficients, and ABS control systems, identifying patterns and correlations;
c. Developing vehicle dynamics systems: A vehicle movement model will be created using MATLAB or Simulink, incorporating tire connection, anti-lock braking control mechanism, and friction coefficient effects;
d. ABS methodology application: The ABS approach will be utilized as a controller in the vehicle's driving simulation, utilizing a specialized method to adapt to changes in friction coefficients;
e. Assessing ABS performance: ABS performance will be evaluated under various friction conditions using a comprehensive simulation technique, focusing on critical performance metrics like stopping distance, wheel slip, and vehicle security;
f. Evaluation of effectiveness: The updated ABS systems will undergo comparative tests under various friction conditions, assessing performance metrics like stopping distance, tire slip, and vehicle balance to evaluate their effectiveness;
g. Result analysis and conclusion: Making inferences about the research objectives will need an analysis of the simulation data and consideration of the outcomes. Evaluation and research will be done on the improved ABS system's performance at different friction coefficients. The study limits, practical application suggestions, and prospects for more research will all be included in the conclusion.

5. ANTI-LOCK BRAKING SYSTEM

In an ABS system, a crucial vehicle safety component, plays an essential role in preventing wheel lock-up during rapid braking situations, thereby significantly enhancing the vehicle's overall stability and steering capabilities [9], [19]. This system is designed to effectively counteract wheel lock-up by promptly and continuously adjusting brake pressure, allowing the wheels to rotate freely and maintaining a consistent level of traction with the road surface. ABS achieves this by employing a dynamic calibration technique, which enables the brake caliper to adapt seamlessly to the vehicle's ever-changing dynamics [20], [21].

5.1. Traditional control strategies and limitations

In normal braking (without an ABS system), pressing the brake pedal causes the brake pads to clamp firmly onto the wheel discs, which can result in the wheels locking up regardless of the vehicle's speed. When the wheels stop rotating, they can no longer be steered, leading to a loss of control as the vehicle continues to slide due to momentum. This situation often results in severe accidents, as illustrated in Figure 1 [22].

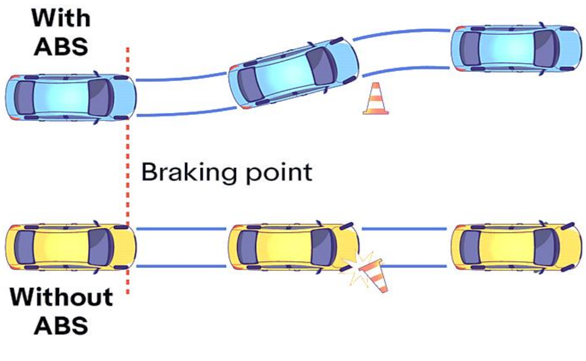


Figure 1. Braking with and without ABS [22]

5.2. Components of the ABS system

The ABS system incorporates several critical components, including sensors to monitor wheel speed, an ECU to interpret data, a hydraulic modulator for brake pressure adjustment, and solenoid valves for quick brake release. Specifically, the ABS system has four major components [23], [24]:

a. Speed sensors: Speed sensors, such as toothed wheels or electromagnetic coils, produce signals from a magnetic field surrounding the wheel, creating voltage changes. The controller evaluates these inputs to predict wheel acceleration and deceleration;
b. Valves: ABS brake lines feature valves that work in three positions: open, isolated, and released. Valve clogging is a typical problem with ABS systems, reducing the system's capacity to open, shut, or change positions. A malfunctioning valve may prevent the system from modulating valves and regulating braking pressure;
c. Pumps: The pump restores hydraulic braking pressure following valve release, managed by the controller, to prevent wheel slippage by altering pump status to maintain the optimum pressure level;
d. The ECU: The ABS system's controller, an ECU, employs wheel speed sensors to detect traction loss, limit brake force, and activate the ABS modulator, regulating braking valve pressure.

5.3. The work of the anti-lock braking system

The ECU of the ABS reads signals from each wheel's speed sensors. When the driver applies the brakes suddenly, the wheel decelerates rapidly, increasing the risk of wheel lock-up. To counter this, the ECU detects the sudden reduction in wheel speed and instructs the valve to close, reducing the brake pad pressure and preventing wheel lock. As the wheel begins to accelerate again, the ECU signals the valve to open, increasing brake pad pressure and slowing the wheel down. This cycle of brake application and release occurs approximately 15 times per second during heavy braking, effectively preventing wheel lock and reducing vehicle sliding. With ABS, drivers can maneuver the car while braking, significantly lowering the likelihood of collisions [24], [25].

5.4. Classification of the anti-lock braking system

The ABS system is classified into three categories based on the number of channels it includes. Each type of ABS responds to different criteria, with the four-channel ABS providing the highest level of performance and safety.

a. Four-channel ABS systems: ABS technology, widely used, is a four-channel system that modulates each wheel separately during braking, enhancing both efficiency and safety;
b. Three-channel ABS: Three-channel ABS is a cost-effective alternative to four-channel ABS. It uses a single sensor to control both rear wheels, which limits ABS intervention during severe braking;
c. One-channel ABS: One-channel ABS, the lowest option, is used in commercial vehicles with a single sensor at the rear axle, focusing on the rear wheels during hard braking.

5.5. A Mathematical of anti-lock braking system

A mathematical model is often used to simulate how an ABS system operates. This model typically includes components such as speed sensors, a control unit, and actuators. The mathematical model helps in understanding the system's operation and the impact of various factors on its performance. This information is crucial for designing and improving the ABS system. Typically, several characteristics are used to calibrate ABS systems. These settings, including the rates of braking pressure reduction and restoration as well as the threshold speed that triggers system activation, determine how the ABS system functions.

5.5.1. The vehicle modeling

Vehicle modeling comprises three essential components: vehicle dynamics, wheel dynamics, and braking system dynamics. Vehicle dynamics involves modeling the overall motion, handling, and response to external forces such as aerodynamics and road conditions. Wheel dynamics focuses on individual wheel behaviors, including tire characteristics, road interactions, and the effects of braking and cornering on traction and stability. Braking system dynamics model the components and interactions within the braking system, including brake mechanisms, hydraulic systems, and control units like ABS, which are crucial for analyzing braking efficiency, stopping distances, and vehicle stability.

a. Vehicle dynamics model

The simplified vehicle's equation of motion can be represented using Newton's second law:

$$m_v \times \dot{V}_v = -F_f \tag{1}$$

where, V_v is vehicle velocity, F_f is road friction force, and m_v is total mass of the quarter vehicle. Based on Coulomb's law, the road friction force is determined:

$$F_f = \mu(\lambda) \times F_N \quad (2)$$

where, F_N is total normal force (road reaction) and $\mu(\lambda)$ is road adhesion coefficients. The total normal force can be expressed by (3):

$$F_N = W = m_v \times g \quad (3)$$

where, W is vehicle weight, and g is the gravitational acceleration. Replacing (4) in (3) gives the expression of the friction force as (4):

$$F_f = \mu(\lambda) \times m_v \times g \quad (4)$$

then,

$$m_v \times \dot{V}_v = -\mu(\lambda) \times F_N = -\mu(\lambda) \times m_v \times g \quad (5)$$

thus,

$$\dot{V}_v = -\mu(\lambda) \times \frac{m_v \times g}{m_v} = -\mu(\lambda) \times g \quad (6)$$

By integration of (6), we get on the vehicle speed. One way to express the quarter vehicle's overall mass is as:

$$m_v = m_{tire} + \frac{1}{4} m_{car} \quad (7)$$

where, m_{tier} is tire mass, and m_{car} is vehicle mass.

b. Wheel dynamics model

The design under consideration is based on a quarter vehicle model, as depicted in Figure 2. This concept has been utilized previously for designing the ABS controller. The equation of motion for the rotational DOF at wheel level, as per Newton's second law, is given by (8):

$$J_\omega \times \dot{\omega}_\omega = T_t - T_b \quad (8)$$

where, T_t is tire torque, which can be mathematically stated as (9):

$$T_t = F_f \times R_r = \mu(\lambda) \times F_N \times R_r \quad (9)$$

then,

$$J_\omega \times \dot{\omega}_\omega = \mu(\lambda) \times F_N \times R_r - T_b \quad (10)$$

$$J_\omega \times \dot{\omega}_\omega = \mu(\lambda) \times R_r \times m_v \times g - T_b \quad (11)$$

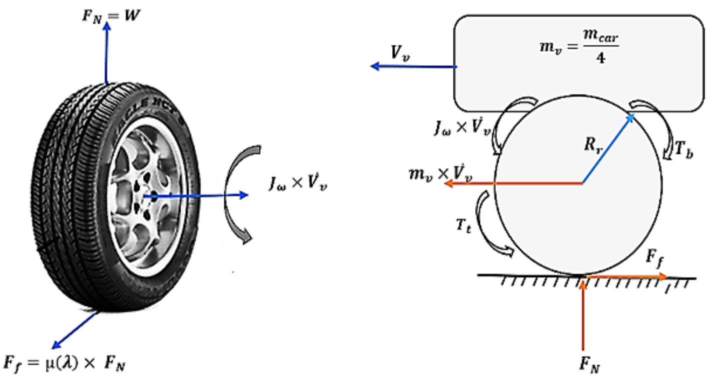


Figure 2. Quarter car braking model

The equation of wheel speed: To find the equation of wheel speed, we integrate of the (12):

$$\dot{\omega}_{\omega} = \frac{1}{J_{\omega}}(\mu(\lambda) \times R_r \times m_v \times g - T_b \tag{12}$$

where, J_{ω} is wheel moment of inertia, ω_{ω} is wheel speed, R_r is wheel radius, T_b is braking torque, and F_f is road friction force.

c. Relative slip

The ABS system must control relative slip around an optimal goal. The relative slip equation is written as (13):

$$\delta = 1 - \frac{\omega_{\omega}}{\omega_v} \tag{13}$$

where, ω_{ω} is angular speed of the wheel, and ω_v is angular speed of the vehicle. The wheel angular speed is calculated:

$$\omega_{\omega} = \frac{T_t - T_b}{J_{\omega}} \tag{14}$$

and, vehicle angular speed is calculated:

$$\omega_v = \frac{V_v}{R_r} \tag{15}$$

where, T_t is tire torque, T_b braking torque and J_{ω} wheel rotational inertia.

d. Slip ratio

The slip ratio is the difference between the vehicle linear speed and the wheel angular speed, indicated by (λ). It is created as (16):

$$\lambda = \frac{V_v - R_r \times \omega_{\omega}}{V_v} \tag{16}$$

e. Slip rate

Differentiating the (16) with respect to time (*t*), get:

$$\dot{\lambda} = \frac{\dot{V}_v(1-\lambda) - R_r \times \dot{\omega}_{\omega}}{V_v} \tag{17}$$

Where, V_v is the vehicle linear speed, R_r is wheel radius, and ω_{ω} is wheel angular speed.

f. Friction model

There is a very broad range of variation in the friction coefficient, which depends on things like: i) The state of the road's surface (dry or wet), ii) Angle of side-slip on tires, iii) the type of tire (winter or summer), iv) vehicle speed, v) the slip ratio between the tire and the road, and vi) the state of the environment, including temperature and humidity. We will solely consider the fluctuation of the friction coefficient function on the longitudinal wheel slip for our simulation. The stable zone of the friction coefficient is shown in Figure 3 [26].

When applying brakes, a wheel slip of 100% causes the wheel to lock yet keeps the car going. The wheel and the car move at the same speed when there is no slide. Wheel slip of about 20% is the ideal friction coefficient. There are two zones on the friction coefficient curve:

a. Stability zone: where the friction coefficient increases with the wheel slip increase.
b. Unstable zone: where the friction coefficient decreases with the wheel slip increase.

The friction coefficient decreases as the wheel slips into an unstable region, causing the wheel to lock and resulting in skidding and vehicle instability. Each type of road has a unique friction curve. Consolidated methods for modeling the tire-road friction coefficient include the Pacejka model, also known as the magic formula, and the Buckhardt model. The equation governing this tire model is given by:

$$\mu(\lambda) = A.(B.(1 - e^{-(C.\lambda)} - D.\lambda) \tag{18}$$

Where, $\boldsymbol{\lambda}$ is the wheel slip, and A, B, C, D are the empirical coefficients.

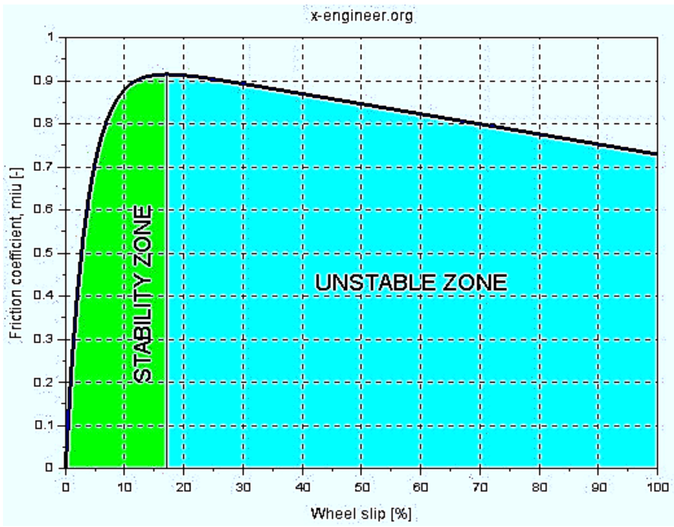


Figure 3. Friction coefficient stability zone [26]

Depending on the value of the coefficients A, B, C and D, the empirical formula (16) can be used to represent the friction coefficient for different road types/states. The values of the Burckhardt's constants for various road conditions are shown in the Table 1. According to (18), Curves showing the link between slip and coefficient of friction for various road conditions were created using simulation, as shown in Figure 4.

Table 1. Surface parameters for different road conditions

Type of roads	A	B	C	D
Dry concrete	0.9	1.07	0.2723	0.0026
Wet asphalt	0.7	1.07	0.5	0.003
Snow	0.3	1.07	0.1773	0.006
Ice	0.1	1.07	0.83	0.007

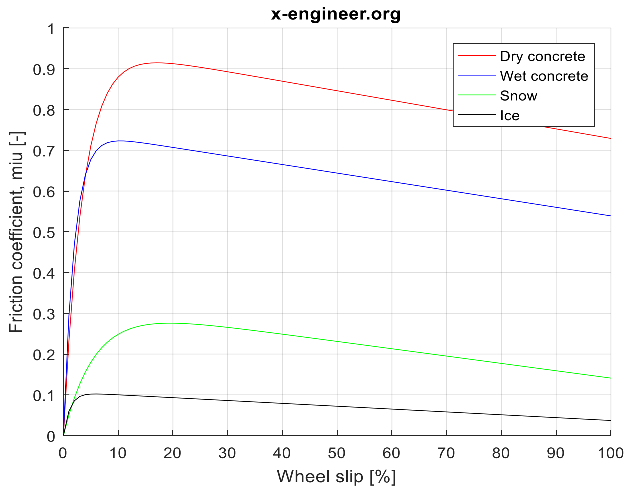


Figure 4. Wheel slip ratio versus road coefficient friction

5.5.2. Parameters of model

Table 2 outlines the key parameters utilized in the ABS model simulation, which are essential for accurately evaluating system performance. Key parameters include vehicle mass, wheel inertia, wheel radius, initial speed, braking torque, slip ratio, and constants for road conditions and control settings. These factors are crucial as they directly influence braking effectiveness, stopping distances, and the overall stability of the vehicle under various conditions. By simulating these parameters, researchers can better understand the ABS's performance across different scenarios and identify potential areas for improvement.

5.6. Simulation of ABS

The quarter-car model, as described in the literature, represents a simplified vehicle and wheel combination used in the simulation. This model assumes that a vehicle with a single wheel account for one-quarter of its total mass. Additionally, it disregards the effects of the suspension system and focuses solely on longitudinal vehicle dynamics.

Table 2. Parameters used in the ABS model

Symbol	Value	Description
m_v	1370 [Kg]	Total vehicle mass
J_ω	5 [kg·m^2]	Wheel inertia
R_r	0.33 [m]	Wheel radius
v_0	88 [m/s]	Initial vehicle speed
F_N	$m_v * g$ [N]	Normal force
ω_0	v_0/R_r [rad/s]	Wheel speed angular
g	9.81 [m/s^2]	Gravitational acceleration
K_f	1 [-]	Force and Torque
T_{bmax}	1500 [N·m]	Maximum braking torque applied to the wheels
TB	0.01 [S]	Hydraulic Lag
λ_d	0.2 [-]	Desired slip
Ctrl	1 or 0	With ABS→ 1 and Without ABS→ 0
K	1000	Proportional gain
Road type	1, ,2, 3, or 4 [-]	Constant for road setting -
$C_1, C_2, \& C_3$	1, 2, …, N [-]	P- controller
A, B, C, and D	-	The constants which depend on road conditions
e	2.2204*10^{-16}	Division by zero protection constant

5.6.1. Modelling of ABS

Figure 5 illustrates a simulation of an ABS, where the braking process targets a desired relative slip d_o as a key parameter. The ABS control signal determines if the system is active, and the P-controller generates a control signal based on the difference between the desired slip and the actual slip δ. This control signal is used to calculate the tire torque T_t, influencing the wheel speed ω_ω and vehicle speed ω_v. These speeds are used to compute the stopping distance S_d and relative slip δ, which is fed back into the system. The friction model uses the relative slip to determine the friction coefficient, calculating the friction force F_f based on the vehicle's normal force F_N. The friction force, together with the vehicle mass m_v, determines the vehicle's acceleration, which is integrated to obtain the vehicle speed and, subsequently, the stopping distance. This closed-loop system dynamically adjusts the braking force to maintain the desired slip ratio, optimizing braking performance and minimizing stopping distance.

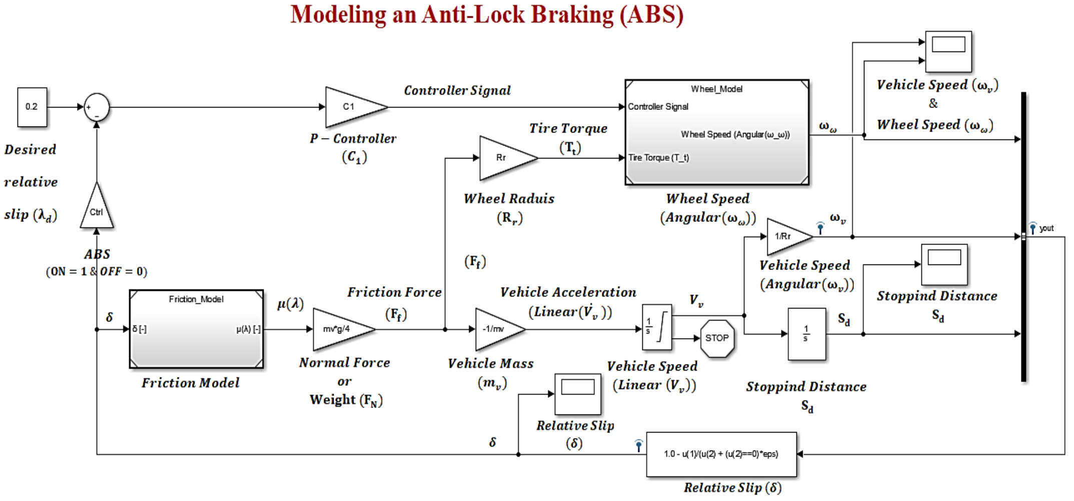


Figure 5. Block diagram of modeling an ABS

5.6.2. Block diagram of vehicle model

Figure 6 shows a simulation of a vehicle model illustrating the relationship among fundamental forces critical for comprehending vehicle performance and safety. It highlights how friction force, which opposes motion between tire and road surfaces, directly influences both acceleration and braking capabilities. The concept of slip is illustrated, demonstrating the loss of traction when frictional grip diminishes, thereby compromising steering and braking control. Weight, represented as gravitational force F_N, contributes to the normal force that dictates friction, influenced significantly by the vehicle's mass and gravity. Vehicle mass, in turn, affects inertia, requiring greater force to change the motion of heavier vehicles. Speed is shown to impact kinetic energy and momentum, correlating directly with stopping distances and the necessary braking forces. Angular velocity, representing rotational speed, is crucial for understanding wheel dynamics within the simulation. Finally, the simulation underscores the critical role of stopping distance, which depends on speed, friction levels, and driver reaction times, emphasizing the dynamic interactions essential for safe and effective vehicle operation.

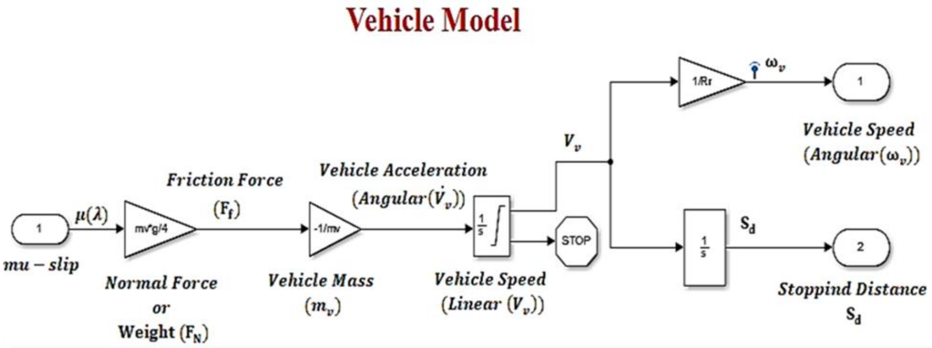


Figure 6. Block diagram of vehicle model

5.6.3. Block diagram of wheel model

Figure 7 illustrates a simulation of a wheel model, providing a detailed depiction of the essential components and interactions within a wheel brake system. It emphasizes the dynamic interplay of force, torque, and control mechanisms crucial for vehicle motion. The system is engineered to manage wheel rotational speed using a hydraulic lag brake, which introduces a controlled delay to enhance braking precision and smoothness. At the core of this configuration is a controller that analyzes inputs such as wheel speed and hydraulic pressure to determine the optimal braking force and torque, crucial for maintaining vehicle stability and preventing skidding during braking. The diagram suggests that a rotational actuator converts hydraulic pressure into mechanical force, applying braking force to brake pads or shoes. This design ensures efficient deceleration while maintaining consistent traction and stability, essential for safe driving under diverse conditions.

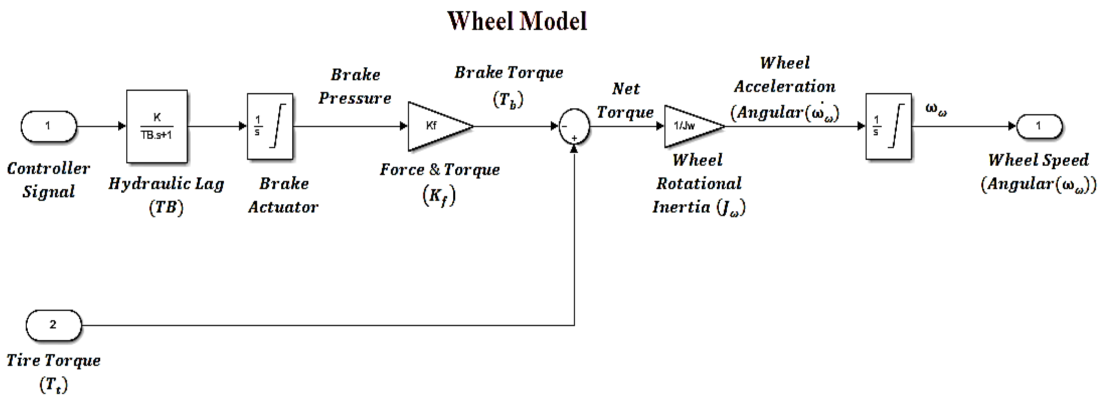


Figure 7. Block diagram of wheel model

5.6.4. Block diagram of friction

Figure 8 illustrates a simulation of the coefficient of friction, showcasing a proportional P controller system designed to manage vehicle dynamics across various road conditions. This system focuses on maintaining stability through the concept of “relative slip,” which measures the difference between the wheel's actual speed and its potential speed without slipping. By adapting control parameters to different friction levels, the system can optimize braking performance effectively. Moreover, the updated approach enhances adaptability, enabling real-time adjustments that improve responsiveness to changing road conditions, ultimately contributing to increased vehicle safety and performance.

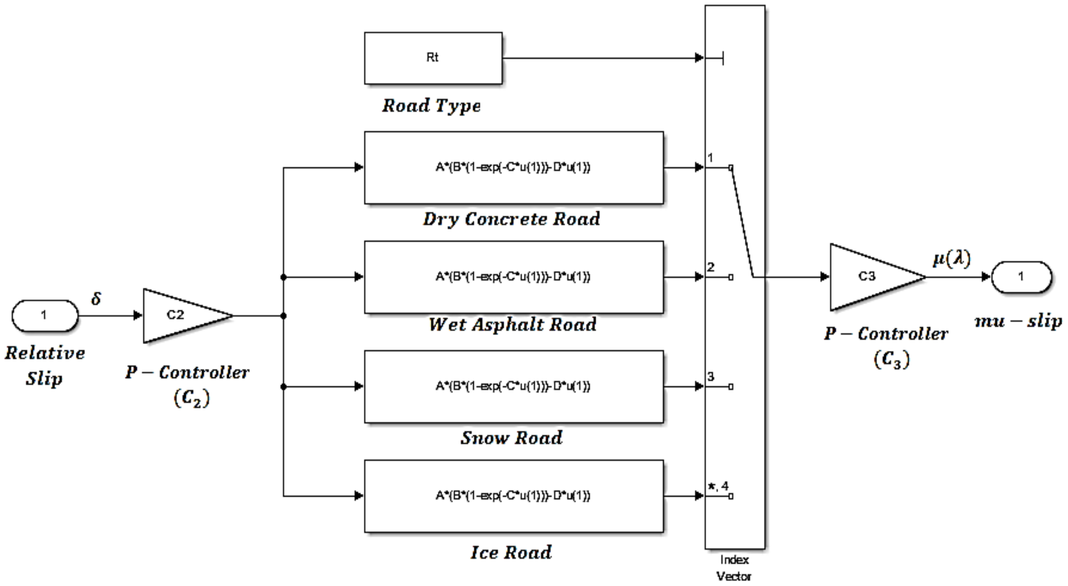


Figure 8. Block diagram of friction model

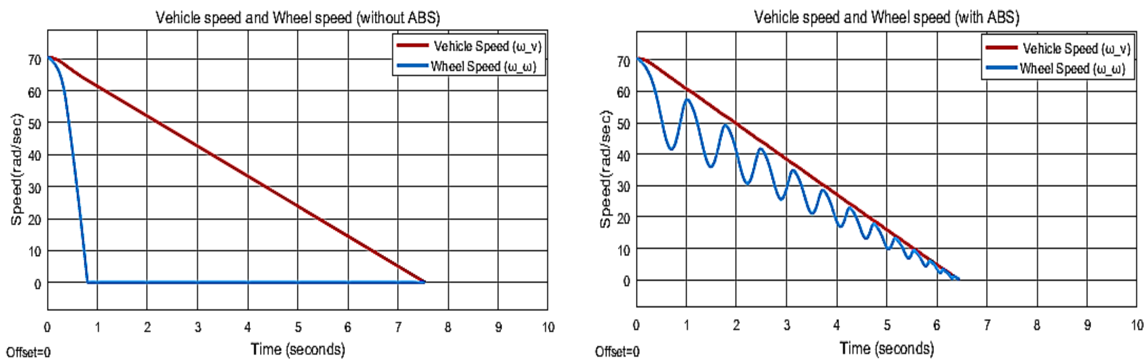
6. RESULTS OF SIMULATION

The input brake torque applied to a four-wheel brake model is compared in the Figures 9 to 11. By applying the model to different road surfaces and adjusting the values of the input magnification coefficient and output coefficient, we can modify the friction coefficient. This allows us to examine scenarios both with and without ABS. The braking performance is simulated and evaluated in terms of wheel speed, stopping time, and relative slip.

6.1. Breaking with and without anti-lock system at (C1=20, C2=100, and C3=2)

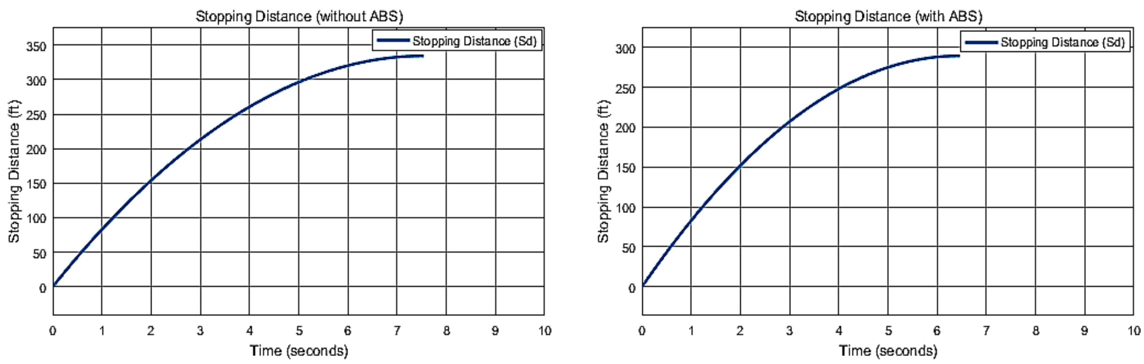
6.1.1. Dry concrete road

The following illustrations depict the outcomes of two car simulations: one with an anti-lock braking system and the other without. Both simulations were conducted on a dry concrete road. The calculation considers factors such as the velocity and tire characteristics of the vehicle, as well as the distance required to come to a stop and the degree of slip between the tires and the road surface. Figure 9 illustrates the impact of the ABS on vehicle deceleration. In Figure 9(a), a vehicle decelerating without ABS experiences complete wheel lock-up, resulting in skidding and a loss of control. In contrast, Figure 9(b) demonstrates how ABS maintains oscillations in wheel speed by repeatedly engaging and releasing the brakes, thereby enhancing vehicle control and reducing stopping distance on slippery surfaces. Figure 10 compares the stopping distances of vehicles with and without an ABS. Figure 10(a) provides compelling evidence that vehicles lacking an ABS system need a distance of 334.32 ft to fully halt within a time span of 7.546 seconds. Conversely, in Figure 10(b), vehicles equipped with an ABS system can stop precisely at a distance of 289.42 ft within a time frame of 6.460 seconds. Figure 11 depicts the influence of the ABS on wheel traction during braking. In Figure 11(a), when ABS is inactive, the relative slip grows fast, causing the wheels to lose traction and slide, which impairs vehicle control. In Figure 11(b), with ABS activated, the relative slip oscillates around a certain value due to the system's continual adjustment of braking force to prevent wheel lockup. This capability promotes grip, improves vehicle control, and minimizes stopping distance.



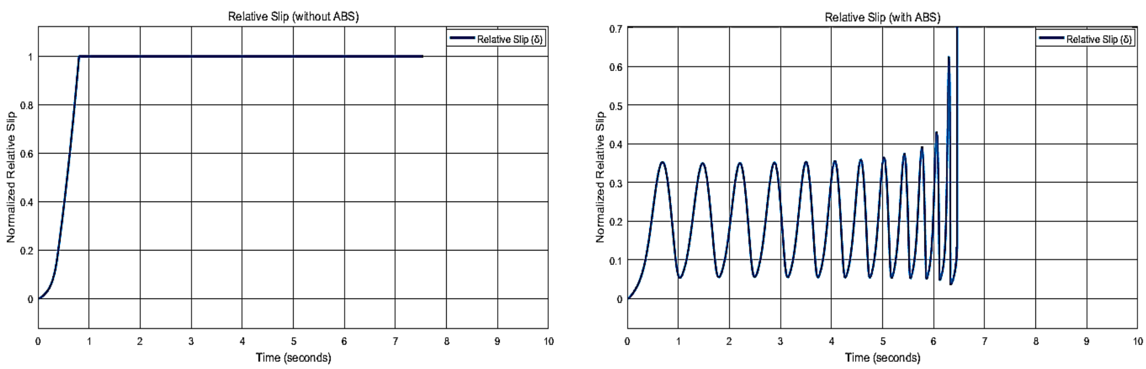
(a) (b)

Figure 9. Vehicle and wheel speed (a) without ABS and (b) with ABS



(a) (b)

Figure 10. Stopping distance (a) without ABS and (b) with ABS

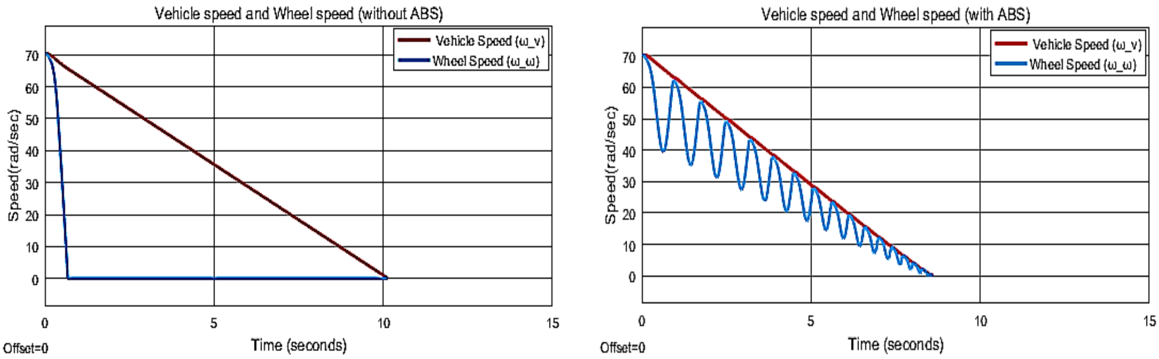


(a) (b)

Figure 11. Relative Slip (a) without ABS and (b) with ABS

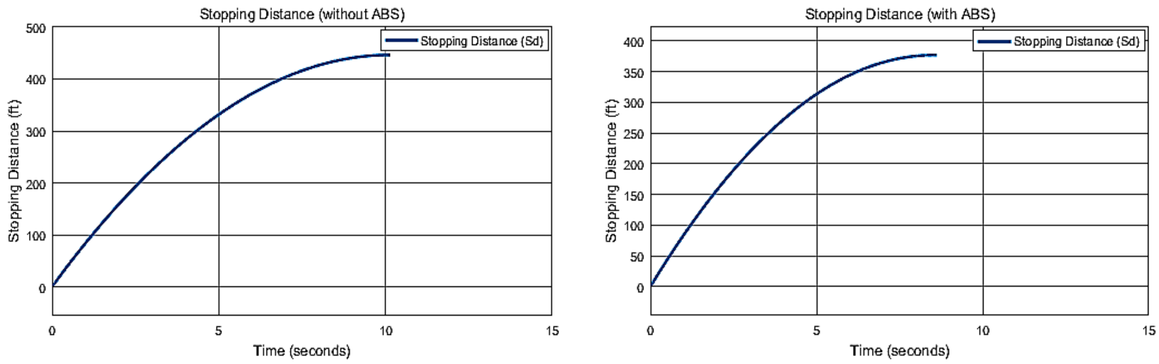
6.1.2. Wet asphalt road

A dry asphalt road is used to simulate the driving experience of two cars, one equipped with an ABS system and one without. The findings from the simulator, presented in the Figures 12 to 14, include analyses of wheel behavior, stopping distance, and relative slip. Figure 12 depicts the influence of the ABS on vehicle deceleration. In Figure 12(a), when ABS is turned off, both the vehicle and the wheel speeds fall, but the wheel speed decreases more quickly, resulting in wheel lock-up and loss of control. In contrast, Figure 12(b) depicts the behavior when ABS is activated, in which both speeds fall but the wheel speed oscillates rather of continually lowering. This oscillation happens when ABS changes brake pressure to prevent wheel lock-up and improve vehicle control during braking. Figure 13 shows the stopping distance of a vehicle with and without an ABS in two different braking scenarios. Figure 13(a) indicates that without the ABS, a vehicle requires a stopping distance of 446.34 feet over 10.142 seconds due to wheel lock-up and subsequent skidding. In contrast, Figure 13(b) demonstrates that with ABS enabled, the vehicle can stop in a shorter distance of 376.83 feet in 8.611 seconds, as the wheels continue to rotate, effectively preventing skidding. Figure 14 demonstrates the relative slip of tires in two scenarios: without the ABS and with it operational. In Figure 14(a), the absence of ABS results in a considerable increase in tire slide, resulting to a loss of vehicle control and a longer stopping distance. Contrary to this, Figure 14(b) illustrates that with ABS activated, the oscillations in slip imply good maintenance of tire traction, hence boosting vehicle control.



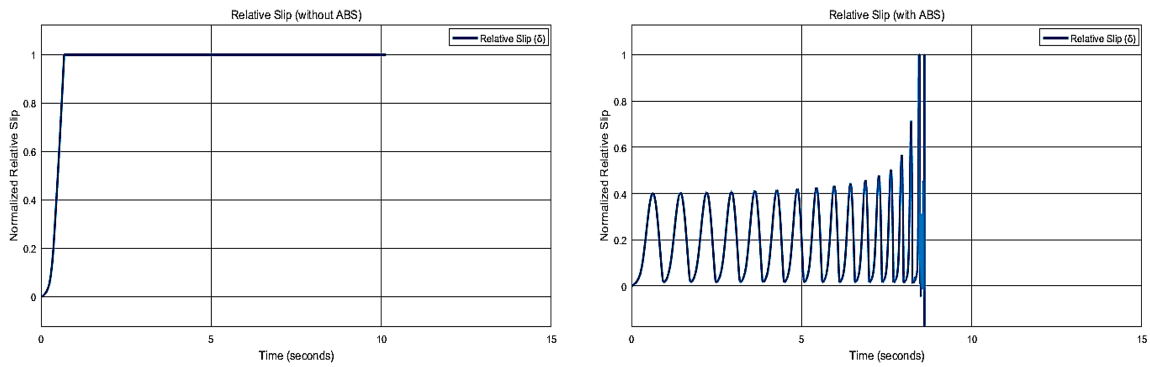
(a) (b)

Figure 12. Vehicle and wheel speed (a) without ABS and (b) with ABS



(a) (b)

Figure 13. Stopping distance (a) without ABS and (b) with ABS



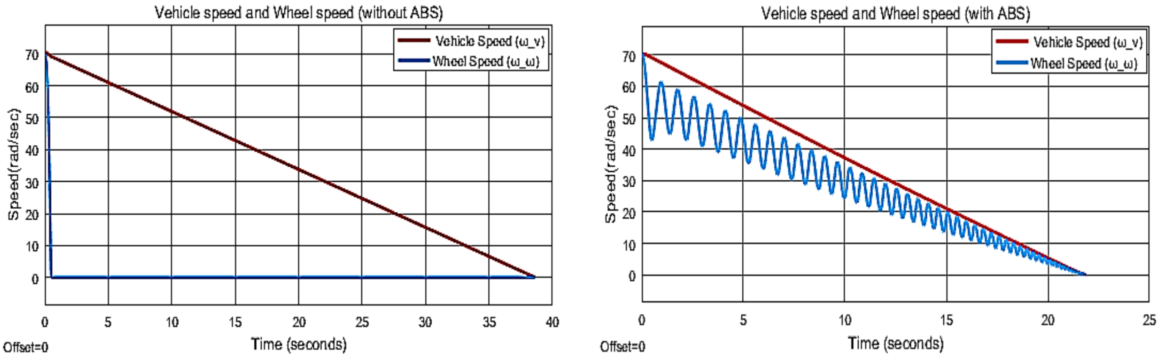
(a) (b)

Figure 14. Relative slip (a) without ABS and (b) with ABS

6.1.3. Snow road

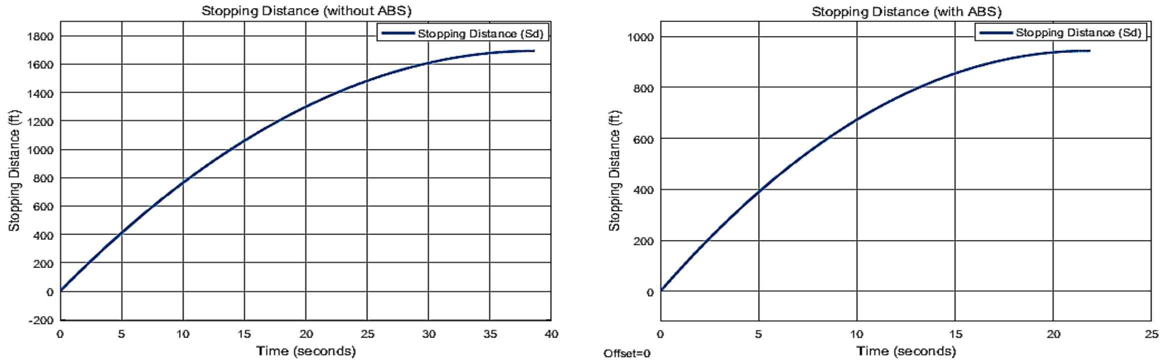
Figures 15-17 the simulation results for two cars on a snow-covered road, one equipped with an ABS system and the other without. The statistics show the relative slip, stopping distance, and wheel and vehicle speeds. Figure 15 depicts the major differences in braking performance between cars equipped with an ABS and those without. Figure 15(a) displays a car without ABS, demonstrating a fast drop in both vehicle and wheel speeds until the wheels lock up. In comparison, Figure 15(b) demonstrates the behavior of a vehicle with ABS, where the oscillating wheel speed curve implies continuous braking pressure adjustment. This minimizes wheel lock-up by maintaining ideal slip, allowing for speedier deceleration while keeping steering control. Figure 16 shows how ABS significantly affect a car's stopping distance in two scenarios: one in which ABS is not present and the other in which it is. Figure 16(a) indicates that vehicles without ABS have a stopping distance of 1,692.23 feet, needing 38.623 seconds to come to a complete stop. This steady rise in stopping distance is mostly due to wheel lock-up, which limits tire-to-road contact and impairs braking efficiency. In contrast, Figure 16(b) illustrates the superior braking performance of automobiles equipped with ABS, which likewise stops within 1,692.23 feet in 38.623 seconds. The greatly decreased stopping distance is related to the ABS system's capacity to avoid wheel lock-up and maximize tire-to-road friction, thereby boosting total braking effectiveness.

Figure 17 presents relative slip curves for a vehicle's tire over a designated time interval, contrasting two scenarios: one with a conventional braking system (without ABS) and the other with an ABS. Figure 17(a) illustrates total tire slide in the absence of ABS, resulting in a relative slip of 100% and consequent loss of control. Figure 17(b) illustrates the impact of ABS, which diminishes slip by oscillating relative slip, so preserving traction and vehicle control.



(a) (b)

Figure 15. Vehicle and wheel speed (a) without ABS and (b) with ABS



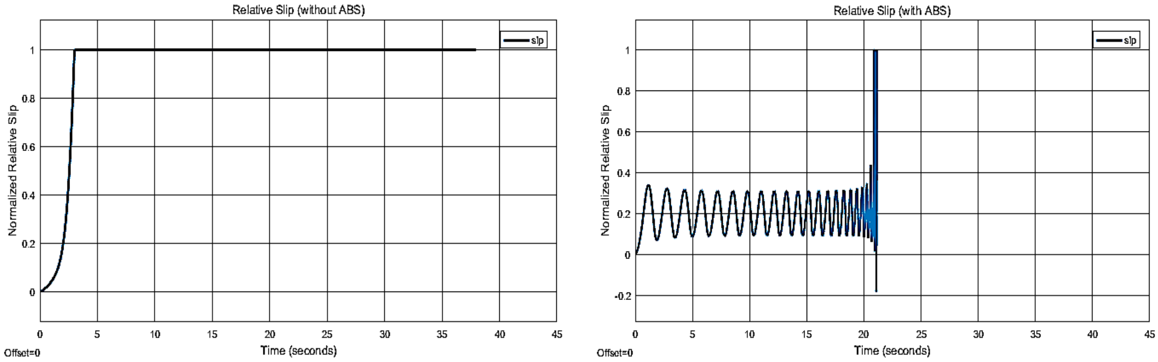
(a) (b)

Figure 16. Stopping distance (a) without ABS and (b) with ABS

6.1.4. Ice road

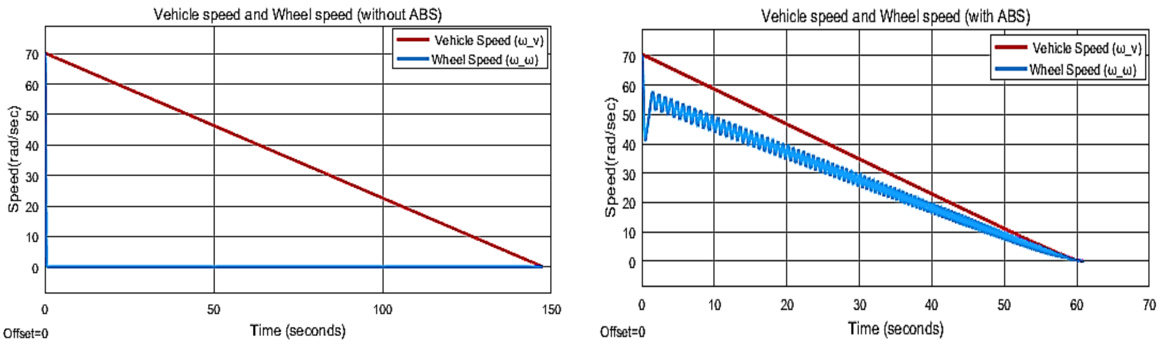
Figures 18-20 represent the simulation results for two automobiles on an ice road, one with ABS system and one without. The values reflect the wheel and vehicle speeds, stopping distance, and relative slip.

Figure 18 illustrates the relationship between vehicle speed and wheel speed while braking, emphasizing the distinction between braking with and without an ABS. Figure 18(a) demonstrates that in the absence of ABS, the wheel speed rapidly decreases to zero, signifying a total wheel lock-up while the vehicle remains in motion, resulting in a loss of control. Figure 18(b) demonstrates that with ABS, wheel speed fluctuates as the system adjusts brake pressure, averting complete lock-up and preserving traction, so enhancing vehicle control. Figure 19 illustrates the effectiveness of an ABS control unit in reducing stopping distances. In Figure 19(a), the vehicle without ABS required 6,472.51 feet and 147.454 seconds to come to a complete stop. In contrast, Figure 19(b) shows that the vehicle equipped with ABS stopped in 2,618.23 feet and 60.961 seconds, demonstrating the system's ability to significantly shorten braking distance and time.



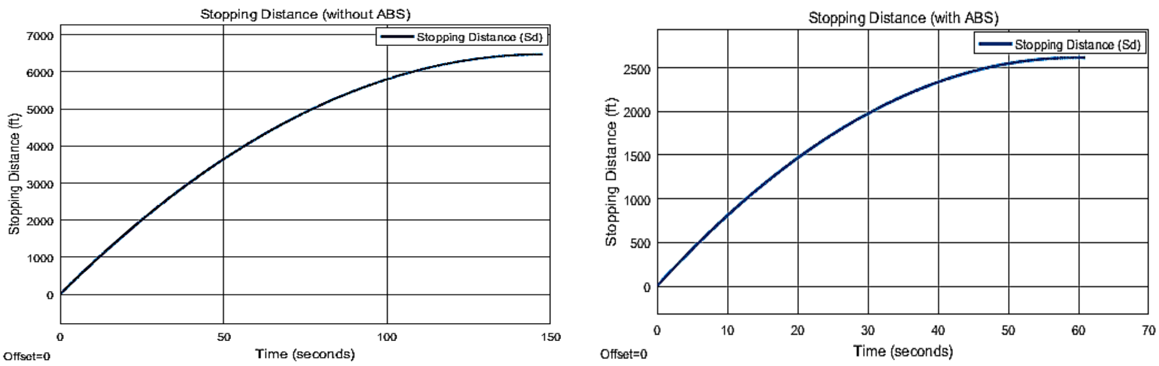
(a) (b)

Figure 17. Relative slip (a) without ABS and (b) with ABS



(a) (b)

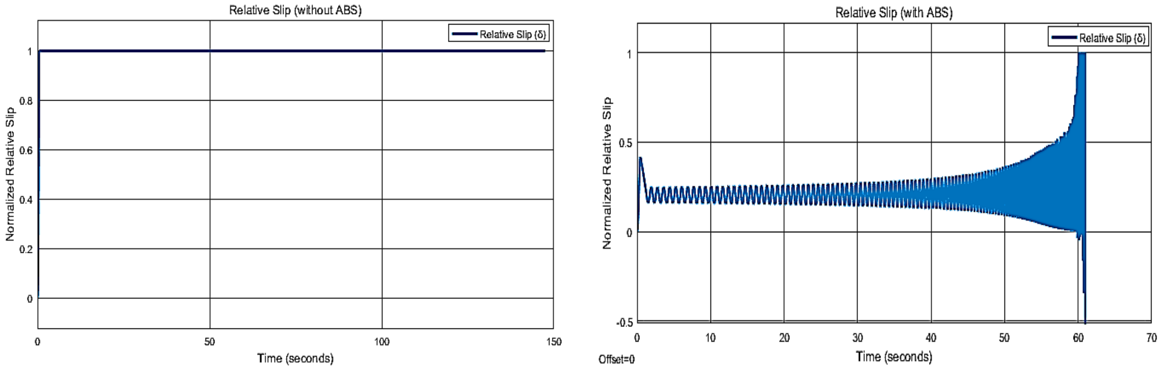
Figure 18. Vehicle and wheel speed (a) without ABS and (b) with ABS



(a) (b)

Figure 19. Stopping distance (a) without ABS and (b) with ABS

Figure 20 demonstrates the behavior of relative slip of the tires with and without the ABS. Figure 20(a) depicts relative slip without ABS, showing total slide at 100%, when the tire stops rotating while the vehicle continues to travel, resulting in a loss of grip and control. In contrast, Figure 20(b) depicts relative slip with ABS, demonstrating oscillations that prevent full lock-up of the wheels, so keeping traction and enhancing vehicle control when braking.



(a) (b)

Figure 20. Relative slip (a) without ABS and (b) with ABS

7. DISCUSSION OF RESULTS

First, we compared our study with the research conducted by Obagbuwa and Makade in 2023, which examined the efficacy of an ABS system in accident prevention compared to traditional braking systems. This study focused on evaluating the performance of both systems in terms of stopping distances and vehicle control. It utilized Monte Carlo sensitivity analysis and simulation tools such as MATLAB Simulink and Python. The results show that ABS significantly reduces stopping distances and effectively prevents wheel lock-up, allowing drivers to maintain control and vehicle speed during sudden braking. Figure 21 illustrates that a wheel equipped with the ABS system reaches a slip ratio of 1 at 15 seconds, indicating that wheel lock-up is prevented. In contrast, a wheel without ABS reaches a slip ratio of 1 after 5 seconds, demonstrating immediate wheel lock-up [27].

Figure 22 illustrates that automobiles with ABS reach their stopping distance faster than those without, therefore lowering the probability of accidents. Figure 23 displays a decline in wheel speed and vehicle speed, resulting in a positive slip ratio, and the automobile stops after 16 seconds. Figure 24 illustrates that vehicle and wheel speed behavior without ABS does not drop consistently, and the wheel speed rapidly approaches 0 within 5 seconds.

Our study specifically examined the coefficient of friction in relation to the design and application of different road surfaces. This approach enabled us to obtain more precise and accurate results. The findings reveal that concrete and wet asphalt exhibited the lowest slip rates among all evaluated surfaces, leading to shorter stopping distances compared to surfaces with higher sliding rates. This trend is also consistent for vehicle and wheel speeds. The data indicate that input brake torque is higher for ABS than for non-ABS braking, as ABS allows the wheels to spin at varying speeds to prevent skidding. Additionally, the results show that ABS achieves a lower slip rate compared to non-ABS braking, maintaining better traction between the wheels and the road surface. Overall, the study demonstrates that ABS brakes outperform non-ABS braking across all road types, with the benefits of ABS being most pronounced on slippery surfaces like concrete and wet asphalt.

The stopping distance and relative slip of the vehicle are illustrated in Figures 25 and 26, respectively, for each of the simulated roads utilized in the model, both with and without ABS control when $C_2 = 100$. Figure 25(a) depicts the deceleration rate of the vehicle while using the brakes under different surface conditions (dry cement, wet asphalt, snow, ice) without the presence of the ABS. We note that the vehicle speed steadily lowers until it comes to a complete stop, but the rate of deceleration varies depending on the surface type, with the deceleration process being slower on slick surfaces like snow and ice. Figure 25(b) illustrates the same phenomenon with the ABS system activated. Here, the vehicle's speed decreases more rapidly and steadily compared to Figure 25(a), as the ABS prevents wheel lock-up, maintaining tire traction on the road. This results in shorter stopping distances and improved vehicle control, even in slippery conditions. Figure 26(a) demonstrates the reduction in a vehicle's wheel speed when brakes are applied under different road surfaces (dry concrete, wet asphalt, snow, and ice) without the ABS. The wheel speed progressively drops until stopping totally, yet deceleration rates are slower on slippery terrain like snow and ice. In comparison, Figure 26(b) depicts the similar scenario with the ABS activated, where the wheel speed drops more rapidly and smoothly. The ABS minimizes wheel lock-up, providing more tire-road contact, shorter stopping distances, and increased vehicle control, even on slick roads.

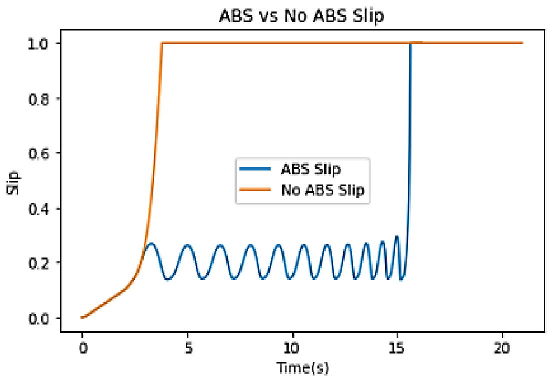


Figure 21. Relative slip with and without ABS [27]

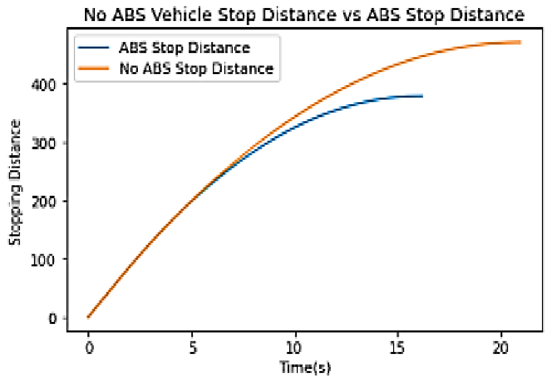


Figure 22. Distance between stops with and without ABS [27]

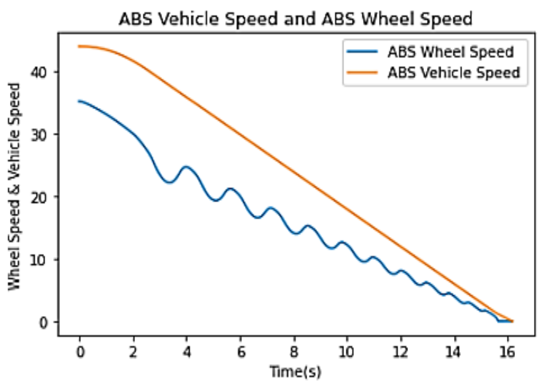


Figure 23. Vehicle speed and wheel speed behavior with ABS [27]

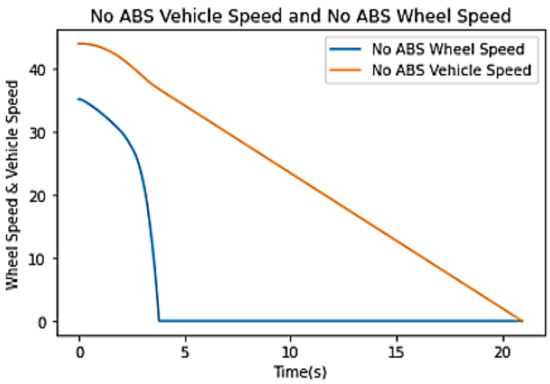
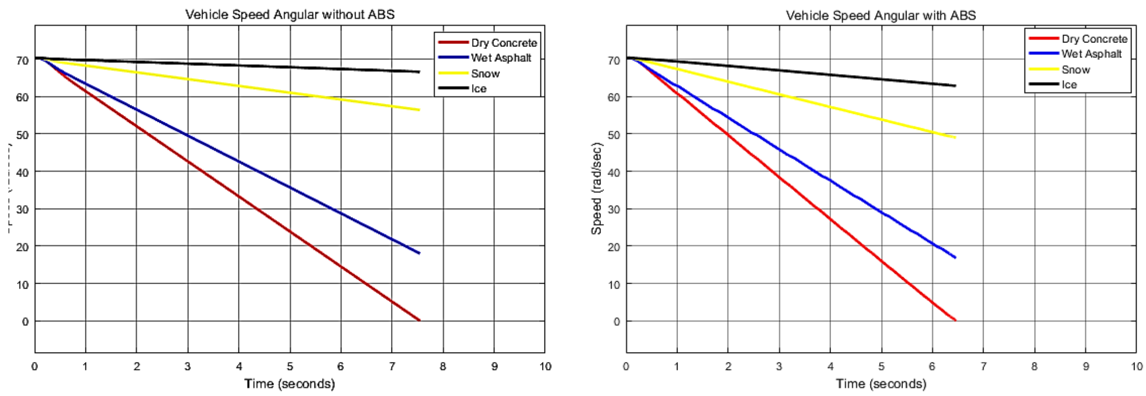
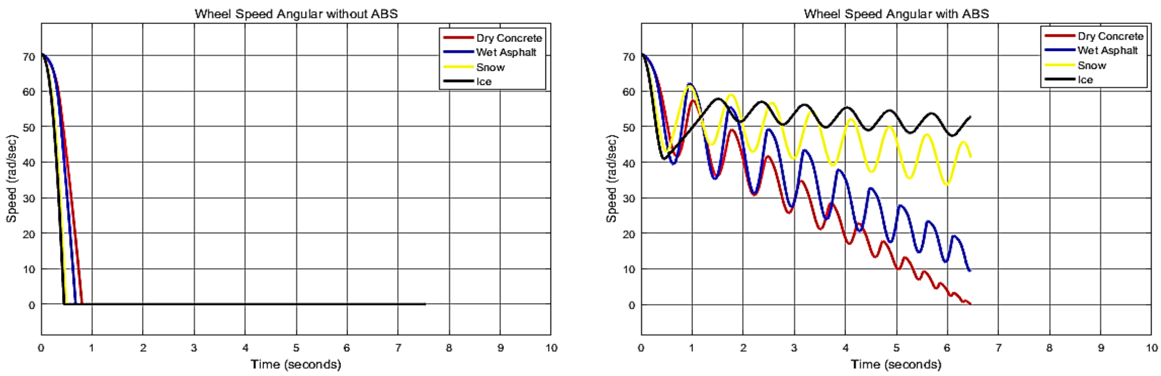


Figure 24. Without ABS, the vehicle's speed and wheel speed behavior are uncontrollable [27]



(a) (b)

Figure 25. Speed angular of vehicle: (a) without ABS and (b) with ABS



(a) (b)

Figure 26. Speed angular of wheel (a) without ABS and (b) with ABS

Upon comparing the outcomes of our investigation with those of the aforementioned study, we find that our stopping time and distance are shorter, and our relative slip is improved. The data presented in Table 3 demonstrate the extent to which ABS reduces stopping distance and time. Without ABS, sudden braking can lock the wheels, leading to potential rollover or skidding. ABS helps prevent this by quickly reapplying brake pressure after reducing it, allowing the wheels to continue rotating normally.

Table 3. ABS vs No ABS stopping time and distance (C1=20, C2=100, and C3=2)

Road	Stopping time (s) (without ABS)	Stopping time (s) (with ABS)	Stopping distance (m) (without ABS)	Stopping distance (m) (with ABS)
Dry concrete	7.546	6.460	101.92	88.21
Wet asphalt	10.142	8.611	136.045	114.86
Snow	38.623	21.877	515.79	287.61
Ice	147.454	60.961	1,972.82	798.04

8. CONCLUSION

This study has successfully introduced a revolutionary method for significantly improving the performance of ABS across a range of friction coefficients. The proposed feedback control unit, utilizing a proportional controller, demonstrated exceptional adaptability in adjusting the braking force based on real-time input signals and friction coefficient data. Compared to both non-ABS scenarios and standard ABS controllers, this approach resulted in markedly improved braking performance across various simulated road surfaces, as evidenced by faster stopping times, reduced wheel slip, and enhanced vehicle stability. The study's findings are highly relevant for enhancing vehicle safety in practical driving situations where friction coefficients can vary. Implementing this method in future ABS systems could lead to safer and more controlled braking across diverse traffic conditions. Additionally, the research indicates that concrete and wet asphalt roads offer quicker stopping times and shorter stopping distances compared to other road types, with reduced sliding rates. Further research may explore advancements such as refining fuzzy rule sets, employing neural networks, and integrating diverse sensor inputs to further enhance ABS controller performance and safety benefits.

REFERENCES

[1] J. El-bakkouri, H. Ouadi, and A. Saad, "Adaptive neuro fuzzy inference system based controller for electric vehicle's hybrid ABS braking," *IFAC-PapersOnLine*, vol. 55, no. 12, pp. 371–376, 2022, doi: 10.1016/j.ifacol.2022.07.340.

[2] S. L. and H. D. N. Zhang, J. Wang, Z. Li, "Multi-agent-based coordinated control of ABS and AFS for distributed drive electric vehicles," *Energies*, vol. 15, no. 5, 2022.

[3] T. A. Johansen, I. Petersen, J. Kalkkuhl, and J. Ludemann, "Gain-scheduled wheel slip control in automotive brake systems," *IEEE Transactions on Control Systems Technology*, vol. 11, no. 6, pp. 799–811, Nov. 2003, doi: 10.1109/TCST.2003.815607.

[4] Yonggon Lee and S. H. Zak, "Designing a genetic neural fuzzy antilock-brake-system controller," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 198–211, Apr. 2002, doi: 10.1109/4235.996019.

[5] A. F. Geleta, M. Gopal, and M. T. Lemi, "Vehicle anti-lock brake system - dynamic modeling and simulation based on MATLAB Simulink and CarSim," *Research on Engineering Structures and Materials*, no. November 2023, 2023, doi: 10.17515/resm2023.22me0601rs.

[6] M.-G. Unguritu and T.-C. Nichitelea, "Design and assessment of an anti-lock braking system controller," *Romanian Journal of*

Information Science and Technology, vol. 2023, no. 1, pp. 21–32, Mar. 2023, doi: 10.59277/ROMJIST.2023.1.02.
[7] Y. Yang, Q. Tang, L. Bolin, and C. Fu, "Dynamic coordinated control for regenerative braking system and anti-lock braking system for electrified vehicles under emergency braking conditions," *IEEE Access*, vol. 8, pp. 172664–172677, 2020, doi: 10.1109/ACCESS.2020.3024918.
[8] S. A. El-Fatah, A.-N. Sharkawy, N. Ghazaly, and A. Moaaz, "A comparative study of different control methods for anti-lock braking system (ABS)," *SVU-International Journal of Engineering Sciences and Applications*, vol. 2, no. 1, pp. 27–34, Jun. 2021, doi: 10.21608/svusrc.2021.65855.1007.
[9] M. Ulum and D. Arifianto Patriawan, "Modeling and performance testing of anti-lock braking system (ABS) with variation of road friction coefficient to braking distance," *Rekayasa*, vol. 15, no. 3, pp. 340–345, Dec. 2022, doi: 10.21107/rekayasa.v15i3.16561.
[10] H. Uzunov, K. Dimitrov, and S. Dechkova, "Experimental determination of the tire-road friction coefficient for a vehicle with anti-lock braking system," *AIP Conference Proceedings*, 2022. doi: 10.1063/5.0103769.
[11] V. Lorenčič, "The effect of tire age and anti-lock braking system on the coefficient of friction and braking distance," *Sustainability*, vol. 15, no. 8, Apr. 2023, doi: 10.3390/su15086945.
[12] D. Savitski *et al.*, "Wheel slip control for the electric vehicle with in-wheel motors: variable structure and sliding mode methods," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 10, pp. 8535–8544, Oct. 2020, doi: 10.1109/TIE.2019.2942537.
[13] B. Sullivan, J. Jiang, G. Mavros, and W.-H. Chen, "An exploration-exploitation approach to anti-lock brake systems," *arXiv preprint arXiv:2306.14730*, pp. 1–22, 2023.
[14] V. K. T. Mantripragada and R. K. Kumar, "Sensitivity analysis of tyre characteristic parameters on ABS performance," *Vehicle System Dynamics*, vol. 60, no. 1, pp. 47–72, Jan. 2022, doi: 10.1080/00423114.2020.1802491.
[15] J.-L. Wei, "Vehicle velocity and road friction coefficient estimation for anti-lock braking system," in *2020 International Automatic Control Conference (CACS)*, IEEE, Nov. 2020, pp. 1–5. doi: 10.1109/CACS50047.2020.9289783.
[16] L. Mims, J. Brooks, R. Gangadharaiah, C. Jenkins, D. Isley, and K. Melnrick, "Evaluation of a novel emergency braking task on a driving simulator with haptic anti-lock braking system feedback," *Safety*, vol. 8, no. 3, Aug. 2022, doi: 10.3390/safety8030057.
[17] B.-F. Wu, P.-J. Chang, Y.-S. Chen, and C.-W. Huang, "An intelligent wheelchair anti-lock braking system design with friction coefficient estimation," *IEEE Access*, vol. 6, no. c, pp. 73686–73701, 2018, doi: 10.1109/ACCESS.2018.2884658.
[18] J. El-bakkouri, H. Ouadi, F. Giri, and A. Saad, "Optimal control for anti-lock braking system: output feedback adaptive controller design and processor in the loop validation test," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 237, no. 14, pp. 3465–3477, Dec. 2023, doi: 10.1177/09544070221140938.
[19] A. J. Abougarair, N. A. A. Shashoa, and M. K. I. Aburakhis, "Performance of anti-lock braking systems based on adaptive and intelligent control methodologies," *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, vol. 10, no. 3, pp. 626–643, Aug. 2022, doi: 10.52549/ijeei.v10i3.3794.
[20] P. Lakhemaru and S. P. Adhikari, "Design and analysis of vehicle anti-lock braking system with fuzzy logic, bang-bang and PID controllers," *Himalayan Journal of Applied Science and Engineering*, vol. 3, no. 1, pp. 8–17, Jun. 2022, doi: 10.3126/hijase.v3i1.46941.
[21] D. A. Soni and D. Jitendra, "Anti-lock braking system," *International Journal of Innovative Research in Engineering & Management*, vol. 9, no. 1, pp. 248–252, Feb. 2022, doi: 10.55524/ijirem.2022.9.1.48.
[22] M. Bach, "Anti-lock Braking (ABS): how does it work?" *ebay.com*, 2023. https://www.ebay.com/motors/blog/anti-lock-braking-abs-how-does-it-work/ (accessed May 22, 2024).
[23] M. Liss, R. Zinko, O. Polishchuk, M. Łukasiewicz, and G. R. Betancur, "Principles of formation of a vehicle's braking system complex diagnostics," *MATEC Web of Conferences*, vol. 332, Jan. 2021, doi: 10.1051/matecconf/202133201018.
[24] H. Rikame, S. Ikkalaki, A. Inamdar, V. Jade, and K. Kadam, "Review on antilock braking system," *YMER*, vol. 21, no. 12, pp. 128–136, 2022.
[25] X. Liu, C. Ma, Y. Jiang, L. Zhang, and Y. Xue, "Research on anti-lock braking system of electro-mechanical braking vehicle based on feature extraction," *Journal of Physics: Conference Series*, vol. 1982, no. 1, Jul. 2021, doi: 10.1088/1742-6596/1982/1/012001.
[26] "Anti-lock braking system (ABS) modeling and simulation (Xcos)," *x-engineer.org*. https://x-engineer.org/anti-lock-braking-system-abs-modeling-simulation-xcos/ (accessed May 22, 2024).
[27] I. C. Obagbuwa and M. Makade, "Anti-lock braking system using monte car- lo simulations," in *Computational Intelligence in Pattern Recognition. CIPR 2022. Lecture Notes in Networks and Systems*, Singapore: Springer, 2023, pp. 653-671, doi: 10.1007/978-981-99-3734-9_53.

BIOGRAPHIES OF AUTHORS

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 email: m.albadwi@ust.edu, or al_badwi@hotmail.com.

Gehad Ali Abdulrahman 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 email: j.alabadi@ust.edu.

Mazen Farid holds a bachelor's degree in computer science and engineering at University of Aden and master's degrees in computer science from Universiti Putra Malaysia; He holds his Ph.D. degree in Faculty of Computer Science and Information Technology, Universiti Putra Malaysia (UPM). His research interest falls under computer networks, scientific workflow scheduling and cloud computing. He has authored several high-reputed journal/conference papers and is a reviewer of many research articles. He can be contacted at email: mazenfareed7@yahoo.com.

Heng Siong Lim received the B.Eng. degree (Hons.) in electrical engineering from Universiti Teknologi Malaysia, Malaysia, in 1999, and the M.Eng.Sc. and Ph.D. degrees in wireless communications from Multimedia University, Malaysia, in 2002 and 2008, respectively. He is currently a professor with the Faculty of Engineering and Technology, Multimedia University. His research interests include the areas of signal processing for wireless communications and advanced digital communication receivers design and cloud-native mobile networking. He can be contacted at email: hslim@mmu.edu.my.

Chin Poo Lee (Senior member, IEEE) received the Master of Science and Ph.D. degrees in information technology in the areas of abnormal behavior detection and gait recognition. She is currently a senior lecturer with the Faculty of Information Science and Technology, Multimedia University, Malaysia. Her research interests include action recognition, computer vision, gait recognition, and deep learning. She can be contacted at email: cplee@mmu.edu.my.

Nasr Alsakkaf is a Dean of Engineering and Computing Faculty of the University of Science and Technology-Aden. Yemen. He has a B.Sc. degree in computer science (1996) and master's in computer management (2014). In addition, Ph.D. in computer management (2019). He has experience in information systems, with emphasis on E-management, E-learning, and E-business. He can be contacted at email: Engineering@ust.edu.