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Comparative Analysis of ABS Braking Performance Using Fuzzy Logic Controller and Bang-Bang Control under Dry and Wet Road Conditions

Dhovan Ilhamdan Prima[1], Ismail Kholid[2], Hamid Nasrullah[3]

[1-2] Department of Automotive Engineering Technology, Politeknik Negeri Madiun, Indonesia, 63133
[3]Department of Automotive Engine, Politeknik Piksi Ganesha Indonesia, Indonesia, 54399

dhovanprima@pnm.ac.id

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Abstract

In this study, The effectiveness of the Anti-Lock Braking System is evaluated by comparing bang-bang control with fuzzy logic control. ABS plays a crucial role in vehicle safety, as it manages braking torque to ensure wheel slip remains at an optimal level, preventing the wheels from locking and maintaining control of the vehicle. A mathematical ABS model was implemented and analyzed using MATLAB/Simulink simulations to examine how both controllers behave. The simulation outcomes highlight that fuzzy logic control performs better than bang-bang control, with advantages such as shorter stopping distances, faster braking responses, and more stable slip control.

Keywords: *Anti-lock Braking System; Fuzzy Logic Control; Bang-bang Control; Simulation; Performance*

Abstrak

Dalam penelitian ini, kinerja Anti-Lock Braking System dievaluasi dengan membandingkan kontrol bang-bang dan kontrol logika fuzzy. ABS memiliki peran penting dalam keselamatan kendaraan karena mengatur torsi pengereman agar slip roda tetap berada pada tingkat optimal, sehingga mencegah roda terkunci sekaligus menjaga kendali kendaraan. Model ABS secara matematis diimplementasikan dan dianalisis melalui simulasi MATLAB/Simulink untuk mempelajari perilaku kedua pengendali. Hasil simulasi menunjukkan bahwa kontrol logika fuzzy memiliki kinerja lebih baik daripada kontrol bang-bang, dengan keunggulan berupa jarak pengereman lebih singkat, respons pengereman lebih cepat, serta kontrol slip yang lebih stabil.

Keywords: *Anti-lock Braking System; Fuzzy Logic Control; Bang-bang Control; Simulasi; Performa*

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1. Introduction

Driving safety is one of the fundamental concerns that receives major attention in the automotive industry [1]. Among the many systems integrated into a vehicle, the braking system plays the most crucial role. Its purpose goes beyond merely decelerating or stopping the vehicle; it is also directly linked to driver safety and the reduction of severe or fatal accidents [2].

ABS is now regarded as a critical element of modern automotive design, because it avoids wheel lock-up when hard braking is applied, thereby enhancing both stability and steering control. In typical accident scenarios, a vehicle often encounters an unexpected obstacle, and the driver must take corrective action upon realizing the danger. Such actions are influenced by several factors, including the distance separating the vehicle from the obstacle, the availability of alternative lanes, and the road surface condition. Without ABS, a vehicle can only maintain safety if the stopping distance is sufficient, the road is straight, and friction forces are balanced on both sides. When these criteria are not fulfilled, the likelihood of single or multiple collisions increases [3].

ABS primarily functions to manage wheel slip, ensuring maximum traction between the tire and road surface [4]. To accomplish this, ABS continuously monitors wheel speeds to detect possible lock-up. When sudden braking is detected, the system temporarily reduces brake pressure before reapplying it at an optimal level. This cycle is repeated at very short intervals, enabling ABS to enhance steering control during abrupt stops. As an outcome, the vehicle can be brought to a stop within minimal distance while ensuring stability in the lateral direction and retaining steering control [5]. Nonetheless, the current ABS design still encounters limitations in achieving fully optimized braking performance [6].

To overcome these challenges, extensive research has been carried out to improve ABS efficiency. Early studies investigated conventional control techniques, such as the application of Proportional-Integral-Derivative (PID) controllers, which were implemented to control the target slip ratio and minimize braking distance in simplified models like the quarter-car model [7][8]. More recently, advanced intelligent control strategies have been explored. Among them, the Fuzzy Logic Controller (FLC) has received considerable attention due to its ability to emulate human reasoning in dealing with system uncertainties and nonlinear behavior. Many researchers have reported the successful implementation of FLC in ABS [9][10][11]. In addition, hybrid approaches have emerged to achieve more robust performance, such as integrating fuzzy logic with PID or Sliding Mode Control (SMC) [12][13][14]. These findings consistently indicate that fuzzy-based strategies enhance stability and provide smoother braking control.

To validate the advantages of a given method, comparative analysis has become an essential research approach in this field. Various studies have compared the performance of different controllers. For example, Mokarram et al. concluded that optimized FLC outperforms PI controllers, while Jiang F. et al. demonstrated that nonlinear PID could shorten stopping distance compared to conventional PID [15][16]. Such comparative approaches are crucial in identifying the most effective control strategy. In this context, the studies conducted by Shah et al. and Khadr et al. are highly relevant, as they specifically compared the performance of fuzzy logic controllers with Bang-Bang controllers, which forms the foundation of this research [17][18].

Although there have been studies comparing these two controllers, there is still room for further exploration in terms of comparative analysis between Fuzzy and Bang-Bang controllers, particularly through simulations on standard platforms such as MATLAB/Simulink under dry and wet road conditions. Therefore, this study specifically aims to conduct such an analysis. The performance of both controllers will be evaluated to provide clear quantitative insights into which approach performs better under the tested scenarios.

2. Method

In this study, a mathematical model was developed based on the quarter-car model. Various mathematical equations were employed to model the braking components, including vehicle dynamics, wheel slip, tire behavior, brake actuators, and the ABS controller. Subsequently, a MATLAB/Simulink block diagram was constructed by incorporating the required parameters, producing vehicle responses such as vehicle speed, wheel speed, and relative wheel slip during the braking process.

In this research, a simplified longitudinal vehicle dynamics model was adopted in the form of a quarter-vehicle model, as illustrated in Figure 1. This model is commonly used in braking system studies because it is capable of capturing the fundamental characteristics of the interaction between the wheel and the road surface. The model assumes that a single wheel represents the overall longitudinal dynamics of the vehicle, thereby allowing a more efficient analysis of forces and torques.

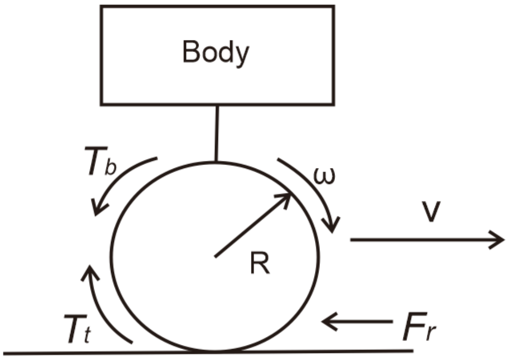

Figure 1. Quarter vehicle dynamic motion

2.1. Wheel Dynamics

The wheel experiences forces and torques acting on it during braking. The total torque T w T w on the wheel is formulated in equation (1) as follows:

$$\boldsymbol{T_w = T_t - T_b = I_w \times a_w} \qquad (1)$$

The traction torque is calculated based on the friction force against the road surface, as expressed in equations (2) and (3):

$$\boldsymbol{T_t = F_r \times R} \qquad (2)$$

$$\boldsymbol{F_r = \mu \times N} \qquad (3)$$

Thus, by substituting equations (1), (2), and (3), the angular acceleration of the wheel can be expressed as follows:

$$\boldsymbol{\alpha_w = \frac{1}{I_w}((\mu \times m \times g) \times R - T_b)} \qquad (4)$$

This equation indicates that the wheel's rotational speed is influenced by the friction force acting on the wheel and the magnitude of the applied braking torque.

2.2. Vehicle Dynamics

The braking force acting on a vehicle longitudinally can be expressed by the following equation 5:

$$\boldsymbol{F_f = m_v \times a_v} \qquad (5)$$

For maximum braking, this force is limited by the longitudinal slip friction coefficient, resulting in equation (6):

$$\boldsymbol{F_f = \mu_s \times m_v \times a_v} \qquad (6)$$

Where $\boldsymbol{\mu_s}$ is the longitudinal slip friction coefficient, and $\boldsymbol{m_v}$ is the mass of a quarter-vehicle.

2.3. Wheel Slip Ratio

An important parameter in brake control is the wheel slip ratio (S), which represents the difference in velocity between the vehicle and the wheel. Slip is calculated using equation (7) as follows:

$$\boldsymbol{S} = \frac{\boldsymbol{V_v - V_w}}{\boldsymbol{V_v}} \tag{7}$$

With the values of $\boldsymbol{v_v}$ and $\boldsymbol{v_w}$ obtained from equations (8) and (9):

$$\boldsymbol{v_v} = \boldsymbol{R} \times \boldsymbol{w_v} \tag{8}$$

$$\boldsymbol{v_w} = \boldsymbol{R} \times \boldsymbol{w_v} \tag{9}$$

Excessive slip values cause the wheel to lock, while too low a slip value indicates that braking is not maximized. The ABS is designed to maintain slip within the optimal range.

2.4. Wheel Friction Modeling

To calculate the friction force generated by the wheel and transmitted to the road surface, the Burckhardt tire model is employed. This model is widely utilized because of its high accuracy in representing the friction coefficient behavior. The mathematical expression of the Burckhardt model is given in equation (10):

$$\boldsymbol{\mu(\lambda) = C_1\left(1 - e^{-C_2\lambda}\right) - C_3} \tag{10}$$

In this context, $\boldsymbol{C_1}$, $\boldsymbol{C_2}$, and $\boldsymbol{C_3}$ are parameters whose values depend on the type of road surface. The corresponding Burckhardt constants for various surfaces summarized in Table 1.

Table 1. Burckhardt Model Coefficient

Road Type	**Parameter 1 (C_1)**	**Parameter 2 (C_2)**	**Parameter 3 (C_3)**
Dry Surface	1.2801	23.990	0.52
Wet Surface	0.86	33.82	0.35

The correlation between slip ratio and the friction coefficient is shown in Figure 2. As illustrated, the maximum friction coefficient is reached at a slip ratio of about 0.2 for all considered road conditions. This slip value is therefore identified as the optimal slip.

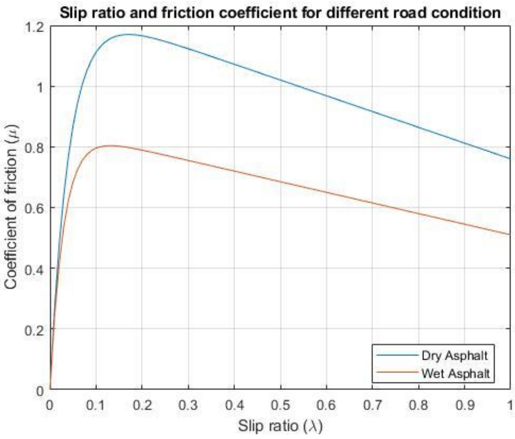

Figure 2. Friction–slip (μ–λ) curve describing tire behavior across different road conditions

The nomenclature for all equations is listed in Table 2.

Table 2. Nomenclatures

Symbol	Description	Unit
$\boldsymbol{T_t}$	*Driving torque*	Nm
$\boldsymbol{T_b}$	*Braking Torque*	Nm
$\boldsymbol{I_w}$	*Wheel rotational inertia*	Kg.m^2
$\boldsymbol{a_w}$	*Angular acceleration of wheel*	Rad/s^2
R	*Tire Radius*	M
$\boldsymbol{\mu}$	*Tire–road friction coefficient*	-
N	*Normal Load*	N
g	*Gravitational Force*	m/s^2
$\boldsymbol{M_v}$	*Mass of The Vehicle*	Kg
$\boldsymbol{a_v}$	*Vehicle Longitudinal Acceleration*	m/s^2
S	*Longitudinal Slip Ratio*	-
$\boldsymbol{V_v}$	*Forward velocity of vehicle*	m/s
$\boldsymbol{V_w}$	*Forward velocity of wheel*	m/s
$\boldsymbol{w_v}$	*Vehicle's angular motion speed*	Rad/s
$\boldsymbol{\mu_s}$	*Slip-based friction coefficient*	-
$\boldsymbol{F_f}$	*Force in longitudinal direction*	N
$\boldsymbol{F_r}$	*Force due to friction*	N

2.5. Simulation Model

The ABS control framework developed in this study employs two types of controllers: the Bang-Bang controller and the Fuzzy Logic Controller (FLC), both implemented within the Simulink environment. The Bang-Bang controller, also referred to as an on–off controller, functions as a feedback mechanism that processes the slip error signal to determine the braking force required for reducing slip and avoiding wheel lock-up. By managing both vehicle velocity and wheel speed simultaneously, this controller enhances braking performance compared to systems without control.

Figure 3 illustrates the Simulink model of the ABS integrated with the Bang-Bang controller. In this configuration, the controller uses slip error as input to calculate the braking force so that excessive slip is reduced while preventing wheel lock. Its operating principle is based on rapid switching between the maximum and minimum brake force when the slip surpasses predefined thresholds. The brake actuator subsystem is mathematically formulated to produce wheel angular acceleration as its output. Subsequently, vehicle velocity and braking distance are obtained through computational blocks based on the equations introduced previously. The slip ratio, derived from vehicle and wheel speeds, is compared against the optimal slip to generate an error signal, which is subsequently used by the controller to adjust the braking force.

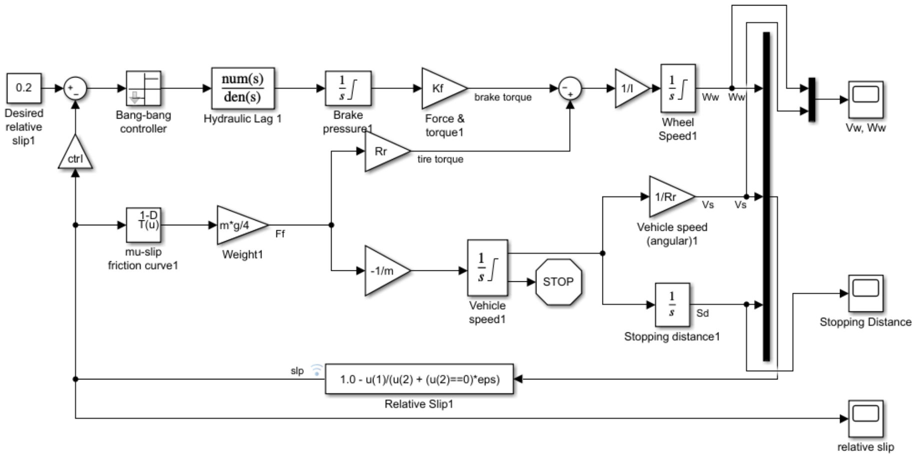

Figure 3. Block diagram illustrating the ABS system with Bang-Bang control strategy

The Fuzzy Logic Controller is employed as an alternative control method that is more adaptive in handling uncertainties and nonlinear characteristics in the braking system. This method can process information expressed in linguistic form and make decisions based on degrees of truth, similar to human reasoning. The advantage of fuzzy logic lies in its ability to describe conditions that cannot be fully represented using conventional mathematical models.

Within the ABS control system that incorporates fuzzy logic, the central goal is to keep the wheel slip ratio at its optimal value while maintaining flexibility to adapt to different road conditions. For this purpose, the fuzzy controller is designed to continuously adjust the target slip in response to changes in surface characteristics.

In this research, the fuzzy controller operates with two main input variables, as illustrated in Figure 4. The first input is the slip error, which is defined as the difference between the actual slip and the desired slip value. The second variable is slip rate of change, which represents the rate of slip variation and indirectly reflects vehicle deceleration. To process these inputs, suitable membership functions are used depending on the required sensitivity. For slip error, triangular functions are employed due to the need for fast response. For slip rate of change, a combination of trapezoidal and Fermi-shaped curves is used because the required sensitivity is relatively lower. The linguistic terms used for slip error consist of five categories: NH (Negative High), NL (Negative Low), ZE (Zero), PL (Positive Low), and PH (Positive High). Meanwhile, slip rate of change consists of three categories: NH (Negative High), ZE (Zero), and PH (Positive High).

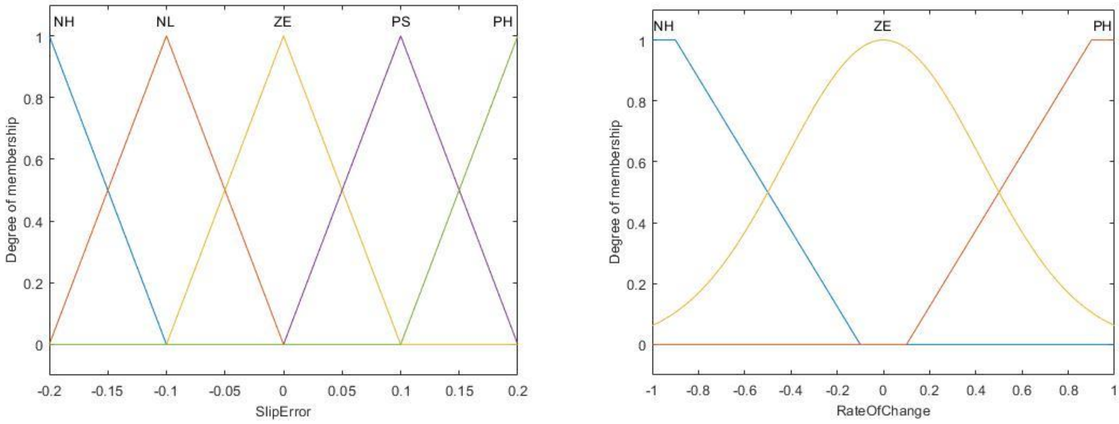

Figure 4. Fuzzy Parameters Representing Slip Error and Slip Rate of Change

The fuzzy inference process then maps the combination of the two inputs into an output using IF-THEN rules, with the OR logic operator as the connector between input variables. The output of this process is a command for brake pressure adjustment, as shown in Figure 5. For this output parameter, a triangular membership function is used due to the need for high sensitivity to changes. The linguistic terms for the output consist of DL (Decrease Pressure Large), DS (Decrease Pressure Small), KP (Keep Pressure), IS (Increase Pressure Small), and IL (Increase Pressure Large). Subsequently, the defuzzification process converts the fuzzy output into a crisp value so that it can be directly applied by the braking system actuator.

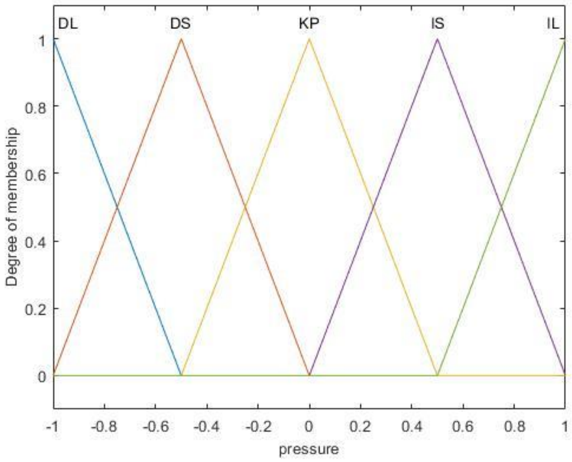

Figure 5. Fuzzy Output Parameter for Brake Pressure

In Table 3, the fuzzy control rules are illustrated as follows:

Table 3. Fuzzy Control Rules

Slip Error/Slip Rate	NH	ZE	PH
NH	DL	DS	KP
NL	DL	DS	KP
ZE	DS	KP	IS
PL	KP	IS	IL
PH	KP	IS	IL

An ABS simulation model based on fuzzy logic control is illustrated in Figure 6.

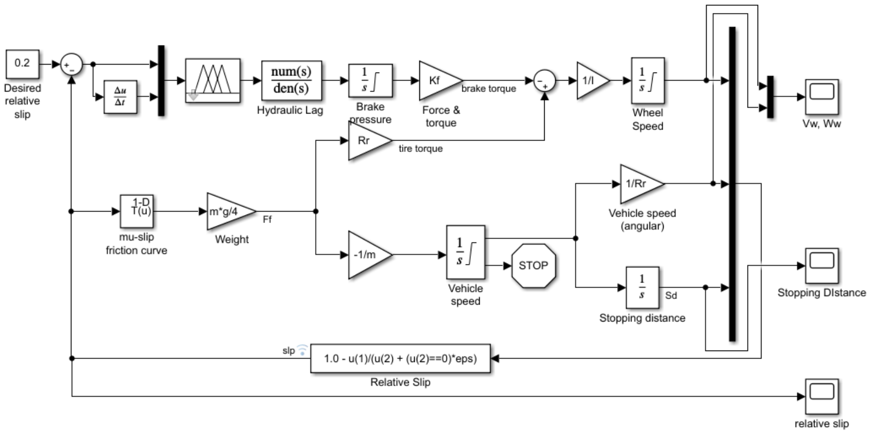

Figure 6. Block Diagram of ABS Control System Using Fuzzy Logic Controller

3. Results and Discussion

The model controlled by Fuzzy Logic (FL) produced simulation results that were then compared with the Bang-Bang controller model, tested under both dry and wet road scenarios. The ABS system performance was analyzed by evaluating the criteria of vehicle speed, stopping distance, longitudinal slip, and wheel speed. These selected criteria have been used by previous researchers in determining the braking system performance. The parameters used in this study are listed in Table 4.

Table 4. Simulation Parameter

Symbol	Definition	Value
M	Mass of The Vehicle	50 kg
v_o	Initial Velocity of Vehicle	88 km/h
G	Gravitational Acceleration	9.81 m/s^2

R_r	Wheel Radius	1.25 m
Tb_{max}	Maximum Brake Torque	1500 Pa
TB	Hydraulic Delay	0.01 Nm
I	Wheel moment of inertia	5 kg.m^2

3.1. Braking Distance Simulation Results

The simulation results of braking distance under dry asphalt and wet asphalt conditions are shown in Figure 7.

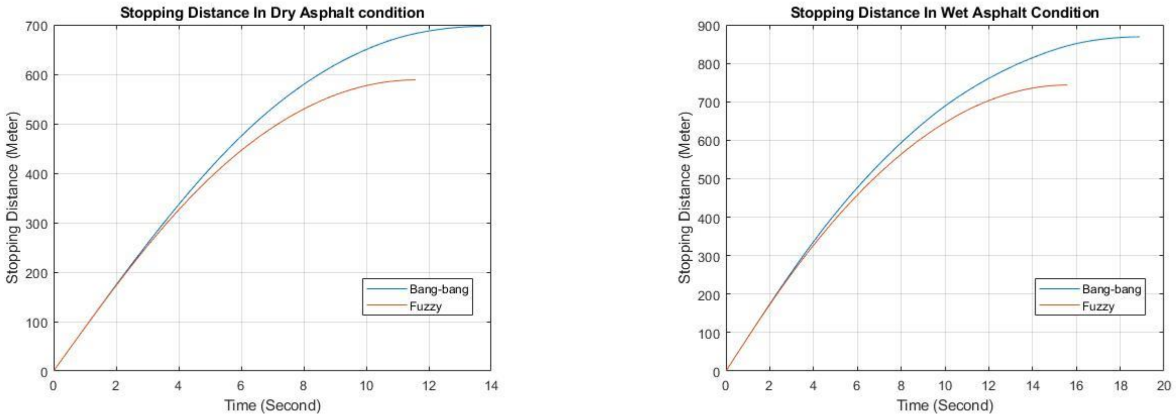

Figure 7. Comparison Stopping Distance of Two Controllers in Dry Surface and Wet Surface

Under dry road conditions, the Fuzzy Logic Controller (FLC) The vehicle was brought to rest at a distance of 600 meters with a braking time of approximately 11 seconds. In contrast, the Bang-Bang controller required a stopping distance of 700 meters and a braking time of about 13 seconds. This difference indicates that the Fuzzy Logic Controller has a better adaptability in proportionally regulating brake pressure, thereby producing optimal braking force without causing excessive slip.

Under wet road conditions, an increase in stopping distance occurred for both methods due to the reduced tire–road friction coefficient. The Bang-Bang controller recorded a stopping distance of 860 meters with a braking time of approximately 18 seconds, while the Fuzzy Logic Controller stopped the vehicle at 740 meters within 16 seconds. Although the performance difference is similar to that under dry road conditions, the shorter stopping distance achieved by the Fuzzy controller demonstrates its capability to maintain braking stability on low-traction surfaces.

Overall, the simulation results indicate that the Fuzzy Logic Controller provides significant advantages in reducing stopping distance compared to the Bang-Bang controller under both road surface conditions. This superiority arises from the ability of the Fuzzy controller to adjust brake pressure smoothly and in real-time, thereby minimizing traction loss and maintaining braking efficiency.

3.2. Vehicle Speed and Wheel Speed Simulation Results

Figures 8 and 9 present the comparison between vehicle speed and wheel speed for the Bang-Bang controller and the Fuzzy Logic Controller under two road surface conditions, namely dry asphalt and wet asphalt.

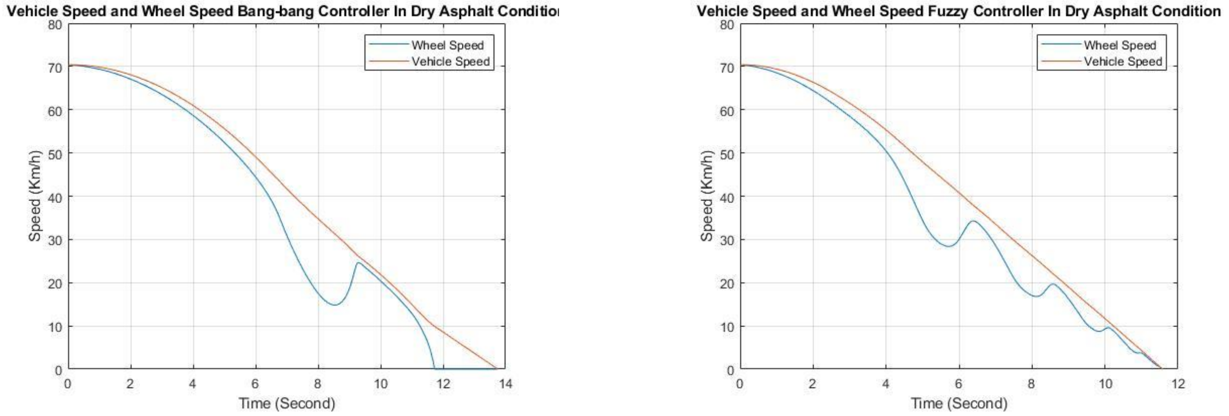

Figure 8. Comparison Vehicle Speed and Wheel Speed of Two Controllers in Dry Asphalt

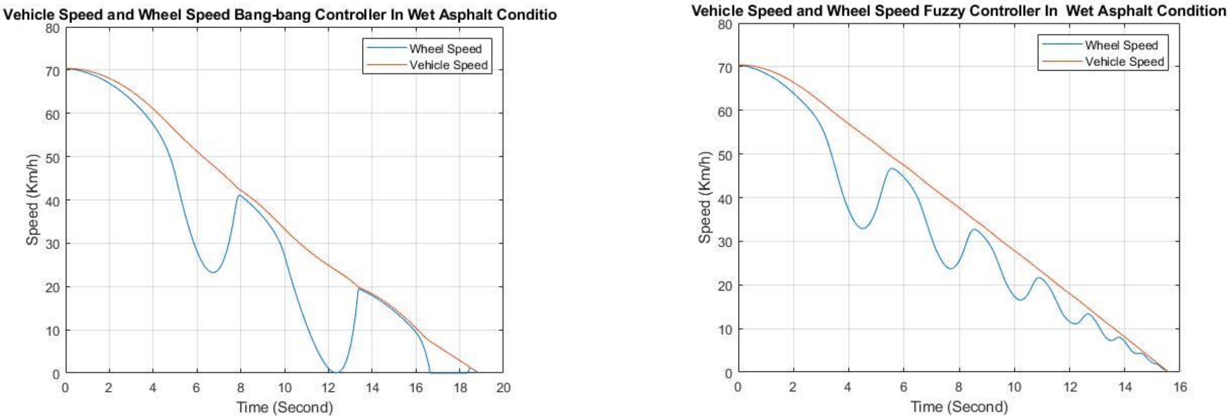

Figure 9. Comparison Vehicle Speed and Wheel Speed of Two Controllers in Wet Asphalt

Under dry road conditions, the Bang-Bang controller graph shows that wheel speed undergoes relatively large fluctuations with respect to vehicle speed, particularly within the 6–9 second interval. These fluctuations are caused by the on–off nature of the Bang-Bang method, which triggers rapid brake–release cycles and tends to produce varying wheel slip. In contrast, the Fuzzy Logic Controller demonstrates a smoother deceleration transition, with smaller wheel speed fluctuation amplitudes that align more closely with the reduction in vehicle speed. This indicates that the Fuzzy controller is capable of proportionally adjusting brake pressure to maintain optimal slip.

Under wet road conditions, the difference in characteristics between the two controllers becomes more pronounced. With the Bang-Bang controller, wheel speed experiences sharp drops accompanied by several sudden peaks, particularly within the 8–12 second and 14–16 second intervals, due to traction loss and repeated brake activation. This phenomenon can potentially increase stopping distance and reduce vehicle stability. Meanwhile, the Fuzzy controller continues to maintain a more consistent deceleration pattern, although the oscillation amplitude increases slightly due to the lower friction coefficient on wet surfaces.

In general, the simulation results demonstrate that the Fuzzy Logic Controller has a superior capability in maintaining alignment between wheel speed and vehicle speed, both on dry and wet roads. This characteristic plays a critical role in preserving vehicle stability and supports the reduction in stopping distance observed in the previous analysis.

3.3. Relative Slip Simulation Results

Figure 10 illustrates the characteristics of the vehicle's relative wheel slip under dry asphalt and wet asphalt conditions for both the Bang-Bang controller and the Fuzzy Logic Controller.

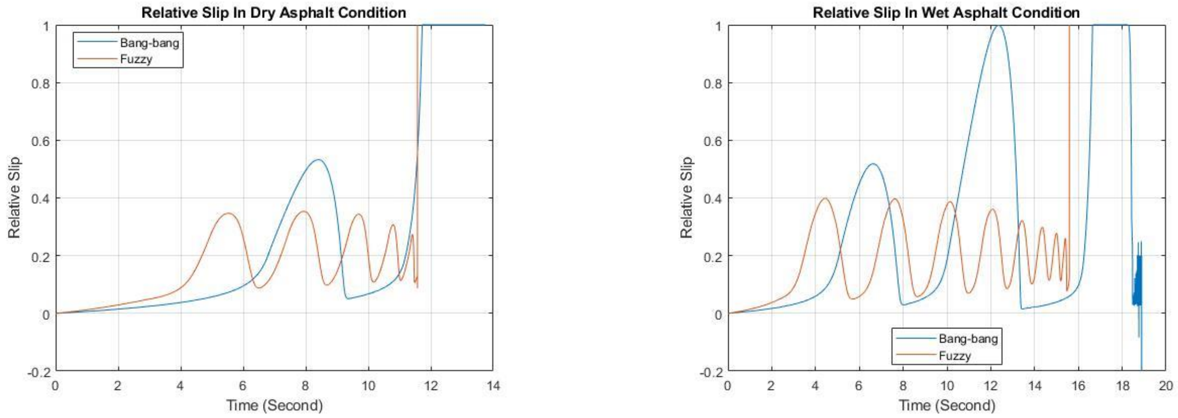

Figure 10. Comparison Relative Slip of Two Controller in Dry Asphalt and Wet Asphalt

Under dry road conditions, it can be observed that both controllers are able to maintain relative slip within a range close to the optimal value (around 0.2–0.3) during most of the braking period. However, the Bang-Bang controller shows a higher slip peak at approximately the 8th second, reaching nearly 0.55, which indicates a tendency of momentary wheel lock-up. In contrast, the Fuzzy Logic Controller exhibits a smoother slip profile with lower peak amplitudes and more controlled fluctuation periods. This difference indicates that the Fuzzy controller is more effective in damping slip oscillations through gradual brake pressure adjustments.

Under wet road conditions, the performance gap between the two controllers becomes more evident. The Bang-Bang controller experiences a significant slip increase at around the 12th second, reaching nearly 0.9, which reflects a drastic loss of traction due to the lower friction coefficient of the wet surface. In addition, the slip fluctuation pattern of the Bang-Bang controller tends to be irregular with large amplitudes, which may compromise braking stability. On the other hand, the Fuzzy Logic Controller is able to maintain slip within a more stable range (around 0.2–0.4) throughout braking, although with a slight increase in amplitude due to the slippery road condition.

Overall, these results reinforce the findings from the previous analyses, in which the Fuzzy Logic Controller demonstrated superior performance in controlling relative slip on both dry and wet surfaces. This capability is crucial for maintaining the balance between optimal traction and vehicle stability, ultimately contributing to the reduction of stopping distance.

4. Conclusion

Based on the simulation results and analysis, the Fuzzy Logic Controller (FLC) has been proven to deliver superior performance compared to the Bang-Bang controller in ABS braking systems, under both dry and wet road conditions. In terms of stopping distance, the Fuzzy controller was able to stop the vehicle within a shorter distance and in less time—approximately 100 meters shorter on dry roads and 120 meters shorter on wet roads compared to the Bang-Bang controller. The analysis of vehicle speed and wheel speed showed that the Fuzzy controller produced smoother and more synchronized deceleration, while the Bang-Bang controller tended to generate large fluctuations due to its on–off control nature. From the perspective of relative slip, the Fuzzy controller consistently maintained slip values within the near-optimal range (0.2–0.4), whereas the Bang-Bang controller frequently exhibited slip spikes that could potentially lead to momentary wheel lock-up. Overall, the implementation of the Fuzzy Logic Controller in ABS provides significant improvements in braking stability, slip control, and stopping distance efficiency. These improvements suggest that FLC has strong potential to enhance vehicle safety, particularly on road surfaces with low friction coefficients.

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