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Research Paper

Predictive Performance of Anti-Lock Braking System with PID Controller Optimized by Gravitational Search Algorithm for a Quarter Car Model: Simulation Modeling and Control

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Abstract

Anti-lock Braking Systems (ABS) are critical safety components in the passenger vehicles. The ABS is designed to prevent wheel lock-up during braking and maintain vehicle control. However, conventional braking systems have produced limitations in stopping distance and slip ratio, especially on varying road surfaces. This research addresses these issues by developing an ABS model using a quarter-car framework incorporated with a PID controller optimized by using Gravitational Search Algorithm (GSA). In this study, the mathematical equation of a quarter-car brake model is derived in representing a conventional braking system to provide a basis system for analyzing it performance. Next, Simulink model is developed in MATLAB to simulate the conventional braking system. To develop an ABS model, a PID controller is developed. The PID parameters are tuned manually using a trial-and-error approach to provide a baseline for comparison. Subsequently, GSA is applied to optimize the PID controller parameters to improve stopping distance and maintain optimal slip ratios. The ABS performance is evaluated by analyzing performance criteria including stopping distance, slip ratio, vehicle speed, and wheel speed. Comparative analysis indicated significant improvements in braking performance against the conventional system. The ABS with PID controller optimized by GSA reduced stopping distances, better slip ratio control, and improved vehicle stability during braking. The expected finding of the proposed ABS with PID optimized by GSA offers considerable advancements in automotive braking technology. These results underscore the potential for real-world applications in enhancing vehicle safety systems, contributing to safer and more reliable passenger vehicle braking performance.

Keywords: Anti-lock braking system; PID controller; Quarter car model; Gravitational search algorithm

1. Introduction

In modern vehicles, the ABS can be regarded as a very important feature for control and stability during emergency braking by preventing wheel lock-up. The current ABS design has some challenges in making optimal braking performance in various road conditions and vehicle speeds. Thus, for present limitations, there arises an urgent need for more advanced and adaptive control strategies to be developed. This work addresses these problems with the application of a PID controller, whose purpose is to minimize the error in braking performance by regulating the braking force. Traditional PID usually requires an accurate tuning of parameters, which may be very difficult in dynamic conditions. To overcome this disadvantage, the Gravitational Search Algorithm (GSA) for optimization of the parameters of the PID controller. This will enable the system to adapt better under various road conditions and improve vehicle safety with increased efficiency in braking.

Recent developments in ABS have recently been related to performance, safety, and energy efficiency in modern hybrid and electric vehicles. For instance, the work by Basrah et al. [1] looked into the integration between the ABS and regenerative braking systems, which is able to improve energy recuperation during braking by optimizing torque blending through NMPC with reduced energy losses while maintaining stability [2]. Rajendran et al. introduced a time-varying sliding mode control for ABS in electric cars, improving slip control under dynamic braking conditions and enhancing vehicle stability. Furthermore, Li et al. [3] developed a hybrid braking system combining mechanical and regenerative brakes to distribute braking torque more efficiently, significantly reducing energy consumption. These innovations contribute to improved braking performance, vehicle control, and energy efficiency in emergency braking scenarios.

Moreover, Khan et al. [4] invented electromagnetic damping phenomena for ABS system. The authors indicated promising results and improved 30% compared to conventional hydraulic system. Ahmad et al. [5] developed electronic wedge brake mechanism as a ABS system. The authors Gowda et al. [6] designed ABS system based on wheel slip estimation. Based on the slip estimation, the brake performance was improved 15% for longitudinal slip, 35% for snow surface and 30% for snow surface. Liu et al. [7] designed electro-mechanical braking system based on feature extraction for ABS. In the finding, the electro-mechanical braking system able to enhance the braking performance with the various advanced safety control. Cao [8] simulated the performance of an ABS system based on hydraulic pressure control and achieved a 20% improvement in braking performance compared to conventional systems.

Most of the previous research demonstrated that the ABS system has improved in dynamic performance by enhancing the controller part. The controller part provides a significant effect on the braking performance of the ABS system. Traditionally, ABS controllers were based on conventional techniques such as PID control, which calculate the required braking force by continuously adjusting the slip ratio but no optimization technique for controller parameters [5], [9]. However, limitations in handling nonlinearities of braking dynamics led to the integration of more sophisticated control methods, such as fuzzy logic, neural networks, and sliding mode control (SMC) [10]. These intelligent controllers offer improved performance in managing wheel slip under varying road conditions, enhancing the braking performance and vehicle stability [11]. For electric vehicles (EVs), ABS is also integrated with regenerative braking systems (RBS), where energy recovery is coordinated during braking [12]. Modern ABS designs are further advanced with adaptive and hybrid control strategies, such as Disturbance Observer (DO) and sliding mode observers, to handle external disturbances and uncertainties in real-time [13]. The continual research and development of ABS have made it a cornerstone of vehicular safety systems, particularly in enhancing both stopping efficiency and ride comfort.

This research introduces a novel ABS model integrating a PID controller optimized using the Gravitational Search Algorithm (GSA). The research gap addressed is optimizing ABS controller parameters using GSA optimization tools for improving braking performance under dynamic conditions compared with conventional tuning methods. This research, a quarter model of braking system is developed by using Newton's Second Law method. Then, the mathematical equation is used to model the brake system in MATLAB Simulink software. Since, the mathematical model of ABS is used similarly technique with Ahmad et al. [5] and Blancas et al. [9], it is difference on controlling method. Ahmad et al. [5] claimed automated tune PID parameters using Fuzzy fractional controller. While Blancas et al. [9] proposed friction coefficient calculation through feedback controller to enhance the PID controller performance for ABS system. Besides that, the hydraulic brake actuator system is also developed to present as the real system of the braking system in the vehicle. The PID controller is developed to control the hydraulic brake actuator system. This study, Ziegler-Nichols method is used for tuning PID parameters. Then, the parameters are optimized by using GSA optimization tool to obtain the optimum performance during sudden braking tests. The performance of PID GSA is compared against the conventional PID in controlling the braking performance. In using the PID GSA, The addition of the PID controller optimized by GSA enhances the vehicle's braking system by dynamically adjusting braking force based on controller performance criteria. This ensures optimal slip ratio control, reducing skidding and shortening stopping distances for improved vehicle safety. The vehicle speed, distance travel, longitudinal slip and wheel speed are considered as performance criteria of conventional braking without controller, PID and PID GSA for the analysis to measure the performance of the proposed controller.

2. Methods

In enhancing the performance of ABS controller, the conventional brake system model in vehicle is required. In this study, the quarter car traction model is developed by using Newton 2nd law metho for deriving the mathematical model. The brake model is developed by considering two braking conditions which is no brake input and brake input applied. The model is based on 2 degrees of freedom (2-DOF) quarter vehicle traction model as shown in **Figure 1**. Many researchers have been done using quarter car model to analyze the performance of ABS system [10], [14], [15], [16], [17], [18], [19]. According to previous researchers finding, the 2-DOF model is used to conduct the analysis of control performance in improving the braking performance on wheel slip and longitudinal dynamics [20], [21]. The used of 2-DOF model is able interacted between braking force, wheel rotation, and vehicle motion, which are the performance criteria to evaluate in this research.

From **Figure 1**, it can be shown that m represents mass of quarter section of vehicle, ω, v, R, T_b , T_t and F_r denotes wheel speed, vehicle longitudinal speed, wheel radius, brake torque, tractive torque, and road resistance. From the diagram, the mathematical model of braking system is derived. The details of derivation for braking system presented as below:

$$\sum T_w = I_w \times \alpha_w \tag{1}$$

where, T_w presents wheel torque, I_w presents moment inertia of the wheel and α denotes wheel angular acceleration. The summation of the torque is considered the torque initiated on the wheel during braking condition. The equation becomes:

$$T_w = T_t - T_b \tag{2}$$

where,

$$T_t = F_r \times R \tag{3}$$

$$F_r = \mu \times N \tag{4}$$

where, μ represents coefficient of friction of the tire and N denotes normal force of the wheel. So, final equation for the braking system will become from the substitution of equation 2, 3 and 4 into Eq. (1).

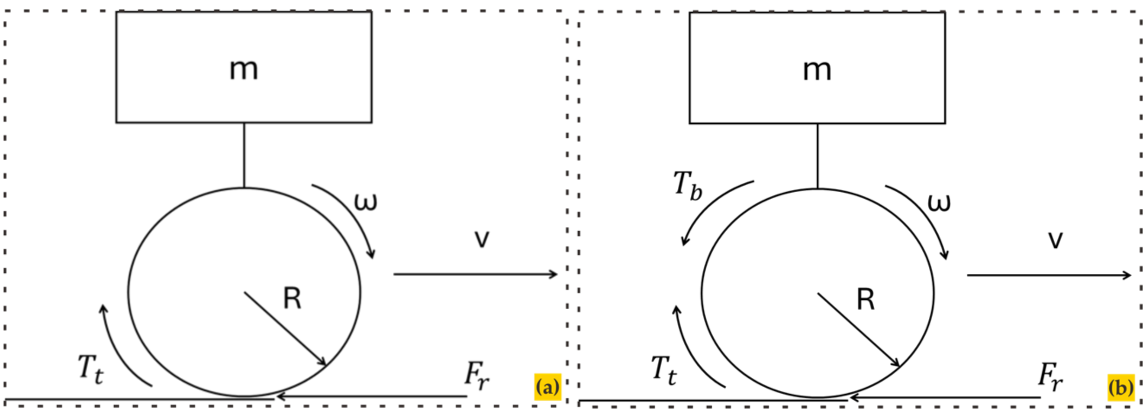

Figure 1. Quarter part of traction model for quarter section of vehicle during brake: (a) No braking input; and (b) Brake input applied

$$\alpha_w = \frac{1}{I_w}(((\mu mg) \times R) - T_b) \quad (5)$$

Hence, the longitudinal force for vehicle,

$$F_f = m_v \times a_v = \mu_s mg \quad (6)$$

where, m_v represents mass of vehicle body, a_v denotes longitudinal acceleration and μ_s represents coefficient of friction in function of longitudinal slip. However, the longitudinal slip equation will become,

$$S = \frac{V_v - V_w}{V_v} \quad (7)$$

where, V_v and V_w represents vehicle speed and wheel speed. The equation for both speeds are presented in Eq. (8) and Eq. (9) below:

$$V_v = R \times \omega_v \quad (8)$$

$$V_w = R \times \omega_w \quad (9)$$

where nomenclatures for the overall equations is listed in **Table 1**.

2.1. *Simulation Model*

In this section, the simulation model is divided in two different models which are convention brake system and anti-lock braking system (ABS) model. The ABS actuator is used for ABS model and added as additional component from the conventional model for presenting the ABS model. The input brake for the conventional model is the step input that has used in this simulation analysis.

2.2. *Conventional Brake System Model*

To evaluate the effectiveness of the control scheme, the conventional model is developed. The model is developed by using MATLAB Simulink software. Then, the model is used the validated model proposed by Haris et al. [10] to ensure the analysis of the braking system performance similar with real implementation. The model for conventional braking system is illustrated in **Figure 2**.

Table 1. Nomenclatures

Symbol	Description	Unit
F_f	Road resistance	N
W_w	Wheel angular speed	rad/s
V_v	Longitudinal vehicle speed	m/s
V_w	Longitudinal wheel speed	m/s
a_v	Longitudinal acceleration	m/s^2
m_v	Vehicle mass	kg
R	Tire radius	m
T_t	Tractive torque	Nm
T_b	Brake torque	Nm
T_w	Wheel torque	Nm
I_w	Wheel moment of inertia	kgm^2
α_w	Wheel angular acceleration	rad/s^2
S	Longitudinal slip	Dimensionless
μ	Coefficient of friction	Dimensionless
g	Gravitational acceleration	m/s^2
N	Wheel normal force	N
$\mu = f(s)$	Coefficient of friction in function of longitudinal slip	Dimensionless

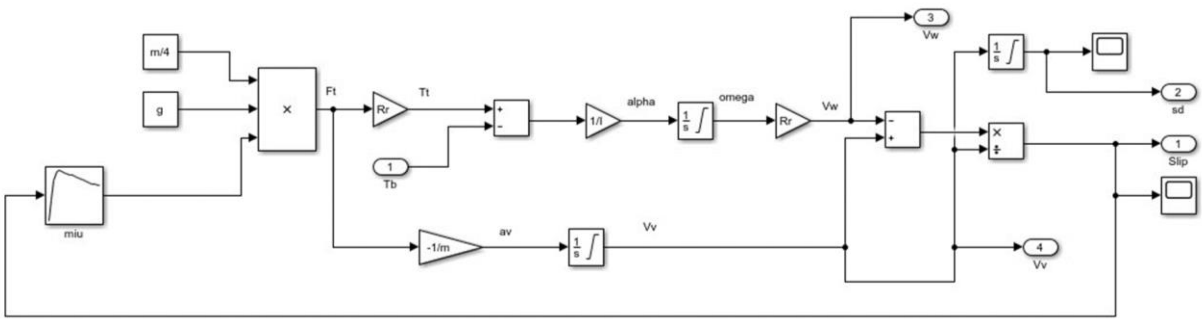

Figure 2. Simulink block diagram for conventional braking system

Based on **Figure 2**, the simulink block diagram is developed by using the equation from mathematical derivation in section modelling of braking system. Through the provided diagram, the coefficient of friction versus slip data is obtained from the 1-D look up table block diagram and it default setting. In the look up table setting the table data is set, *mu* and *slip* for breakpoint value. Then, the data for coefficient of friction and slip is generated automatically. Hence, to conduct the simulation for the conventional brake system, the simulation parameters are used. The parameters are listed in **Table 2**.

2.3. Anti-lock Brake System (ABS)

In order to develop ABS system, the hydraulic brake actuator is required. The hydraulic actuator is used to control the pressure of the hydraulic oil in the brake system pipeline in avoiding sudden braking condition lose control, wheel lock and tire skidding. In this simulation, the hydraulic brake actuator is modeled by using MATLAB Simulink software as shown in **Figure 3**. Then, the convention brake model is associated with hydraulic brake actuator in producing a completed ABS system for quarter car model.

From **Figure 3**, the hydraulic brake actuator component consists of hydraulic lag, brake pressure and for force and torque gain to provide a brake torque for the brake system during braking. The hydraulic lag is developed in the form of transfer function to represent delay from controller to the hydraulic response. The consideration of the hydraulic lag is considered for presenting the actual behavior of the hydraulic oil flow through pipeline to the brake system. The input electrical current is used for the hydraulic lag to present the hydraulic actuator for pressurizing the hydraulic oil into the ABS brake module. The electric current signal is supplied hydraulic lag based on the feedback of the controller during braking event. While the output for the hydraulic lag produced brake pressure to create the brake torque for the brake system. The completed system for ABS system is presented in **Figure 4**.

2.4. Control Scheme for ABS System

In the actual system of braking system, the component of the conventional brake system consists of brake pedal, master cylinder, brake pipeline, brake caliper (front) and brake cylinder (rear). All the components are operated without any controller system during braking event. In this study, the ABS module is added to control the flow of hydraulic oil distributed to the brake caliper and brake cylinder. The ABS module can be modeled as shown in **Figure 5** using MATLAB Simulink software. ABS brake controller has provided an unique challenges to the designer especially to obtain optimal performance in term

Table 2. Simulation parameters for conventional brake system

Symbol	Value (Unit)
I	5 kg.m^2
Kf	1 N/m
PBmax	1500 Pa
Rr	1.25 m
Tb	0.01 Nm
g	9.81 m/s^2
m	50 kg
v0	80 km/h

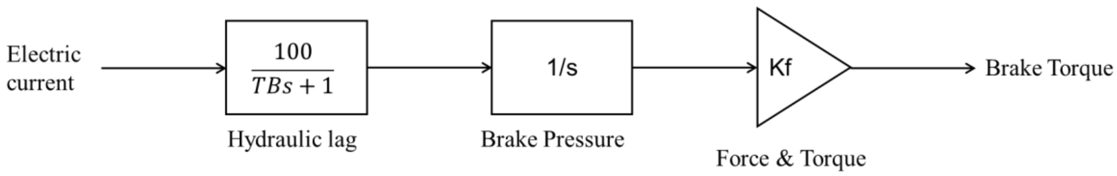

Figure 3. Hydraulic brake actuator model

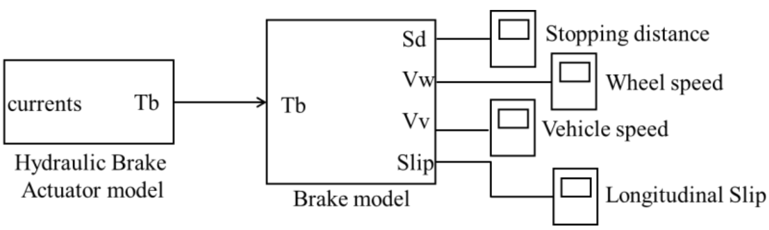

Figure 4. ABS system

of skidding, wheel locking during braking and lose control of steering wheel tends accident during sudden braking condition. The challenging to develop the ABS controller is the controller should have optimum parameters to serve optimum performance for the ABS system. depending on road conditions, the maximum braking torque may vary over a wide range, the tire slippage measurement signal, crucial for controller performance, is both highly uncertain and noisy, on rough roads, the tire slip ratio varies widely and rapidly due to tire bouncing, brake pad coefficient of friction changes, and the braking system contains transportation delays which limit the control system bandwidth [22].

As mentioned before, the ABS system consists of a conventional hydraulic brake system integrated with antilock components which affect the control characteristics of the ABS. ABS control is a highly a nonlinear control problem due to the complicated relationship between friction and slip [23]. In this study, the PID controller is proposed to control the ABS system. As known, the PID controller was used by many researchers to implement in many applications because the robustness of the controller in obtaining the optimal performance for the system. In the ABS application, many researchers have been invented by using PID controller with presented the promising result to prevent skidding, wheel locking and slip of the tire during sudden braking condition. The basic control system for ABS system is shown in **Figure 5**. ABS control system is compared between conventional, and ABS associated with the PID controller. The primary control objective is maintaining the optimal slip ratio for maximum traction during braking. The slip ratio determines the level of traction between the tire and the road. Maintaining an optimal slip ratio (typically around 0.2) maximizes braking efficiency and prevents wheel lock-up or skidding. In this study, single input single output for the control structure is used. The SISO method more efficient and it is proving many research used SISO in ABS control techniques [24], [25], [26]. It is to avoid lag of controller performance in sudden braking condition. To obtain optimum performance of the ABS system, the parameters of the PID controller is optimized by using GSA optimization tool. ABS behavior is inherently non-linear due to varying tire-road friction coefficients and wheel dynamics. GSA, with its global search capabilities, is well-suited to handle such non-linearities when tuning the PID controller, improving overall braking efficiency and vehicle safety.

2.5. *Gravitational Search Algorithm*

GSA is intrinsically designed to balance the exploration part-the searching of the global solution space-and the exploitation part, namely fine-tuning around promising solutions. This helps the algorithm in PID tuning for ABS to explore various globally available parameter sets and then zoom in on the most effective PID parameters to fine-tune the control performance. In fact, ABS systems have to face different conditions of roads, such as dry, wet, and icy surfaces, along with dynamic braking forces. GSA's ability to change the positions of the agents based on gravitational mass, which is directly proportional to the fitness, could enable the algorithm to dynamically change the PID parameters concerning different braking scenarios with robust control performance. The PID GSA parameters is listed in **Table 4**. The GSA algorithm structure can be described as gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the square of the distance between them [27]:

$$F = G\frac{M_1 M_2}{R^2} \quad (10)$$

where F is the magnitude of the gravitational force; G is the gravitational constant; M_1 and M_2 are the mass of the first and second particles respectively; and R^2 is the distance between two particles.

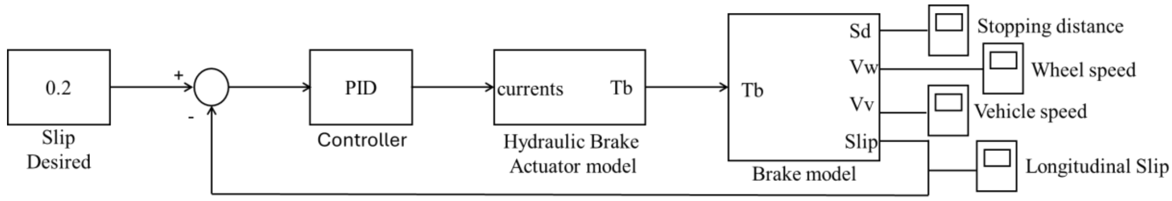

Figure 5. ABS control system

Referring to Newton's second law of motion, when a force, F, is applied to a particle, its acceleration, a, depends only on the force and its mass, M:

$$a = \frac{F}{M} \quad (11)$$

Thus, by considering three masses in theoretical physics, Newton's laws are expressed in the following equations:

$$F_{ij} = G\frac{M_{aj} \times M_{pi}}{R^2} \quad (12)$$

$$a_i = \frac{F_{ij}}{M_{ii}} \quad (13)$$

where the gravitational force, F_{ij}, acts on mass i by mass j proportionally product of active gravitational of mass j and passive gravitational of mass i and inversely proportionally to the square distance between them; a_i is proportional to F_{ij} and inversely proportional to the inertia mass of i. However, M_{aj} and M_{pi} represent the active gravitational mass, i and passive gravitational mass, j, respectively, while M_{ii} represents the inertia mass of particle i.

Moreover, the N agents (masses) are also considered in a system; the position of the i^{th} agent can be expressed in Equation 14, where x_i^d represents the position of i^{th} agent in the d^{th} dimensions:

$$X_i = \left(x_i^1 \ldots x_i^d \ldots x_i^n\right) for\ i = 1, 2, \ldots n \quad (14)$$

At a specific time t, the force acts on mass i from mass j, which can be expressed in Eq. (15) and Eq. (16), where ε is the small constant and is the Euclidian distance between agent i and agent j:

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \varepsilon}\left[x_j^d(t) - x_i^d(t)\right] \quad (15)$$

$$R_{ij}(t) = \left\|x_i(t), x_j(t)\right\|_2 \quad (16)$$

In order to provide stochastic characteristics, the total force that acts on agent i in dimension d be a randomly weighted sum of d^{th} component of the force exerted from other agents, where $rand_j$ is a random number in the interval [0,1]:

$$F_i^d(t) = \sum\nolimits_{j=1, j\neq i}^{N} rand_j F_{ij}^d(d) \quad (17)$$

Meanwhile, by considering the law of motion, the acceleration of agent i at the time, t and indirection d^{th}, $a_i^d(t)$ is expressed as follows:

$$a_i^d(t) = \frac{F_d^i(t)}{M_{ii}(t)} \quad (18)$$

Moreover, the ensuing velocity of an agent is considered as a fraction of its current velocity that is added to its acceleration. Thus, the position, x, and velocity, v, are defined in the following equations, where $rand_i$ is a uniform random variable in the interval [0,1]:

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \quad (19)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (20)$$

The gravitational constant, G, is first initialised and then reduced with time to control the search accuracy. Accordingly, G is a function of initial value (G_o) and time t, where fit_i represents the fitness value of the agent i at time t:

$$(G_o) = G(G_o, t) \quad (21)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (22)$$

$$m_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \quad (23)$$

As for a minimisation problem, the best (t) and worst (t) can be defined as follows:

$$best(t) = \min fit_j(t)\,; j \in \{1, \ldots\ldots N\} \quad (24)$$

$$worst(t) = \max fit_j(t)\,; j \in \{1, \ldots\ldots N\} \quad (25)$$

Meanwhile, **Figure 6** presents the flow process of GSA, according to [27], [28] who further described the flow process in detail.

In this study, GSA was applied to obtain the optimum value of the PID controller. There are three parameters for the optimisation of PID, which are the proportional gain, K_p, integral gain, K_i and derivative gain, K_d, to the brake force requirement. In order to evaluate the agents' fitness at any given velocity, the fitness function was set. The GSA varied for each parameter independently up to the point of optimum performance, which indicates the identification of minimum fitness. The fitness function and the choice of parameters for search space were selected carefully to facilitate faster convergence. Since PID was the robust controller for industry application, average slip ratio error of controller. Since both indicators were among the most important aspects for evaluation in this study, the selected fitness function for the control strategy

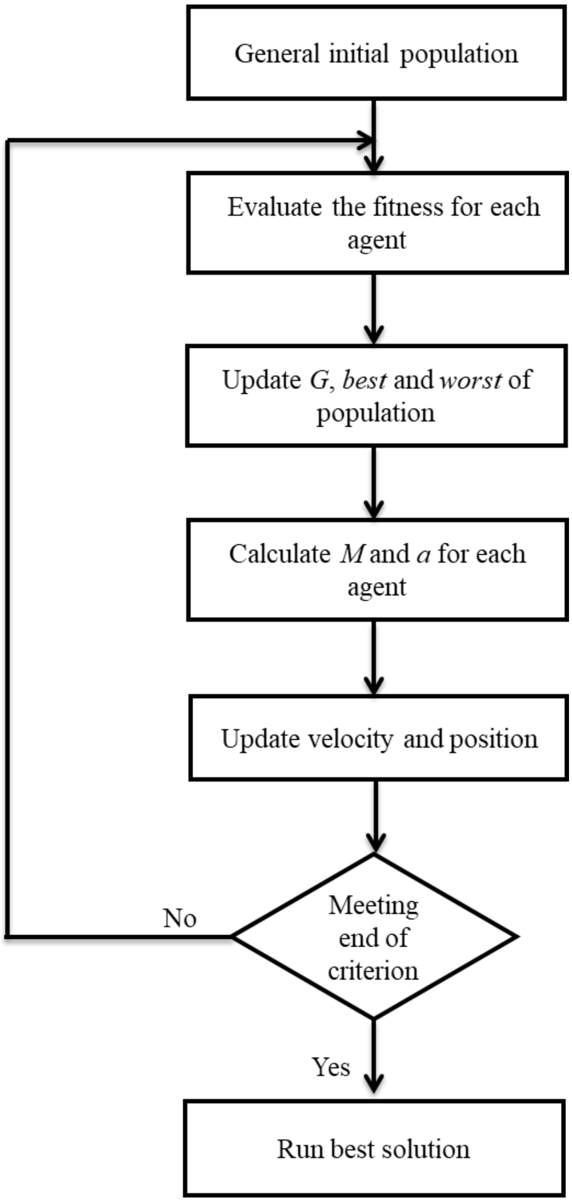

Figure 6. GSA optimization process flow

referred to the root mean square (RMS) value of slip error, *e*, between the desired slip and actual slip. The fitness function for the GSA as presented:

$$Fitness\ Function, f(Kp, Ki, Kd) = \sqrt{e^2(t) + (slip^2)} \quad (26)$$

where $e(t)$ represents the comparison between the desired slip and actual slip of the tire, while *slip* refers to the slip response of braking system.

As shown in **Table 3**, the similar approach for the tuning of control parameters, GSA configuration and proposed parameter values Amer et al. [29] and Rashedi et al. [27] were considered for this study. Firstly, the number of agents (N_a) and the number of iterations (N_i) were selected using the Nicholas Ziegler method by observing the number of iterations required for the solution to converge. Following that, the search space for each parameter was defined by setting the value of lower and upper limits. The limit for each parameter was established after a series of sensitivity analysis, where the controller response was indicated under different parameters. Apart from ensuring convergence, these limits were chosen to avoid the controller from entering the unstable region. Otherwise, the overall optimisation procedure had to cease. Meanwhile, the number of dimensions was determined based on the number of variables that require optimisation.

3. Result and Discussion

The performance of ABS system is analyzed by evaluating the criteria of vehicle speed, distance travel, longitudinal slip and wheel speed. These selected criteria are used by previous researchers in determining the performance of the braking system [30], [31], [32], [33]. All the criteria are examined in time domain. However, the performance of ABS system for the simulation testing is focused on the longitudinal direct which means the straight road [34], [35], [36]. The input of simulation testing is the step input as torque brake for convention braking system. **Figure 7** shows the result of vehicle speed for conventional brake (solid line or black), ABS with PID (dash line or blue) and ABS optimized by PID GSA (dotted line or red). Based on the result, the ABS optimized by PID GSA was demonstrated better performance than conventional braking system

Table 3. GSA parameters for ABS control

Parameter	Value
Number of agents, N_a	50
Number of iterations, N_i	100
Beta, β	0.1
Epsilon, ε	0.01
Number of dimensions, d	3 (Kp,Ki,Kd)

Table 4. PID GSA optimized parameter

	PID Parameters			PID GSA Parameters		
	Kp	*Ki*	*Kd*	*Kp*	*Ki*	*Kd*
Values	50	1	0.2	49.52	0.95	0.14

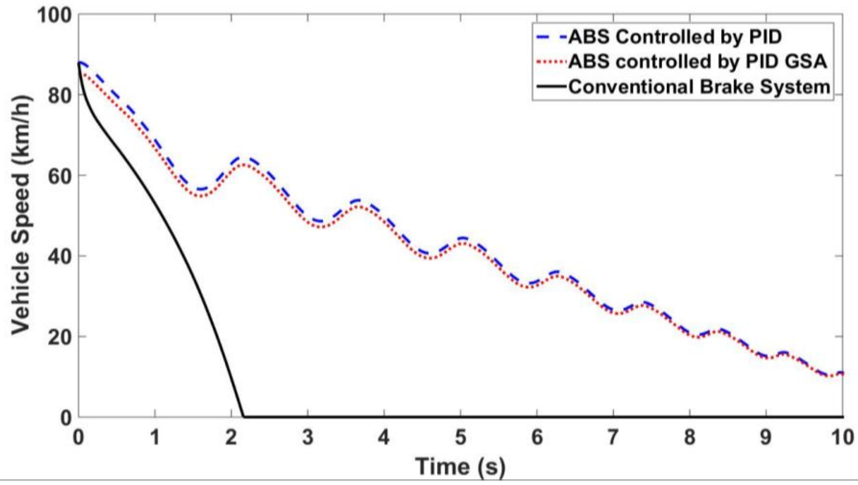

Figure 7. Vehicle speed versus time

and ABS controlled by PID. The conventional braking system was able to decrease the vehicle speed from 80 km/h to 0 km/h in 2.5 seconds. But from this analysis, the conventional braking system produced skidding to the vehicle and this motion was tended uncontrolled motion to the driver during sudden braking event. However, the ABS optimized by PID GSA was able to this drawback by producing intermittent braking force to decrease the vehicle speed when sudden braking event. The GSA PID controller optimizes braking by applying intermittent brake forces to prevent wheel lock-up and maintain vehicle stability. This results in a slower initial speed reduction compared to conventional brakes, which may apply maximum braking force instantly. The evidence can be founded through the results below.

Another criterion for evaluating the braking performance is the braking distance of vehicle body. The result for distance travel is shown in Figure 8. Through the result, ABS optimized by PID GSA was produced a short distance travel during braking compared to others. A comparison performance between ABS optimized by PID GSA and ABS controlled by PID is obtained by evaluating the percentage of error. The ABS optimized by PID GSA was better 5% than ABS controlled by PID.

Figure 9 shows the longitudinal slip result for conventional braking system, ABS controlled by PID and ABS optimized by PID GSA. By using the ABS optimized by PID GSA, the tire longitudinal slip for the vehicle is maintained at 0.2. So that, the performance of the ABS actuator was able performed well compared to the others. Otherwise, the performance of the ABS controlled by PID was slightly different compared to ABS optimized by GSA because the desired value of the tire longitudinal slip angle of the controller is set based on the critical value of longitudinal slip ratio for the passenger vehicle.

The wheel speed result for quarter car brake model is illustrated in Figure 10. The ABS optimized by PID GSA results demonstrate the wheel speed of quarter car decrease from 90 km/h to 5 km/h in 10 second during braking event. The conventional braking system was able to decrease the wheel speed from 90km /h to 30 km/h in 10 seconds. Based on the results obtained, it can be concluded that the ABS optimized by PID GSA was able to use for ABS actuator for enhancing the braking performance. By using the optimization technique, the performance of ABS controller was enhanced and the proposed controller can be used in experimental testing and validation process in the future works.

4. Conclusion

The quarter car brake model integrated with a PID controller optimized using the Gravitational Search Algorithm (GSA) was successfully developed and evaluated through MATLAB Simulink simulations. The simulation results demonstrated significant improvements in braking performance compared to conventional braking systems and ABS systems with manually tuned PID controllers. The proposed ABS system optimized by PID-GSA achieved promising braking performance in term of reducing stopping distances and maintaining a stable slip ratio where it is critical for vehicle safety. Specifically,

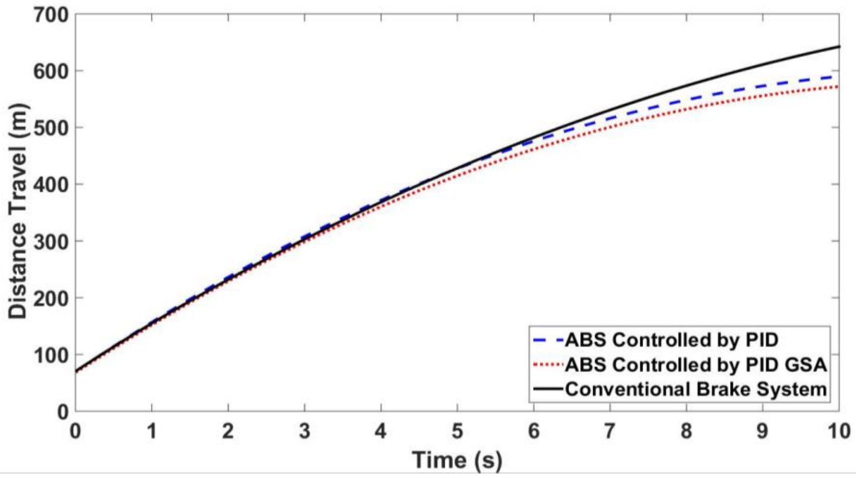

Figure 8. Distance travel versus time

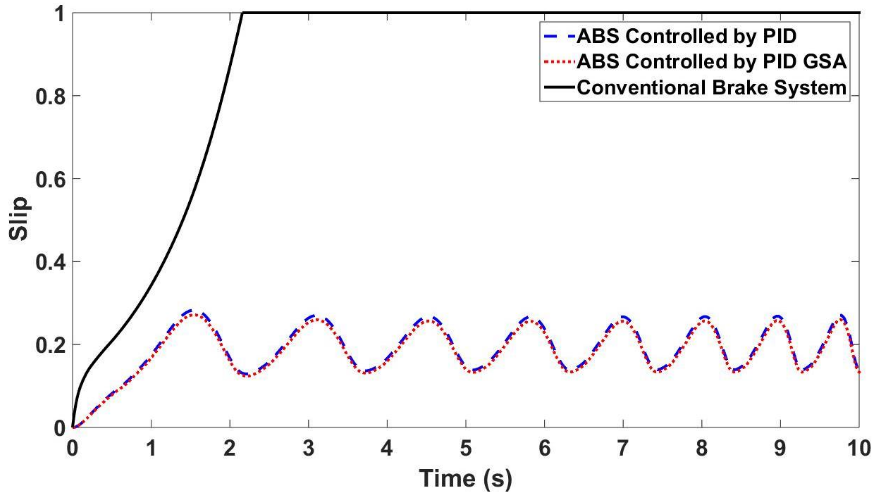

Figure 9. Longitudinal slip versus time

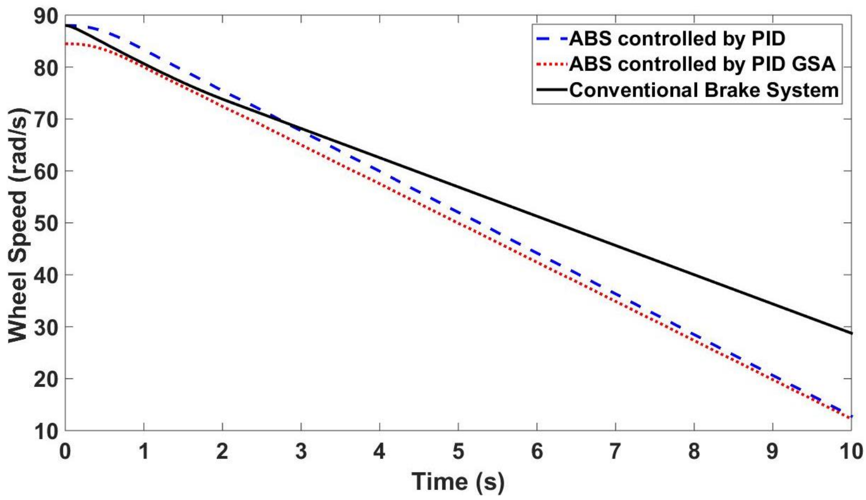

Figure 10. Wheel speed versus time

the ABS with PID-GSA was reduced the vehicle stopping distance by 10% compared to the ABS system with PID. The slip ratio was consistently maintained at the optimal value of 0.2 for ensuring maximum traction during sudden braking event. It shown the slightly difference between ABS with PID and ABS with PID-GSA. These simulation results demonstrated the effectiveness of the proposed ABS system in enhancing braking efficiency, stability, and safety. Based on the simulation analysis, the ABS optimized by PID GSA enhanced the ABS braking performance in 10% improvement compared to others in term of distance travel, vehicle speed, tire longitudinal slip and wheel angular speed. Future research should focus on experimental validation of the proposed ABS model using hardware-in-the-loop (HIL) testing or real-vehicle implementation. For others future work, the validation process will conduct by developing the quarter car test rig that represented similar with the 2-DOF model in this model diagram. The experimental test rig is equipped with one to one component of the quarter-car model to realize the validation results.

Author's Declaration

Authors' contributions and responsibilities

Conceptualization: MSR, FA, and VRA; Methodology: RR and MIMA; Formal analysis: MSR, FA and VRA; Resources: SMH: MAMS, and MM; Data curation: MSR, RR, and MIMA; Writing, review and editing: MSR, SMH, MAMS, and MIMA; Visualization: MSR, FA, SMH, VRA.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authorsdeclare no competing interest.

Additional information

No additional information from the authors.

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