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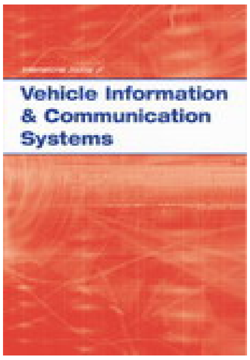

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Research on pattern recognition of automobile anti-lock braking system

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Abstract: The Anti-lock Braking system (ABS) plays a pivotal role in ensuring the stability of driving operation. The study proposes an ABS based on pavement identification based on the establishment of a vehicle dynamics model, which first determines the type of road surface and then realises brake control through adaptive fuzzy PID. The outcomes show that on dry concrete roads, the wheel speed under the control of this method quickly tracks up to the body speed after 0.1 s. The braking distance was 69.87 m and 47.68 m on the mixed soil road and ice road respectively. In the actual docking road test, the method can quickly and accurately identify the optimal slip rate, with a braking time of only 3.842 s, indicating that the method can achieve effective identification and efficient control of the car ABS, which provides a reference technical means to further improve the car driving safety.

Keywords: anti-lock braking; road surface recognition; fuzzy control; PID.

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1 Introduction

The massive expansion of highways and the development of the automotive industry have led to an increase in car ownership, and the safety of car driving has received more and more attention, making the updating of braking system technology particularly important. In the traditional braking system, the braking of the car is achieved by the reaction force of the braking torque applied to the wheels (Huang et al., 2018). If a large force is suddenly applied to the brake pedal during the braking process, it will cause a rapid reduction in wheel speed until the rotation achieves complete lock-up. However, at this point the vehicle will slip due to inertial locking, resulting in a large slip on the road, while the lateral adhesion of the tyre on the ground disappears, making it difficult for the

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car to resist side slippage and the braking direction loses stability, leading to dangerous conditions such as rollover and tailback (Batayneh et al., 2021). This has led to the emergence of ABS, which not only has the functions of traditional braking systems but also prevents the occurrence of such phenomena as locking and slipping, tyre slippage and so on, thereby stabilising the steering direction during the braking process and avoiding sideslip and drifting (Aghasizade et al., 2018). The ABS is mainly hydraulically controlled, which transmits the appropriate braking torque to the wheels, shortens the braking distance, increases the service life of the tyre and greatly enhances the safety performance of the vehicle. The existing logic threshold control methods are easy to implement and simple to control, but the parameters controlled are single and fluctuate greatly, making it difficult to achieve the best control effect. Moreover, the current ABS largely ignores the role of road surface identification and cannot accurately carry out braking control, making its control accuracy and flexibility poor, which affects driving safety. Therefore, the research first establishes the vehicle dynamics model and proposes the anti-lock braking system framework; Then, the control accuracy of the anti-lock braking system is optimised from the perspective of road recognition, and the innovative combination of fuzzy control and PID control is put forward, which is based on the road recognition adaptive fuzzy PID control, in order to further improve the braking control effect.

2 Related work

The ABS is a standard safety equipment for vehicles that many car manufacturers focus on today, and has received a lot of attention from researchers as it is closely related to many traffic accidents on wet, icy and dry roads. The method is mainly based on the non-linear characteristics of tyre forces to deal with road friction information and vehicle slip and other parameter strategy problems and uses motors as drivers at front wheel, but rear wheels are dominated by hydraulic (Han et al., 2019). The high performance of the method was proved in simulation experiments. Challa et al. (2020) studied rule-based anti-lock braking control algorithms and model-based anti-lock braking way algorithms by analysing the loss of directional stability and manoeuvrability during vehicle locking. Its validity of it was checked in experiments. The main function of the ABS is to prevent wheel lock and slip, it is a vehicle braking control system, this process is monitored and controlled using an anti-lock brake controller to maintain the slip rate. Mary and Bharathy (2020) developed a new anti-lock brake system based on Simulink to provide more advanced control of the vehicle and experiments showed that it minimised the car's. The improvement of braking performance in the field of electric vehicles was studied by Gong et al. (2019). A new wire-controlled actuator based on an electromagnetic linear motor was manufactured, which developed an anti-interference controller and state observer in the mathematical modelling, description of the braking principle and actuator structure and the simulation and experimental outcomes showed an extremely fast actuation response with a response time of only 15ms and better anti-interference performance (Gong et al., 2019). The ABS is a prominent part of the vehicle, serving unprompted guards during braking for operational safety. Xue et al. designed a single-wheel, fully electric anti-lock braking test rig consisting of an electric brake, flywheel, rollers and wheels to verify the operational efficiency of the algorithm in the laboratory and to save cost and time for practical road testing (Xue et al., 2021). In order to improve the stability and adaptability of the automobile ABS control algorithm, Zhu et al. (2023) analysed the control method based on the logic threshold and the control method based on the slip rate. The results show that the logic threshold control method has strong operability but poor adaptability, the sliding mode control has strong robustness but needs to suppress chattering and the PID control algorithm is simple and easy but needs to improve the transient response of the system (Zhu et al., 2023).

Fuzzy control can simplify the complexity of system design, and its accuracy in the field of control has received the attention of many professionals. Feng and Hu (2021) designed a discrete fuzzy control adaptive PID for the e-braking performance of the anti-lock system is difficult to meet the requirements and the slip rate is low. output and the car adhesion coefficient as input, the experiments demonstrated that the slip rate is around 20% (Aksjonov et al., 2020). In the process of verifying the ABS based on intelligent open-loop fuzzy logic, Aksjonov et al. (2020) simulated various braking mixture situations and tire-road adhesion conditions and responded to the performance degradation of the ABS by developing a fuzzy control-based road surface identification tool. The outcomes validate the feasibility and application potential of the approach (Feng and Hu, 2021). The responsiveness and control accuracy of wheel motors need to be improved. Wang and He (2018) developed an anti-lock controller method based on an improved linear quadratic optimal control algorithm, which first established a longitudinal dynamics model of the vehicle and applied the constructed composite control system regulation strategy to the ABS controller, outcomes in better display accuracy and response speed (Aksjonov et al., 2020). During the braking process of an ABS, changes in braking pressure consistently excite weight transfer and wheel load oscillations become more severe. Koylu and Yigit (2021) developed an integration between the ABS and the suspension system accordingly, which used rules for determining the control strategy in two phases of the same damping, medium-hard and hard and the outcomes showed that the method shortened the braking distance (Wang and He, 2018). The purpose of an ABS is to enhance braking performance, which can be degraded in adverse road conditions. Kumar et al. (2021) applied an electronic control unit as a sliding controller to the ABS, which was able to accept inputs from various road conditions and four-wheel speeds and thereby process the accumulated data, showing that it was able to predict the response to vehicle speed and wheel speed at different times, providing a better response speed (Koylu and Yigit, 2021). Kumar et al. (2021) established the mathematical model of the anti-lock braking system, simulated the fuzzy logic and PID controller in the MATLAB environment and controlled the braking force according to the relative slip, road conditions, friction coefficient and other parameters. The results show that the PID controller has better performance than the fuzzy logic and bang-bang controller (Kumar et al., 2021).

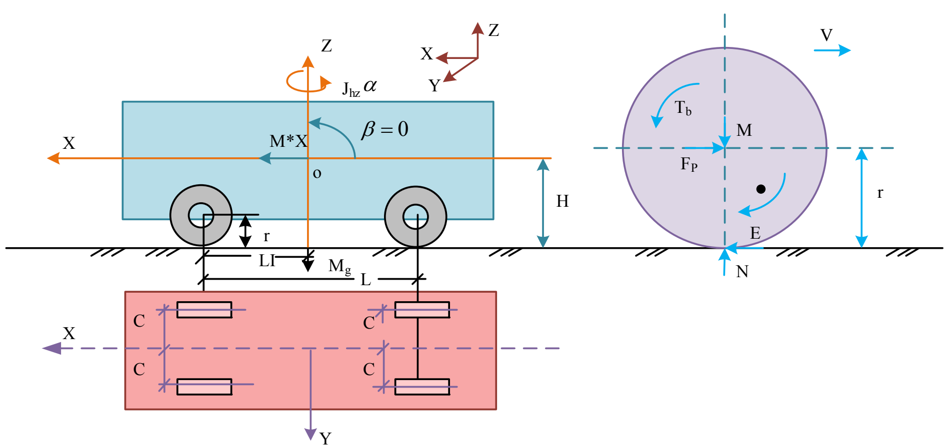
In summary, the improvement of ABS is an important technical tool for the safe operation of vehicles. Most researchers have addressed the shortcomings of ABS to optimise their control, but there have been fewer improvements to the controllers of the system and less research into road surface recognition. Therefore, the study establishes an ABS based on pavement distinguishment based on the vehicle dynamics model to achieve a better braking effect.

3 ABS for vehicles based on road surface recognition

3.1 Vehicle dynamics model

The vehicle dynamics model is the basis for the mathematical modelling of the ABS. There are four types of vehicle dynamics models today: four-wheeled vehicle model, two-wheeled vehicle model, single-wheeled model and general car model, while the braking system is the centre of the study, so some factors with less influence are ignored, such as wheel rolling resistance, air resistance, the influence of the vehicle steering system and suspension system on the braking system, etc. (Kumar et al., 2021). The first step is to establish a coordinate diagram of the vehicle structure, using L for the vehicle wheelbase, M for the total vehicle mass, H for the space between the car barycentre and ground, β for the angle of rotation of the transverse pendulum and J for the inertia of the transverse pendulum. The dynamics of the single-wheeled vehicle are also modelled. ω is wheel palstance, r which means wheel rolling radius, F means ground braking force, N represents the normal reaction from the ground on the tire and Tb represents the braking torque of the brakes. The coordinates of the complete vehicle structure and the dynamics model of the single-wheeled vehicle are shown in Figure 1.

Figure 1 Coordinate sketch of vehicle structure and dynamics model diagram of the single-wheel vehicle



Whereas, after considering only the longitudinal motion of the car and neglecting a series of factors such as air resistance, the structure of the single-wheeled vehicle model is relatively simple and more suitable for analysing the ABS, the kinematic equations of the car are shown in equation (1).

$$m\dot{v} = F_{\varphi} \tag{1}$$

In equation (1), m represents the car's mass, v represents the speed of travel and φ is the ground adhesion coefficient. The equation of motion of the car wheels is shown in equation (2).

$$J\dot{\omega} = F_{\varphi}r - T_b \tag{2}$$

In equation (2), J represents the wheel inertia and r represents the wheel radius. The longitudinal forces on the wheels of the car are given in equation (3)

$$F_{\varphi} = \varphi F_Z \tag{3}$$

In equation (3), Z represents the braking strength. The vertical load on a car wheel is shown in equation (4).

$$\begin{cases} Z_f = mg\dfrac{zh_g + b}{L} \\ Z_r = mg\dfrac{a - zh_g}{L} \end{cases} \tag{4}$$

In equation (4), Z_f represents the normal reaction force on the front wheel, b represents the distance from barycentre to back shaft, a is the distance from barycentre to epipodium, L is the axle distance, Z_r represents the normal reaction force on the rear wheel and h_g represents centroid height. The main function of the braking system model can display the relationship between braking torque and braking pressure. Current ABS include air-top brakes, pneumatic brakes and hydraulic brakes and to model the brakes, the pressure loss from the brake line braking is ignored. Under realistic conditions, there is a hysteresis in the braking pressure caused by the brakes, which needs to be described by an inertial link, as shown in equation (5).

$$P = \frac{100}{\left(TB \cdot s + 1\right)} * p \tag{5}$$

In equation (5), P represents the post-hysteresis braking pressure, p represents the initial braking pressure, s means braking time, TB means the hysteresis factor. The braking torque equation is shown in equation (6).

$$T_b = k_f * P \tag{6}$$

In equation (6), k_f represents the braking efficiency factor and T_b the braking torque. The tyre model of the vehicle is then established, which mainly explains the relationship between the adhesion and the rest of the parameters and is the core part of the vehicle dynamics system. The bilinear model and the physical model are the two main types of current tyre models. The bilinear model (Lakhemaru and Adhikari, 2022) is chosen because the physical model requires too many parameters and can hinder subsequent modelling. The bilinear model is a simplified tyre model, clearly represented by two-line equations, with a clear physical meaning and high fitting accuracy, which can be better applied to computer simulation. Three different bilinear models, low-, medium- and high-adhesion coefficient, are chosen according to the variability of the frictional characteristics of the road surface, as shown in equation (7).

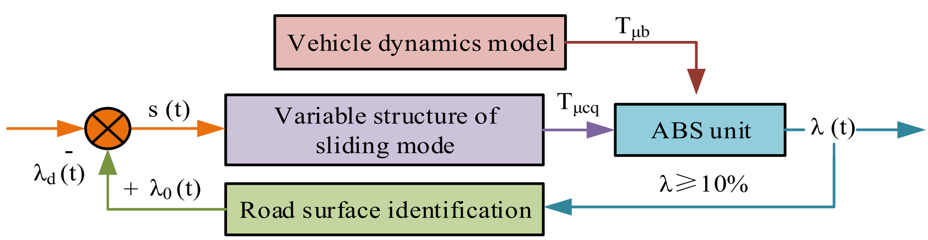
$$\begin{cases} \mu_h = \begin{cases} 4.2s, s \le 0.2 \\ 0.9 - 0.3s, s > 0.2 \end{cases} \\ \mu_m = \begin{cases} 3.5s, s \le 0.18 \\ 0.657 - 0.15s, s > 0.18 \end{cases} \\ u_l = \begin{cases} \frac{4}{3}s, s \le 0.15 \\ 0.203 - 0.02s, s > 0.15 \end{cases} \end{cases} \quad (7)$$

In equation (7), s represents the slip rate, μ_h, μ_m and μ_l are the high-, medium- and low-adhesion coefficients, respectively. The slip rate is the proportion of the slip component in the braking process, i.e., from the start of braking to the final wheel lock, and is shown in equation (8).

$$s = \frac{v - \omega r}{v} \times 100\% \quad (8)$$

After completing the modelling of the vehicle dynamics model, the framework of the ABS is shown in Figure 2. The vehicle is in regular braking at the beginning, and as the braking torque gradually increases and the slip rate exceeds 10%, the road surface recognition model identifies the type of road surface the vehicle is travelling on, from which this optimum slip rate is given and finally the anti-lock braking control of the wheels is achieved through the anti-lock braking device.

Figure 2 Anti-lock brake system frame



3.2 *ABS based on road surface recognition*

The best slip ratio got from pavement recognition will change accordingly according to the change of apex adhesion coefficient, and the control precision of the ABS also receives the influence of the reference slip rate to a great extent, so the ABS needs effective pavement recognition to achieve the setting of the best slip ratio (Klug et al., 2019). The summit adhesion coefficient is obtained from the relationship between the actual change in wheel angular velocity and the theoretical change at the same time when the car is driven on different road surfaces, and the change in angular velocity is calculated as shown in equation (9).

$$\Delta\omega_1 = \int_0^1 \frac{\mu N r - T_0}{I} dt \quad (9)$$

In equation (9), T_0 is the magnitude of the braking torque and w_1 means wheel palstance at the moment when t takes the value of t_1. When either the coefficient of adhesion or the slope present on different road surfaces are the same, the sum of the two must not be equal, so the road surface characteristic coefficients of the proposed vehicle model are shown in equation (10).

$$U(\lambda) = \dot{\mu}_x(\lambda) + \mu_x(\lambda) = c_1\left(c_2 - 1\right) \exp\left(-c_2\lambda\right) - c_3\lambda + c_1 - c_3 \tag{10}$$

In equation (10), c_1, c_2 and c_3 represent the fit coefficients, λ_0 represents the optimum slip ratio, μ_x means summit adhesion coefficient and $U(\lambda)$ is the pavement characteristic coefficient. The values of c_1, c_2, c_3, λ_0 and the corresponding μ_x for different pavement types are shown in Table 1.

Table 1 Fitting coefficient, optimal slip ratio and corresponding peak adhesion coefficient of different pavements

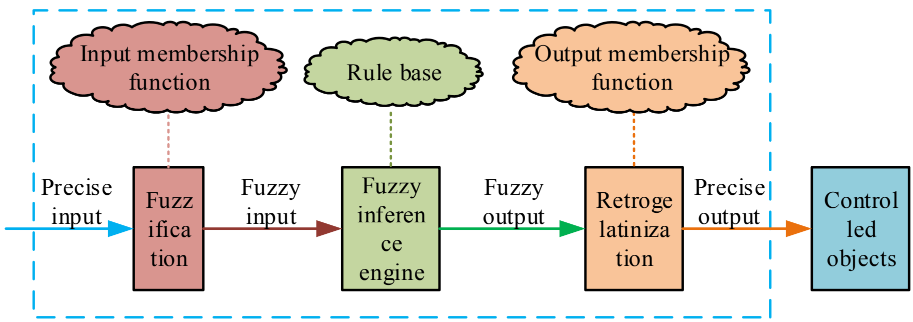
Pavement	c_1	c_2	c_3	λ_0	μ_{xmax}
Wet asphalt	0.857	33.82	0.35	0.1306	0.8009
Ice	0.05	306.39	0.646	0.3996	0.9995
Dry asphalt	1.280	23.99	0.52	0.1700	0.1699
Wet cobblestone	0.400	33.71	0.12	0.1401	0.3796
Snow	0.195	94.13	0.67	0.1401	0.3796
Dry cobblestone	1.371	6.46	0.67	0.3996	0.9995
Dry cement	1.197	25.17	0.54	0.1598	1.0893

At slip rates above 10%, the pavement will converge to the optimum pavement adhesion coefficient. Based on the relationship between pavement type and longitudinal adhesion coefficient, the pavement types are classified into three categories, snow and ice pavement, wet pavement and dry pavement (Heydrich et al., 2021). When λ is in the interval (0, 0.5), all pavement types except dry pavement can meet the optimum slip rate greater than 0.1. Therefore, when λ is in the interval (0, 0.1), it is regarded as a low-adhesion pavement, and when it is in the interval (0.1, 0.5), it is a high-adhesion pavement. By dividing the difference between the three road surface types into dynamic recognition intervals, the ABS can repeatedly recognise the current road surface, and in the event of a system miscalculation or a change in road surface type, a change in slip rate will cause the system to immediately make the correct recognition. The interval curve for the road surface to be recognised is shown in equation (11).

$$\begin{cases} L_i(\lambda) = \dfrac{U_i(\lambda) + U_{i+1}(\lambda)}{2}, \left(\lambda = 1, 2\right) \\ L_3(\lambda) = U_3(\lambda) + 2 \end{cases} \tag{11}$$

In equation (11), i indicates the type of road surface. And for identifying effectively when the braking starts as an icy or snowy road surface, to avert the appearance of a locking drag, the system identifies it as an icy or snowy road surface when $\lambda > 0.45$ to ensure accurate identification and control of low adhesion road surfaces. The controller for anti-lock braking is then optimised (Aksjonov et al., 2018). Fuzzy control is based on a fuzzy language and expresses expert operating experience and knowledge experience using fuzzy reasoning methods, and realises the operation and control of the controlled object using a computer simulating the human operating style and thinking. Its ability to control non-linear systems better in the absence of accurate mathematical models, as well as strong adaptability and learning ability, has a certain feasibility of application in automotive ABSs (Phadke et al., 2020). The core of fuzzy control is the fuzzy processing of sets and inputs, a process that requires the fuzzy controller to process some complex rules through fuzzy reasoning to raise the exactitude of operations and obtain accurate values (Wang and Choi, 2021). The fuzzy control first obtains the output quantity based on the input quantity, then transforms it into fuzzy linguistic variables and finally obtains the fuzzy control quantity based on fuzzy reasoning under certain fuzzy rules and fuzzy linguistic variables constraints. The basic principle of fuzzy control is shown in Figure 3.

Figure 3 Basic principle of fuzzy control

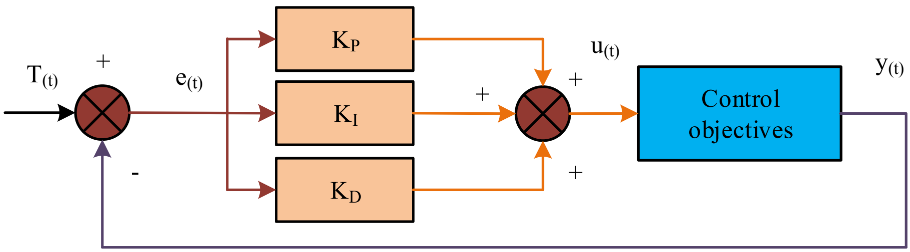


The fuzzy control system fuzzes the input signal into a fuzzy quantity which is recognisable by the controller and then transmits it at a very fast rate to the fuzzy inference section where it is quickly judged and analysed to obtain a reference conclusion. The outcome of fuzzy reasoning is a fuzzy value which cannot be applied directly to the control object and needs to be defuzzified, i.e., transformed accordingly to an exact value (Uraulis et al., 2019). The PID control, as a closed-loop control method, contains two increments, control pressure and control slip rate, which can achieve a better control effect when the response rate of the control slip rate is less than the requirement of pressure control. And PID controller structure is simple, has reliable work, good stability and is easy to adjust, in industrial control and has been widely used (Wang and He, 2019). PID controller is a linear combination of the system deviation in the presence of proportional, integral and differential composition of the control quantity, and then the object under control to implement control. Proportional control is the basis of PID control, integral control is used to eliminate steady-state errors, but there is the possibility of increased fine-tuning, and differential control can improve the response of inertial systems and attenuate the tendency to overshoot. the principle of PID control is shown in Figure 4.

In a PID controller, a control deviation is formed between the actual output value and the determined value, as shown in equation (12).

$$\begin{cases} e(t) = T(t) - y(t) \\ u(t) = K_p \left[e(t) + \dfrac{1}{T_I} \displaystyle\int_0^t e(t)dt + T_D \dfrac{de(t)}{dt} \right] \end{cases} \tag{12}$$

Figure 4 Basic schematic diagram of PID control



In equation (12), $T(t)$ represents the actual output value, K_p means scale factor, TI means integration constant, TD is the differential time constant and $e(t)$ represents the determination value. However, PID controllers are often poorly parameterised and prone to poor adaptability in the controlled process, etc. Combining them with fuzzy control makes them adaptable and flexible controllers, i.e., adaptive fuzzy PID controllers. The transfer function between its control quantity and deviation is shown in equation (13).

$$U(s) = K_p\left(1 + \frac{1}{T_i \cdot s} + T_d \cdot s\right)E(s) \tag{13}$$

In equation (13), u represents the control quantity, e represents the deviation, $U(s)$ and $E(s)$ is obtained from u and e through the Rasch transform respectively, T_d, T_i and K_p represent the differential coefficient, integral coefficient and proportional coefficient, respectively. The adaptive fuzzy PID can self-tune the PID parameters online to meet the requirements of the PID parameters at different moments in time, and reason out the PID matrix that can be corrected online in real-time by fuzzy rules, as shown in equation (14).

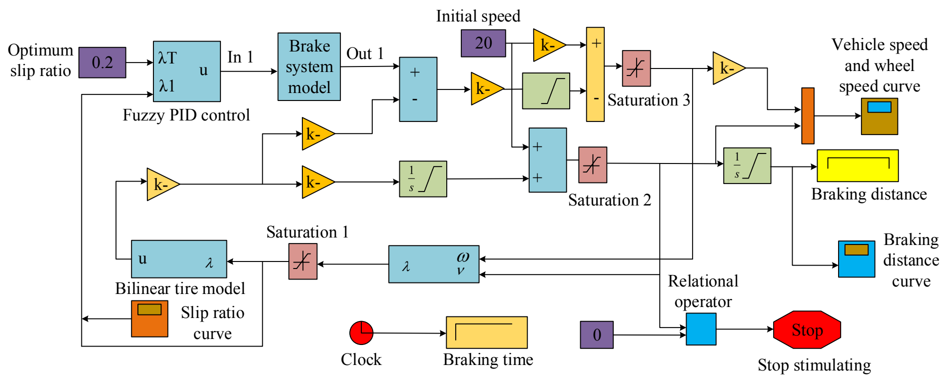
$$\begin{cases} K_p = K'_p + \Delta K_p \\ K_i = K'_i + \Delta K_i \\ K_d = K'_d + \Delta K_d \end{cases} \tag{14}$$

In equation (14), ΔK_p, ΔK_i and ΔK_d are the inputs and K'_p, K'_i and K'_d are the parameters obtained by the trial-and-error method. In an ABS, the greater the slip deviation rate, the greater the rate of change. The greater the rate of change exhibited by the angular velocity of the wheels, the higher the slip deviation rate at that point, from which the fuzzy rules are derived. Finally, inverse fuzzification is carried out to convert the fuzzy quantity to the actual quantity. The centre of gravity method is highly accurate and widely used in this process. It is calculated by finding the centre of the area enclosed by the fuzzy set affiliation function curve and the horizontal coordinates, and selecting the value of the horizontal coordinates of this centre to obtain the representative value of the fuzzy set, which is shown in equation (15).

$$Z = \frac{\sum_{i-1}^{n} u(z_i)}{\sum_{i=1}^{n} u(z_i)} * z_i \tag{15}$$

In equation (15), z_i represents the affiliation function of Z, and $u(z_i)$ is the domain element of the argument. Finally, the final vehicle ABS based on pavement recognition adaptive fuzzy PID control is obtained as shown in Figure 5.

Figure 5 Auto anti-lock braking system based on adaptive fuzzy PID control of road surface identification

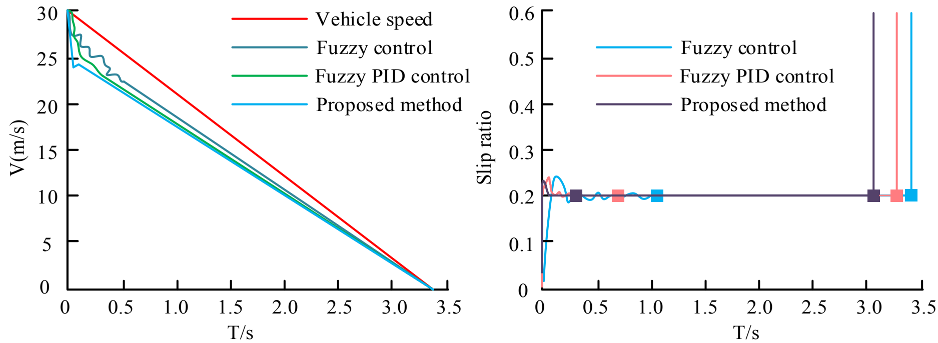


4 Analysis of application outcomes

The research puts forward a braking method based on road recognition adaptive fuzzy PID control for the pattern recognition of automobile anti-lock braking system. The verification of its application effect is essentially the verification of the anti-lock braking effect under the control of the proposed method during the vehicle driving process. Fuzzy control, fuzzy PID control and the adaptive fuzzy PID control based on road surface identification proposed in the study were chosen for comparison. Firstly, experiments were conducted on a dry concrete road surface with the initial speed of the car set at 30 m/s, the sampling step time set at 0.001 s, the experiment time at 10 s and the optimum slip rate at 0.2. The outcomes of the car holding brake under the three controls are shown in Figure 6.

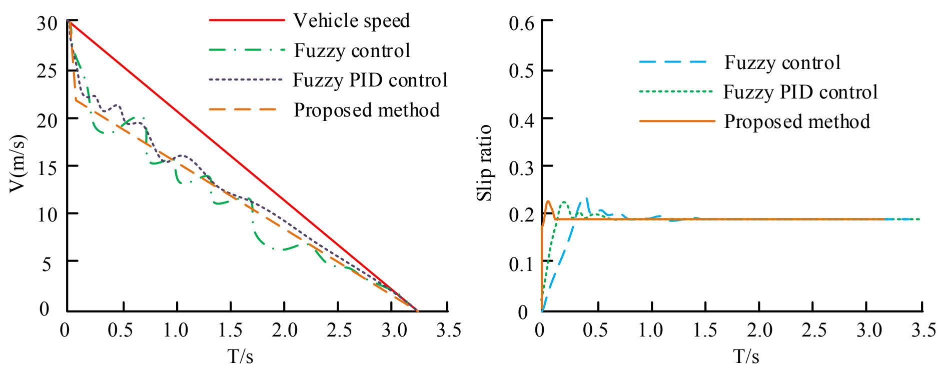
Figure 6 demonstrates the anti-lock braking outcomes of the three methods on the dry concrete road, Figure 6(a) demonstrates the outcomes of the body speed and wheel linear speed change curve and Figure 6(b) demonstrates the outcomes of the wheel slip rate change during braking. From Figure 6(a), the wheel speed under fuzzy control jittered more frequently within 0.5 s and only gradually tracked up to the body speed after 0.5 s. The wheel speed under fuzzy PID control still jittered for a longer time within 0.5. The proposed method, on the other hand, has no fluctuation amplitude after 0.1 s and quickly approaches the body speed. In Figure 6(b), the fuzzy control stabilises at the optimum slip rate after 1 s, while the proposed method gradually stabilises within 0.1 s and stays at the optimum slip rate as early as possible until the braking stops. The experiments were then carried out on wet asphalt pavement with the same parameters as the dry concrete pavement and the outcomes obtained are shown in Figure 7.

Figure 6 Anti-lock braking outcomes of three control methods on dry concrete pavement



(a) Vehicle speed and wheel speed change (b) Slip rate change curve during wheel braking

Figure 7 Anti-lock braking outcomes of three control methods on wet asphalt pavement



(a) Vehicle speed and wheel speed change (b) Slip rate change curve during wheel braking

Figure 7 shows the experimental outcomes of the three control methods on wet asphalt pavement. As can be seen from Figure 7(a), on the asphalt pavement, the fuzzy-controlled wheel speed has large fluctuations up to 3 s and only starts to approach the body speed when approaching 3 s, the fuzzy PID-controlled wheel speed has more fluctuations within 1.5 s and starts to approach the body speed after 1.5 s, while the proposed method tracks quickly towards the body speed from the beginning and is free of fluctuations and can maintain a stable braking speed. Figure 7(b) shows that the fuzzy-controlled car gradually stabilises at the optimum slip rate at 1.5 s and maintains smaller oscillations thereafter, the car under fuzzy PID control stabilises near 1.0 s, while the proposed method shows shorter fluctuations within 0.2 s and then continues to maintain at the optimum slip rate and ends braking near 3.0 s. The three control methods then experimented on wet clay and ice surfaces with an optimum slip rate of 0.36, an initial vehicle speed of 25 m/s and a time of 10 s for the wet clay surface and an optimum slip rate of 0.1, an initial vehicle speed of 10m/s and a time of 11 s for the ice surface, with a sampling step time of 0.001 s for both surface types and the outcomes obtained are in Table 2.

Table 2 Anti-lock braking outcomes of three control methods on ice and wet soil roads

Category	*Wet soil pavement*				*Icy pavement*			
	First stabilisation time(s)	*Divergent time(s)*	*Braking time(s)*	*Braking distance(m)*	*First stabilisation time(s)*	*Divergent time(s)*	*Braking time(s)*	*Braking distance(m)*
Fuzzy control	1.028	5.637	5.672	72.08	0.821	9.972	9.961	50.24
Fuzzy PID control	1.006	5.609	5.613	70.54	0.359	9.853	9.946	49.75
Proposed method	0.132	4.541	5.499	69.87	0.324	9.744	9.925	47.68

As can be seen from Table 2, on wet dirt roads, the wheel braking time under fuzzy control is the longest of the three methods, at 5.672 s, with a braking distance of 72.08 m. The braking time for fuzzy PID control is 5.613 s, with a braking distance of 70.54 m. while the proposed method has the shortest braking time and braking distance, at 5.499 s and 69.87 m, respectively, on icy roads. The braking distances were 50.24 m and 49.75 m for fuzzy control and fuzzy PID, respectively, and 47.68 m for the proposed method, which were 2.56 m and 2.07 m shorter, respectively with better braking effect. Finally, the proposed method is applied to practice, and an ordinary Class B vehicle is selected as the experimental object. Its basic information is shown in Table 3.

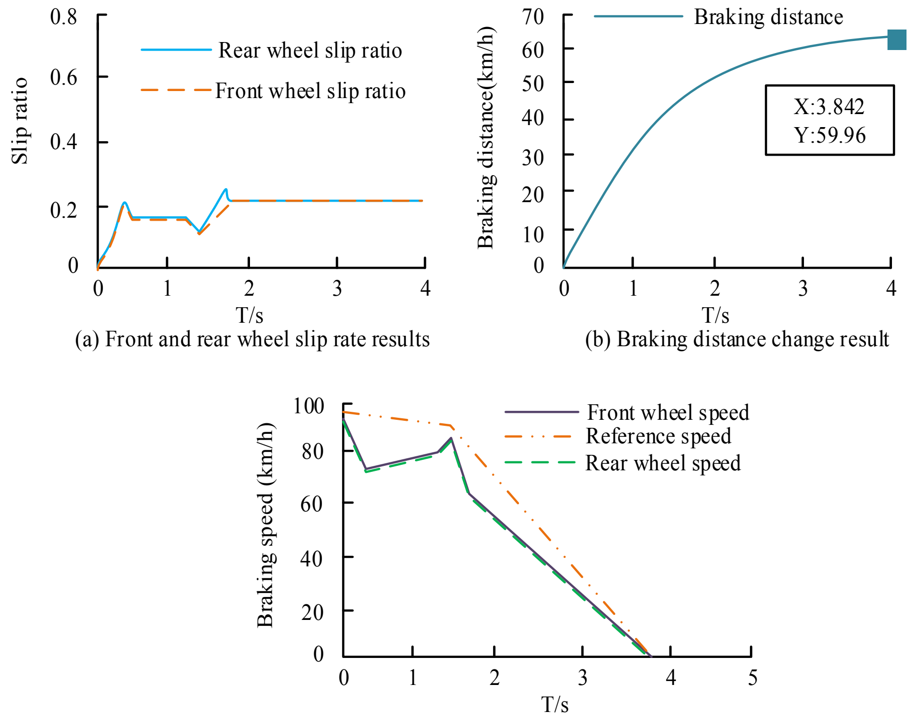
Table 3 Basic information of the selected vehicle in practical implementation

Vehicle information category	*Numerical value*
Vehicle mass	1110 kg
Front wheelbase	1.04 m
Rear wheelbase	1.56 m
Centroid height	0.54 m
Tire radius	0.31 m
Initial braking speed	25 $m \cdot s^1$
Wheelbase	12.60 m
Wheel moment of inertia	0.6 kgm^2

The road conditions on which the car is driven are complex and prone to change in practice, so this section focuses on docking road experiments to validate the control effectiveness of the proposed method. The slip ratio of the single target was set to 0.2, and the vehicle started braking on a low-adhesion road, at which time the ABS under single target slip rate fuzzy PID control and the measured braking distance and time were 64.31 m and 4.084 s, respectively. After the braking distance was 30 m, the vehicle drove onto a high-adhesion road and the docking road experimental outcomes of the proposed method were demonstrated in Figure 8.

Figure 8(a) shows the slip rate change of front and rear wheels of the vehicle, Figure 8(b) shows the change of braking distance and Figure 8(c) shows the change curve of front and rear wheel speed and reference speed. It can be seen from Figure 8(a) that the slip rate of the front and rear wheels of the vehicle only fluctuated slightly in a short time before 2 s, and then stabilised rapidly. It can be seen from Figure 8(b) that the braking distance of this method is 59.96 m, and the braking time is 3.842 s. Compared with the single target slip rate, it reduces 4.35 m and 0.244 s, respectively, with better braking effect. It can be seen from Figure 8(c) that the proposed method has a small fluctuation in 4 s, the front and rear wheels can accurately and quickly identify the optimal slip rate and it tends to be consistent in a very short time, indicating that the method has a strong self-tuning ability. Overall, the proposed method has strong adaptability, can adapt to complex road conditions and has better braking effect.

Figure 8 Experimental outcomes of the proposed method on the docking pavement



(a) Front and rear wheel slip rate results

(b) Braking distance change result

(c) Brake speed result

5 Conclusion

The ABS is an important technology to realise the stability and safe driving of automobiles, which is of great significance to the improvement of the competitiveness of domestic automobiles. The study first establishes the vehicle dynamics model, then builds the ABS based on road surface identification and applies the adaptive fuzzy PID method to realise the ABS. The experimental outcomes demonstrate that the method has less wheel speed fluctuation after 0.1 s on dry concrete roads. On wet asphalt roads, the fuzzy-controlled wheel speed only starts to approach the body speed around 3 s, and the fuzzy PID control starts to approach the body speed after 1.5 s. The proposed method tracks quickly towards the body speed from 0 s onwards and can maintain a stable braking speed degree. The braking time for this method was 9.925 s and 5.499 s on ice and wet dirt roads, respectively, providing faster braking speed and efficiency. In actual docked pavement experiments, the method yielded braking distance and time reductions of 4.35 m and 0.244 s, respectively, providing better braking outcomes and improved braking accuracy. However, during the study, comparisons were not carried out on a wider variety of road surfaces due to time and conditions, so further exploration in this area is pending.

References

Aghasizade, S., Mirzaei, M. and Rafatnia, S. (2018) 'Novel constrained control of active suspension system integrated with anti-lock braking system based on 14-degree of freedom vehicle model', *Proceedings of the Institution of Mechanical Engineers Part K Journal of Multi-body Dynamics*, Vol. 232, No. 4, pp.501–520.

Aksjonov, A. Ricciardi, V. and Augsburg, K. et al. (2020) 'Hardware-in-the-loop test of an open loop fuzzy control method for decoupled electro-hydraulic antilock braking system', *IEEE Transactions on Fuzzy Systems*, Vol. 11, pp.2–5.

Aksjonov, A., Vodovozov, V. and Augsburg, K. et al. (2018) 'Design of regenerative anti-lock braking system controller for 4 in-wheel-motor drive electric vehicle with road surface estimation', *International Journal of Automotive Technology*, Vol. 19, No. 4, pp.727–742.

Batayneh, W., Bataineh, A. and Jaradat, M.A. (2021) 'Intelligent adaptive fuzzy logic genetic algorithm controller for anti-lock braking system', *International Review on Modelling and Simulations*, Vol. 14, No. 1, pp.44–54.

Challa, A., Ramakrushnan, K., Subramanian, S.C., Vivekanandan, G. and Sivaram, S. (2020) 'Analysis of thresholds in rule-based antilock braking control algorithms', *IFAC-PapersOnLine*, Vol. 53, No. 1, pp.404–409.

Feng, X. and Hu, J. (2021) 'Discrete fuzzy adaptive PID control algorithm for automotive anti-lock braking system', *Journal of Ambient Intelligence and Humanized Computing*, Vol. 4, pp.3–10.

Gong, X., Qian, L., Ge, W. and Wang, L. (2019) 'Research on the anti-disturbance control method of brake-by-wire unit for electric vehicles', *World Electric Vehicle Journal*, Vol. 10, No. 2, pp.44–49.

Han, K., Lee, B. and Choi, S. (2019) 'Development of an antilock brake system for electric vehicles without wheel slip and road friction information', *IEEE Transactions on Vehicular Technology*, Vol. 25, pp.5506–5517.

Heydrich, M. Ricciardi, V. Ivanov, V, Mazzoni, M and Augsburg, K. (2021) 'Integrated Braking control for electric vehicles with in-wheel propulsion and fully decoupled brake-by-wire system', *Vehicles*, Vol. 3, No. 2, pp.145–161.

Huang, W.H., Lu, Y.J. Li, S.H. and Zhang, J.N. (2018) 'ABS control and hardware in loop investigation for a heavy duty vehicle based on road recognition', *Beijing Ligong Daxue Xuebao/Transaction of Beijing Institute of Technology*, Vol. 38, pp.67–71.

Klug, S., Moia, A., Verhagen, A., Grges, D. and Savaresi, S. (2019) 'The influence of bicycle fork bending on brake control', *Vehicle System Dynamics*, Vol. 59, No. 3, pp.6–21.

Koylu, H. and Yigit, H. (2021) 'A novel approach on improvement of the dynamic wheel load oscillations by integrating suspension system into ABS during braking with ABS', *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 43, No. 7, pp.2–21.

Kumar, R., Divyanshu and Kumar, A. (2021) 'Nature based self-learning mechanism and simulation of automatic control smart hybrid antilock braking system', *Wireless Personal Communications*, Vol. 116, No. 2, pp.3–18.

Lakhemaru, P. and Adhikari, S.P. (2022) '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.

Mary, A. and Bharathy, G.T. (2020) 'Anti lock braking system using simulink', *International Journal of Contemporary Research and Review*, Vol. 10, No. 5, pp.51–54.

Phadke, S.B. Shendge, P.D. and Wanaskar, V.S. (2020) 'Control of antilock braking systems using disturbance observer with a novel nonlinear sliding surface', *IEEE Transactions on Industrial Electronics*, Vol. 67, No. 8, pp.6815–6823.

Uraulis, V., Surblys, V. and Abanovi, E. (2019) 'Technological measures of forefront road identification for vehicle comfort and safety improvement', *Transport*, Vol. 34, No. 3, pp.363–372.

Wang, J. and He, R. (2018) 'Improved linear quadratic optimal control of ABS for an electric vehicle', *Harbin Gongye Daxue Xuebao/Journal of Harbin Institute of Technology*, Vol. 50, No. 9, pp.108–115.

Wang, J.C. and He, R. (2019) 'Hydraulic anti-lock braking control strategy of a vehicle based on a modified optimal sliding mode control method', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 233, No. 12, pp.3185–3198.

Wang, Z. and Choi, S.B. (2021) 'A fuzzy sliding mode control of anti-lock system featured by magnetorheological brakes: performance evaluation via the hardware-in-the-loop simulation', *Journal of Intelligent Material Systems and Structures*, Vol. 32, No. 14, pp.1580–1590.

Xue, X., Cheng, K., Chan, W.W., Fong, Y.C. and Fan, Y. (2021) 'Design, analysis and application of single-wheel test bench for all-electric antilock braking system in electric vehicles', *Energies*, Vol. 14, No. 5, pp.1294–1298.

Zhu, S., Fan, X., Qi, G. and Wang, P. (2023) 'Review of control algorithms of vehicle anti-lock braking system', *Recent Patents on Engineering*, Vol. 17, No. 2, pp.30–45.