IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 20, 2021, accepted March 2, 2021, date of publication March 9, 2021, date of current version March 17, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3064960

Global Sliding Mode Control for Nonlinear Vehicle Antilock Braking System

HONGWEI WANG, SHAOWEN WU, AND QIANYU WANG
School of Control Engineering, Northeastern University at Qinhuangdao, Qinhuangdao 066004, China

Corresponding author: Hongwei Wang (wanghw0819@163.com)

This work was supported in part by the Natural Science Foundation of China under Grant 61903072, in part by the Fundamental Research Funds for the Central Universities under Grant N2023018, and in part by the Higher Educational Science and Technology Program of Hebei Province under Grant QN2019317.

ABSTRACT In order to further improve the braking performance of the nonlinear antilock braking system (ABS), an improved global sliding mode control scheme is presented. First, a nonlinear global sliding mode surface is designed. The method can eliminate the reaching phase compared with conventional linear sliding mode surface, and guarantee the system robustness during the whole control process. Then, a novel control law is proposed to satisfy the sliding mode reaching condition, and the theoretical proof is given. Simulation results demonstrate that the proposed global sliding mode control scheme enables the wheel slip-ratio to converge to optimal value quickly with the small oscillation, and has relatively short braking distance and braking time, which is very suitable to prevent the wheel from being locked during braking. The proposed global sliding mode control scheme is verified by joint simulation using MATLAB and CarSim, and shows good braking performance when the car is driving under extreme road conditions, which indicates the effectiveness of the proposed sliding mode control scheme.

INDEX TERMS Antilock braking system (ABS), global sliding mode control, braking performance, slip-ratio, MATLAB and CarSim.

I. INTRODUCTION

The antilock braking system(ABS) as an essential component can improve safety and reliability of vehicle, have been installed for some decades. The main function is to prevent the wheel from being locked during braking and increase braking performance. The main goal is to design a controller and ensure the slip-ratio to maintain the desired value, which will improve the wheel tractive force and obtain an optimal later force from the road surface. In this way, the braking distance and time are further reduced, and the stability of vehicle is improved. Due to the relationship between the road-tire adhesion coefficient and slip-ratio is uncertain and nonlinear for various road conditions, so it is vital to design a robust controller for the nonlinear ABS [1].

At present, some scholars have proposed the friction model between the road-tire adhesion coefficient and wheel slip-ratio for different road conditions, such as the Magic formula model [2], the LuGre friction model [3] and the Burckhardt formula model [4]. These models accurately represent the adhesion coefficient, and provide the basic theory to design the controller. Recently, many researchers have proposed some control methods for ABS, such as PID control [5], [6], intelligent control [7]–[10], and robust control [11]–[15]. These schemes try to accurately control the slip-ratio to maximize effectiveness of the tire force in the longitudinal direction.

Sliding mode control (SMC) theory is considered to be a useful technique in the past several decades, and has received much attention with many advantages, such as fast response, robustness, and anti-interference. Some results have been researched and obtained [16], [17]. In [16], SMC method is applied to unmanned aerial vehicle. In [17], the adaptive SMC based on local recurrent neural networks is used for the underwater robot. At present, SMC scheme has been applied to the ABS because of its excellent dynamic characteristics and robustness. The adaptive SMC algorithm based on the vehicle velocity estimation and tire-road friction coefficient estimations for ABS is reported in [18]. Using disturbance observer with a novel nonlinear sliding surface is seen in [19]. In [20], a grey system modeling approach for SMC is proposed for the ABS. In [21], sliding surface design on the performance of SMC in ABS is studied. A modified

The associate editor coordinating the review of this manuscript and approving it for publication was Shihong Ding.

optimal SMC method for the ABS is proposed in [22]. However, the robust characteristic is guaranteed only after the system reaches the sliding surface, and robustness is not guaranteed during the reaching phase. The global sliding mode control is used to eliminate the reaching phase, the critical point is to keep the system state trajectory on the sliding mode surface, so the control scheme has better robustness [23]–[27]. However, there are few papers on global sliding mode control used in antilock braking systems. However, there are few papers about global sliding mode control used in ABS. In [28], an adaptive global sliding mode control strategy for ABS is designed. In [29], a robust ABS method based on global sliding mode control is proposed, but its braking performance and control effect are not particularly ideal. They ignore some external interference factors in the process of designing the controller. No studies have been reported in the literature concerning global sliding mode control for ABS considering air resistance and wheel rolling resistance.

To solve the problems mentioned above, we propose an improved global sliding mode controller in this paper. First, a global sliding mode surface is designed. It can guarantee the robustness of system during the whole control process. Then, an improved sliding mode control law is presented by using an exponential function to drive the system states to the sliding mode surface, which not only improves the braking performance, but also keeps the slip rate near the expected value. Simulation results show the proposed global sliding mode control method can get well braking performance under wet asphalt road condition and make the wheel slip-ratio maintained at the desired slip-ratio. Finally, the validity of the proposed algorithm is verified by joint simulation using MATLAB and CarSim.

The rest of this article is organized as follows: Section II describes the mathematical modeling. Section III discusses the controller design. The simulation results are included in section IV. Section V gives the joint simulation results using MATLAB and CarSim, and section VI summarizes this article.

II. SYSTEM MODELING

The ABS has strong nonlinearity and uncertainty. It is difficult to describe the real vehicle dynamics. To simplify the braking problem, we studied a quarter car model, and the diagram is shown in Figure.1.

The nonlinear dynamic equations are established based on the traditional mathematical model [25].

$$\dot{\omega} = \frac{\left(F_t - F_f\right) R}{J} + \frac{T_e - T_b}{J} \tag{1}$$

$$\dot{V} = -\frac{F_t}{M} - \frac{F_a}{M} \tag{2}$$

$$F_t = \mu(\lambda) F_z \tag{3}$$

$$F_f = f_0 + 3.24 f_s (f_b V)^{2.5} \tag{4}$$

$$F_a = \frac{1}{2} f_d A_t \rho V^2 \tag{5}$$

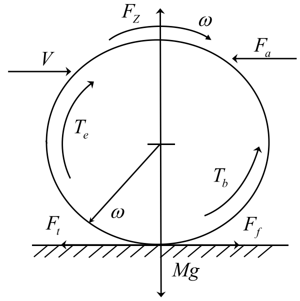


FIGURE 1. A quarter car model.

where J is the moment of inertia of the wheel, ω is the angular velocity of the wheel, F_t is longitudinal tire force of the wheel, F_f is the rolling resistance of the wheel during the braking operation, T_e is driving torque, T_b is the braking torque, V is the longitudinal vehicle velocity, M is the mass of the quarter vehicle, F_a is the air resistance, $\mu(\lambda)$ is the road-tire adhesion coefficient which is a function of the wheel slip-ratio λ, F_z is the normal load on the tire, $F_z = Mg$, f_0 is the foundation coefficient, f_s is the velocity influence coefficient, f_b is the scaling factor, f_d is the air resistance coefficient, A_t is the area under the force of air resistance, ρ is the air density.

The slip-ratio λ is defined as the following equation.

$$\lambda = \frac{V - \omega R}{V} \tag{6}$$

Taking the time derivative of slip-ratio, we have

$$\dot{\lambda} = \frac{-\dot{\omega} R + (1 - \lambda) \dot{V}}{V} \tag{7}$$

Substituting (1)-(5) into equation (7) yields

$$\dot{\lambda} = \frac{1}{V}\left(\frac{R^2 F_f}{J} - \frac{(1-\lambda) F_a}{M}\right) - \frac{1}{V}\left(\frac{R^2}{J} + \frac{1-\lambda}{M}\right) \times F_z \mu(\lambda) + \frac{R}{JV} T_b \tag{8}$$

In the actual ABS, the slip-ratio λ should be controlled at the optimal slip-ratio λ_d, corresponding to the peak adhesion coefficient $\mu_{\max}$ to maximize the use of ground adhesion. However, the braking force is influenced by the road environment. Many empirical and analytical expressions have developed the road-tire friction coefficient $\mu(\lambda)$. In this paper, we use a widely used Magic Formula (MF) model, it is given as follows.

$$\mu(\lambda) = D \sin\{C \arctan[B\lambda - E(B\lambda - \arctan(B\lambda))]\} \tag{9}$$

where B is the stiffness factor, C is the shape factor, D is the peak value, E is the curvature factor. These coefficients depend on the road conditions.

Then the time derivative of equation (9), we have

$$\frac{d}{d\lambda}\mu(\lambda) = \frac{BCD\left[(1-E) + \frac{E}{1+B^2\lambda^2}\right]}{\left\{1 + [B\lambda - E(B\lambda - \arctan(B\lambda))]^2\right\}} \cdot$$

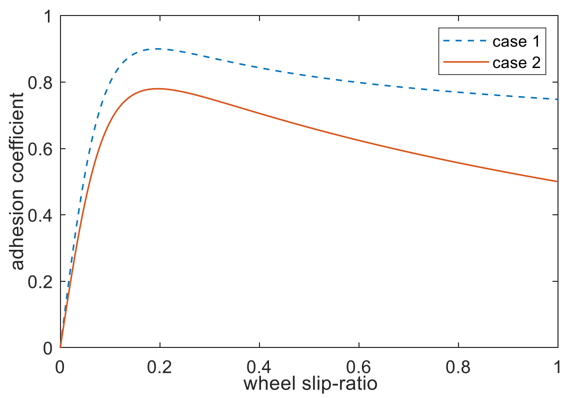


FIGURE 2. Typical relationship between the adhesion coefficient and the wheel slip-ratio on different road conditions.

$$\cos\{C \arctan[B\lambda - E(B\lambda - \arctan(B\lambda))]\} \tag{10}$$

The maximizing the braking force will be generated at the optimal slip-ratio, making

$$\frac{d\mu(\lambda)}{d\lambda}\Big|_{\lambda=\lambda_d} = 0 \tag{11}$$

Combining with the equations (10) and (11), we have

$$\cos\{C \arctan[B\lambda - E(B\lambda - \arctan(B\lambda))]\} = 0 \tag{12}$$

We can obtain the optimal slip-ratio λ_d for different road conditions.

The famous MF model is used to analyze the results in this paper. We choose two cases including dry concrete and wet asphalt road for simulation analysis. The parameters are given as follows, case 1: $B = 6.0, C = 2.2, D = 0.9, E = 0.98$; case 2: $B = 6.0, C = 2.1, D = 0.78, E = 0.8$ for dry concrete and wet asphalt road, respectively. The typical relationship curves are given in Figure.2. It is found that the optimal slip-ratio is around 0.2, which is consistent with the analysis results of other literature [30]. The MF model is used for all subsequent simulations.

III. DESIGN SLIDING MODE CONTROLLER FOR ANTILOCK BRAKING SYSTEM

SMC is a nonlinear feedback control scheme, and it can make systems very robust to parameter perturbation and external disturbances. The scheme consists of two steps. First of all, the sliding mode surface is chosen. It can provide the desired asymptotic behavior. Then, the control law is designed to drive the state trajectories of the system onto the sliding mode surface, and subsequently ensures the states stay on the surface.

In this paper, the aim is to design a sliding mode controller so that the wheel slip-ratio λ can track the desired slip-ratio λ_d as fast as possible. The error equation of slip-ratio is given as follows.

$$x(t) = \lambda - \lambda_d \tag{13}$$

A. DESIGNING SLIDING MODE SURFACE

Without loss of generality, the traditional linear sliding mode surface is chosen as follows.

$$S(x,t) = Kx(t) \tag{14}$$

where $K > 0$.

The system response of traditional sliding mode control can be divided into two parts: reaching mode and sliding mode. Its robustness only exists in the sliding mode stage. For the traditional controller design, there are several drawbacks, such as robust performance is not ensured because the sliding regime may occur only at the origin of the phase plane, and response is sensitive to system perturbation during the reaching phase. Compared with the traditional sliding mode control, the global sliding mode control has a very robust performance.

The global sliding mode surface introduces a nonlinear function in the sliding mode switching function, thereby eliminating the reaching mode of control system. It ensures that the initial state of the system is located on it, the system is constrained to the sliding surface by a sliding mode controller, so the sliding mode invariably exists, and robust performance is ensured throughout an entire response.

We define the nonlinear global sliding mode surface as

$$S(x,t) = Kx(t) - F(t) \tag{15}$$

where $K > 0$. To guarantee sliding mode motion of the system lies on the sliding surface in the beginning, the function $F(t)$ drives the system states in arbitrary state space directly to the sliding surface without a reaching phase. One of the advantages of the global sliding mode control is that it can have sliding mode characteristics over the entire range without a reaching phase. For this, the conditions of the function $F(t)$ should be satisfied, that is

$$F(0) = Kx(0) \tag{16a}$$
$$F(t) \to 0 \quad \text{as } t \to \infty \tag{16b}$$
$$\dot{F}(t) \text{ exists and is bounded} \tag{16c}$$

In Eq.(16), condition (16a) represents the initial location of the states on the sliding surface, (16b) represents asymptotic stability, and (16c) represents the existence of the sliding mode.

According to these conditions, the function $F(t)$ is given as follows.

$$F(t) = F(0)e^{-\eta t} \tag{17}$$

where $\eta > 0$, and η is small enough.

From the function $F(t)$, we can see that the system state is initially located in the sliding regime. The asymptotic stability of the closed-loop system and the existence of a sliding mode are all satisfied.

Substituting equation (17) into (15) yields

$$S(x,t) = Kx(t) - F(0)e^{-\eta t} \tag{18}$$

Substituting equation (13) into (16a) yields

$$F(0) = K(\lambda_0 - \lambda_{d0}) \tag{19}$$

where λ_0 and λ_{d0} are the initial value of λ and λ_d, respectively. So we have

$$F(0) = -K\lambda_d \tag{20}$$

Then we will obtain the global sliding mode surface function.

$$S(x,t) = Kx(t) + K\lambda_d e^{-\eta t} \tag{21}$$

B. DESIGNING SLIDING MODE CONTROL LAW

In the previous section, the designed sliding mode surface can guarantee the asymptotic stability of the system. Next, we will find the sliding mode control law to drive the state trajectories of system onto the sliding surface in a limited time, and maintain on the sliding mode surface.

The designed control law needs to satisfy the following sliding mode reaching condition.

$$S(x,t)\dot{S}(x,t) < 0 \tag{22}$$

Refs [24] and [25] using the traditional isotropic and exponential reaching law, respectively. It is found that the exponential reaching law can obtain better performance. The traditional exponential reaching law is given.

$$\dot{S}(x,t) = -\varepsilon_1 \mathrm{sgn}(S(x,t)) - \varepsilon_2 S(x,t) \tag{23}$$

where $\varepsilon_1 > 0, \varepsilon_2 > 0$, sgn is the symbol function.

It is no difficult to prove the control law (23) can satisfy the sliding mode reaching condition. The smaller numerical parameters ε_1 and the larger numerical parameters ε_2 are chosen to speed up the arrival rate and reduce the chattering. But the control law (23) will bring a certain chattering nearby the equilibrium point of the system. The system states are unable to eventually converge to an equilibrium point, which means that the slip-ratio cannot eventually reach the expected value. The steady-state characteristics of the system are not very ideal. The main reasons are analyzed as follows. When the states of the system reach the sliding mode surface, $S(x,t)$ is very small and the first term $\varepsilon_1 \mathrm{sgn}(S(x,t))$ in (23) plays the primary role. But it is only a constant value and cannot ensure the states of the system converge to the origin, and the effect of inertia will cause a certain amplitude of chattering.

To solve the above problem, we present an improved exponential reaching law as

$$\dot{S}(x,t) = -\varepsilon_1 (\ln(1 + |\alpha_1 S(x,t)|)) |\alpha_2 S(x,t)| \; \mathrm{sgn}(S(x,t)) - \varepsilon_2 S(x,t) \tag{24}$$

where $\alpha_1 > 0, \alpha_2 > 0$

When $S(x,t)$ is large, the control law (24) can perform the characteristic of control law (23), and the arrival rate is rapid by existing the term $(\ln(1 + |\alpha_1 S(x,t)|)) |\alpha_2 S(x,t)|$, so the effect is much well than the control law (23).

When $S(x,t)$ is small, $\ln(1 + |\alpha_1 S(x,t)|)$ will close to 0, compared with control law (23), the arrival rate of the control law (24) is much slower, and the inertia is relatively small, which means the chattering has significantly been reduced.

We introduce the following sliding mode control law

$$T_b(t) = T_{eq}(t) + T_s(t) \tag{25}$$

According to sliding mode equivalent control condition $S(x,t) = 0$, the equivalent term $T_{eq}(t)$ is designed to keep the system on the sliding surface. When $S(x,t) \neq 0$, the switching term $T_s(t)$ is designed to compensate for the discontinuous control.

Theorem 1: Considering the nonlinear vehicle ABS (8), if the control law (25) is chosen as follows

$$T_{eq}(t) = \frac{J}{R}\left[\left(\frac{R^2}{J} + \frac{1-\lambda}{M}\right) F_z \mu(\lambda) + \frac{(1-\lambda)F_a}{M} - \frac{R^2 F_f}{J} - V\eta\lambda_d e^{-\eta t}\right] \tag{26}$$

$$T_s(t) = \frac{JV}{R}\{-\varepsilon_1 (\ln(1 + |\alpha_1 S(x,t)|)) |\alpha_2 S(x,t)| \times \mathrm{sgn}(S(x,t)) - \varepsilon_2 S(x,t)\} \tag{27}$$

The reaching condition is established.

It is no difficult to prove that the reaching law chosen by Theorem 1 satisfies the sliding mode reaching condition, which can guarantee the system asymptotically stabilized via the sliding mode surface (21).

Proof: We choose the Lyapunov function

$$V(t) = \frac{1}{2}S^2(x,t) \tag{28}$$

The time derivative of $V(t)$ along the trajectory of the system (8) is

$$\begin{aligned}
\dot{V}(t) &= S(x,t)\dot{S}(x,t) \\
&= S(x,t)\left[\frac{1}{V}\left(\frac{R^2 F_f}{J} - \frac{(1-\lambda)F_a}{M}\right) - \frac{1}{V}\left(\frac{R^2}{J} + \frac{1-\lambda}{M}\right) F_z\mu(\lambda) + \frac{R}{JV}T_b(t)\right] \\
&= S(x,t)\left[\frac{R\eta\lambda_d}{J} e^{-\eta t} - \varepsilon_1 \ln[1 + |\alpha_1 S(x,t)|] \times |\alpha_2 S(x,t)| \,\mathrm{sgn}(S(x,t)) - \varepsilon_2 S(x,t)\right] \\
&= \frac{R\eta\lambda_d}{J} e^{-\eta t} S(x,t) - \varepsilon_1 \ln[1 + |\alpha_1 S(x,t)|] \times \left|\alpha_2 S^2(x,t)\right| - \varepsilon_2 S^2(x,t)
\end{aligned} \tag{29}$$

When $S(x,t) < 0$,

$$\frac{R\eta\lambda_d}{J} e^{-\eta t} S(x,t) < 0 \tag{30}$$

We have

$$\dot{V}(t) < 0 \tag{31}$$

When $S(x,t) > 0$, if $\frac{R\eta\lambda_d}{J}$ is small enough, $\frac{R\eta\lambda_d}{J} e^{-\eta t} S(x,t)$ may be ignored. In an actual vehicle antilock

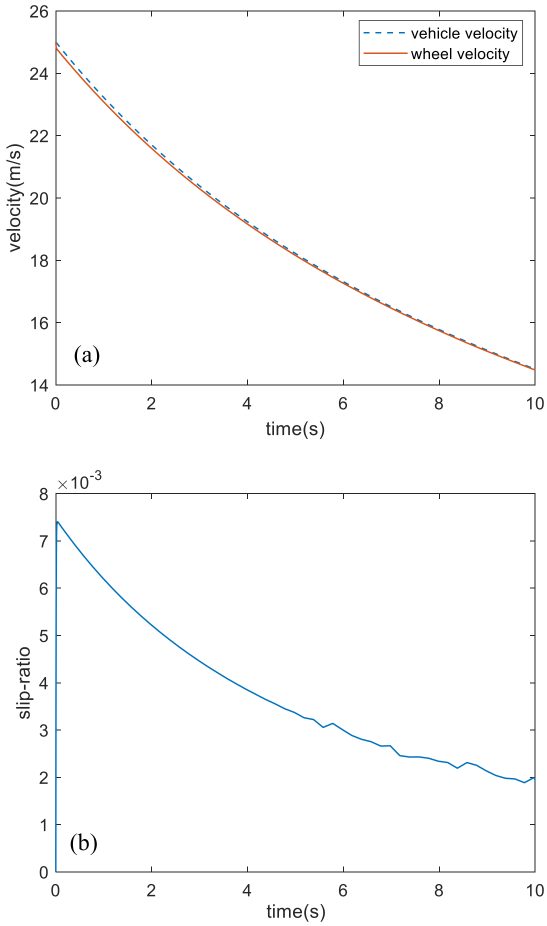


FIGURE 3. Simulation results for dry concrete without a controller and $T_b = 0$: (a) velocity (b) slip-ratio.

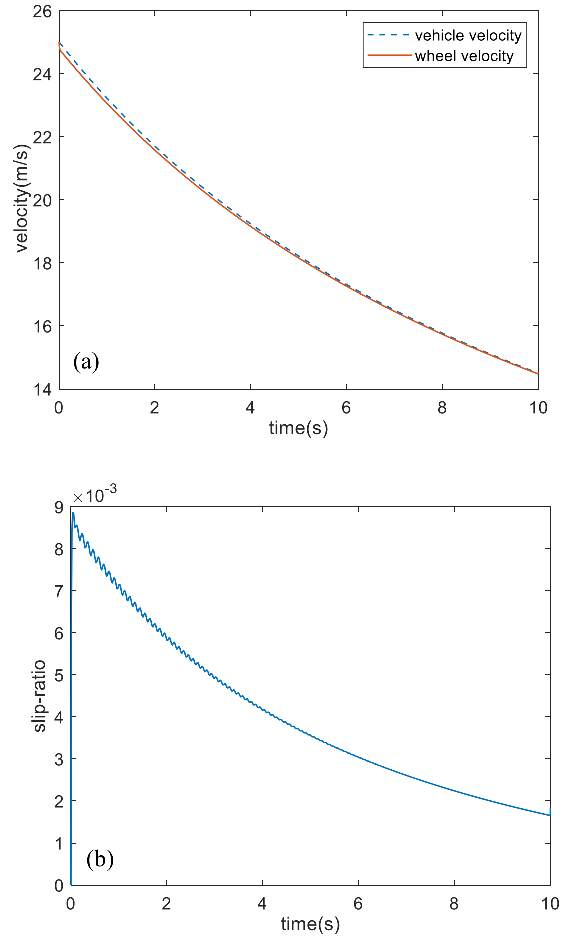


FIGURE 4. Simulation results for wet asphalt without a controller and $T_b = 0$: (a) velocity (b) slip-ratio.

braking system, $\frac{R\lambda_d}{J}$ is very small. By choosing the proper parameter η, we can obtain

$$\dot{V}(t) < 0 \tag{32}$$

Based on the above analysis, we can conclude that the proposed control law (25) can satisfy the sliding mode reaching condition.

IV. SIMULATION

In this section, we validate the effectiveness and performance of the proposed global sliding mode control scheme by Matlab simulation. In the process of designing the controller, the two conflicting requirements must be taken into consideration at the same time. The first requirement is that the controller has a good transient response, the regulating time is rather short, and the overshot is very small. The second emphasis is that the steady performance, such as small steady error and accurately tracking capability. In the simulation, we will draw comparisons the braking performance among the traditional sliding mode controller, the traditional global sliding mode controller, and the proposed global sliding mode controller under the various road conditions.

TABLE 1. The parameters of the system.

$J=1.1kg\cdot m^2$	M=415kg	g=9.8m/s^2	R=0.326m
ρ=1.29kg/m^3	f_0=0.01	f_s=0.005	f_d=0.539
A_d=2.04m^2	f_b=2.237		

The performance and effectiveness of sliding mode controller are verified in a series of numerical simulations. The parameters of the system are given in Table 1.

In this simulation, we consider two cases, including dry concrete and wet asphalt road. We can get the optimal slip-ratio based on equation (12), they are 0.1938 and 0.1959 for case 1 and case 2, respectively, and this is consistent with the analysis in Figure 2.

First, we carry out simulation research on the nonlinear ABS without a controller. Considering the initial velocity is $25m/s$ with $T_b = 0$, the curves of velocity and slip-ratio are shown for two cases in Figure 3 and Figure 4, respectively. According to the simulation results, it can be intuitively seen that the difference between vehicle velocity and wheel velocity is small, so the slip-ratio is approximately equal to zero.

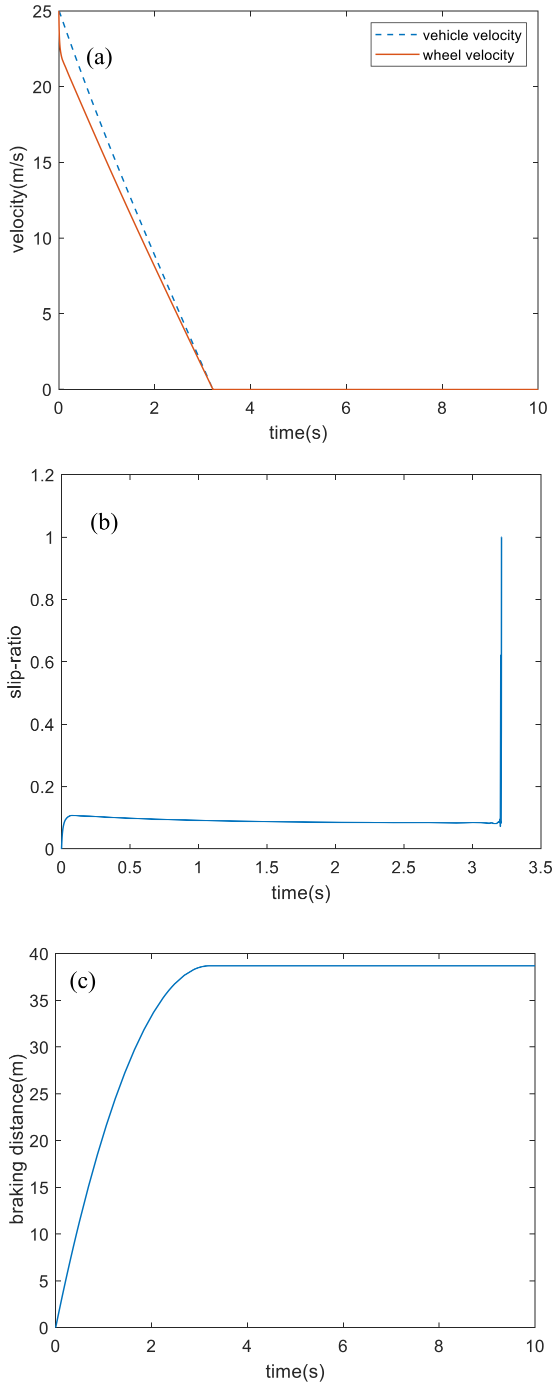


FIGURE 5. **Simulation results for dry concrete without controller and $T_b = 1000N \cdot m$: (a) velocity (b) slip-ratio (c) braking distance.**

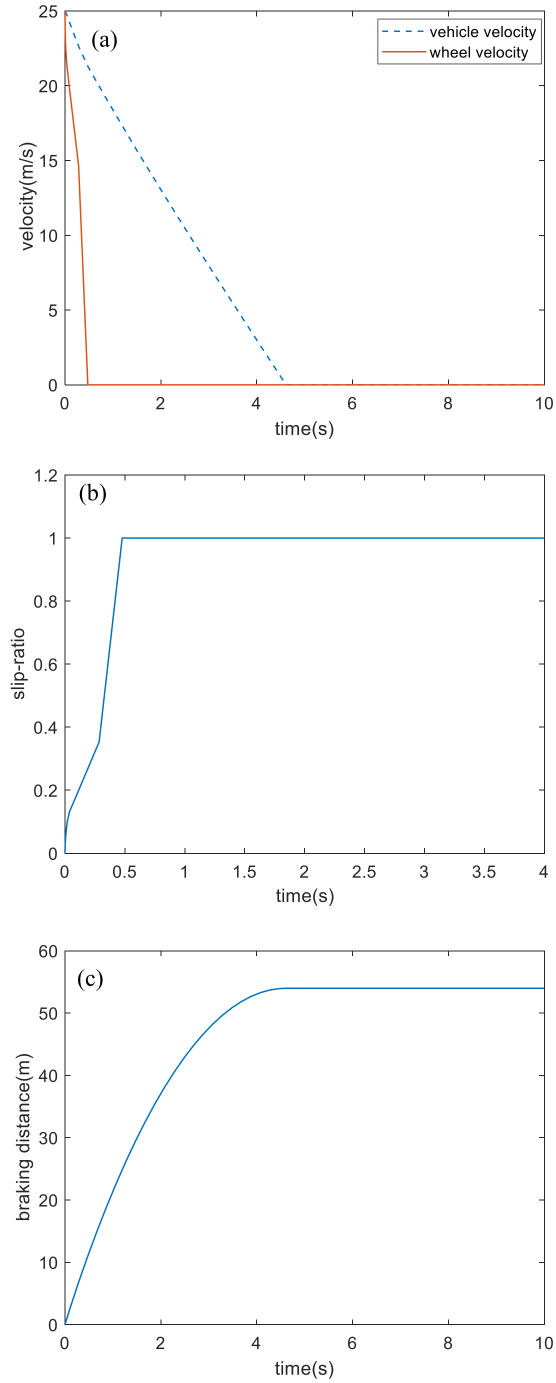


FIGURE 6. **Simulation results for wet asphalt without controller and $T_b = 1000N \cdot m$: (a) velocity (b) slip-ratio (c) braking distance.**

For Figure 3(a) and Figure 4(a), we can see that the vehicle velocity and wheel velocity will slowly decrease from the starting point of 25m/s. This is because the air resistance and rolling resistance will be taken into account when the vehicle is running. Moreover, the higher the air resistance vehicle velocity is, the greater the drag will be. So the vehicle velocity will decrease faster at the beginning. Then it is going to go down slower and slower, which is consistent with the actual situation.

In order to further verify the effectiveness of the system without a controller, considering the initial velocity of the car is $25m/s$ with $T_b = 1000N \cdot m$, the curves of velocity and slip-ratio are shown for two cases in Figure 5 and Figure 6, respectively. From Figure 5(b) and Figure 6(b), it is seen that the slip-ratio will rise from 0 to 1, which indicates the wheels appear to be locked when the braking torque is large enough. When the braking torque is always applied, the wheel will be locked until the whole vehicle stops. Especially in wet asphalt road condition, under the action of braking torque, the wheel

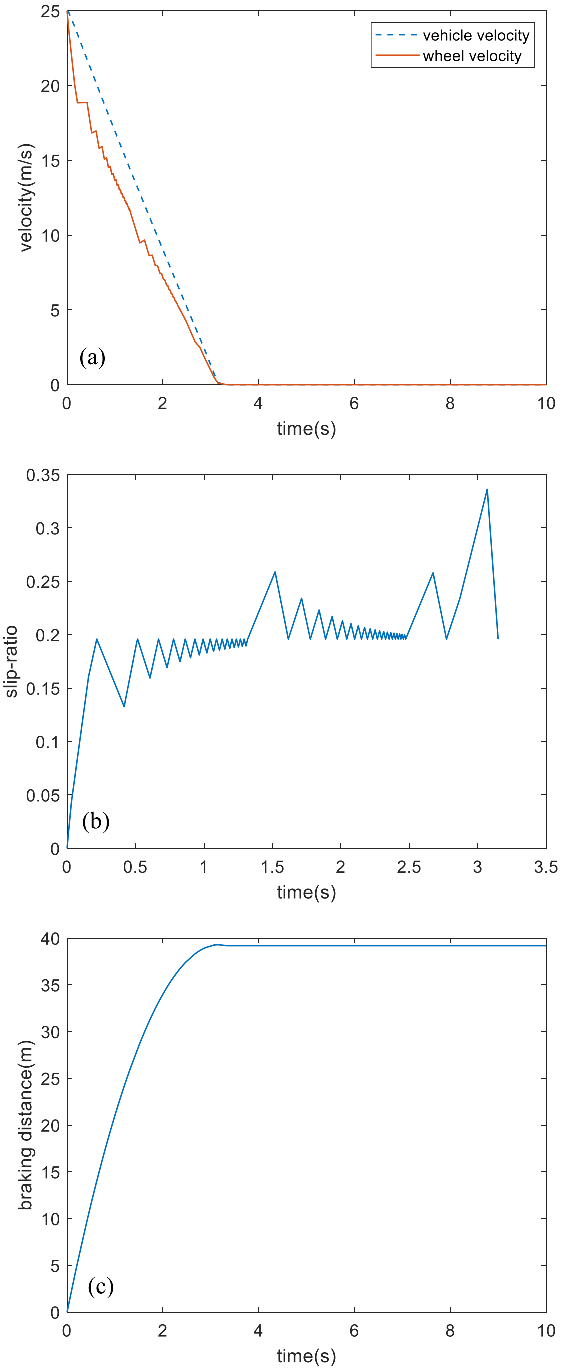


FIGURE 7. **Simulation results for wet asphalt with linear sliding mode controller using traditional exponential reaching law: (a) velocity (b) slip-ratio (c) braking distance.**

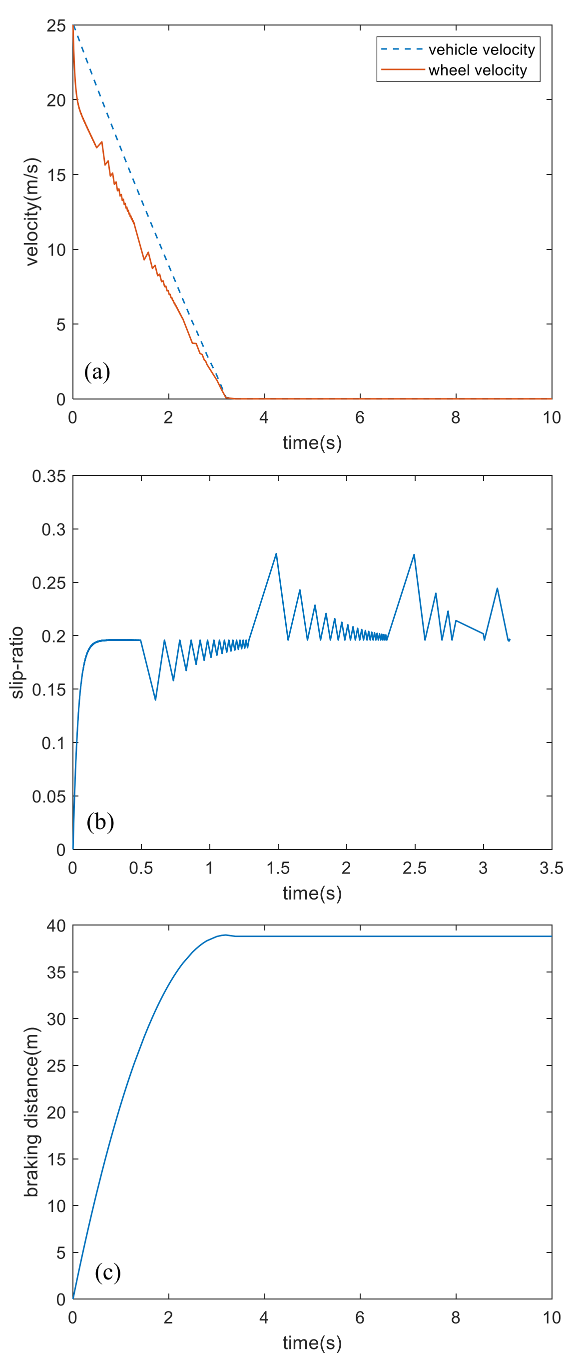


FIGURE 8. **Simulation results for wet asphalt with global sliding mode controller using traditional exponential reaching law: (a) velocity (b) slip-ratio (c) braking distance.**

velocity becomes zero when the time is 0.4778 s, the vehicle velocity is about 21.3 m/s, the wheel appears to be locked. By analyzing the above simulation results, the model of ABS is established to meet the requirements. Also, the braking performance parameters are given in Table 2. The comparison shows that there are a greater braking distance and time on the wet asphalt pavement. The road condition is rather bad, so we choose wet asphalt pavement as the controller research simulation environment.

TABLE 2. **Braking performance for two cases without controller and $T_b = 1000N \cdot m$.**

	braking distance(m)	braking time(s)
dry concrete	38.69	3.211
wet asphalt	53.98	4.614

In this section, simulation results are carried out using wet asphalt in order to investigate the performance of the sliding mode controller using the traditional exponential reaching

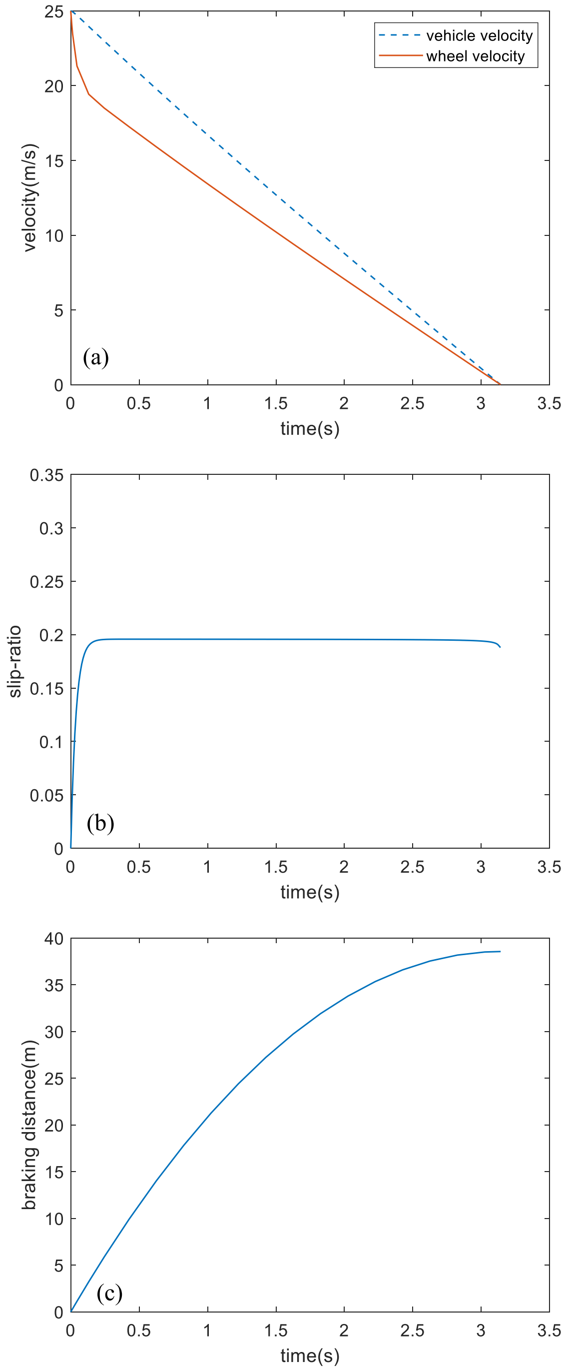


FIGURE 9. Simulation results for wet asphalt with global sliding mode controller using an improved exponential reaching law: (a) velocity (b) slip-ratio (c) braking distance.

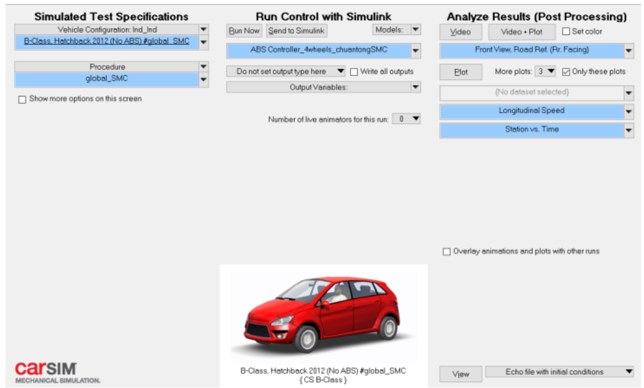


FIGURE 10. CarSim main interface.

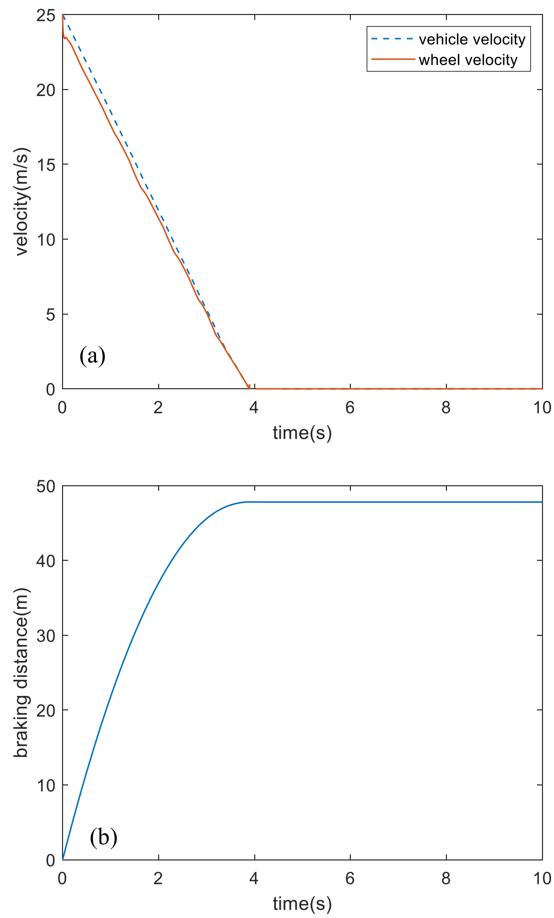


FIGURE 11. Joint simulation results for wet asphalt with linear sliding mode controller using traditional exponential reaching law: (a) velocity (b) braking distance.

law. The parameters of sliding mode surface and control law are $K = 1$, $\eta = 26$, $\varepsilon_1 = 0.7$, $\varepsilon_2 = 6$, $\alpha_1 = 100$, $\alpha_2 = 1$. Figure.7 and Figure 8 give the simulation results to study the performance of the traditional global sliding mode controller and the linear sliding mode controller. The braking performance results are shown in Table 3. We can see that the global sliding mode control scheme can obtain fast and stable responses. The slip-ratio has small chattering. The scheme has a smaller braking distance and braking time, which indicates the global sliding mode control method is very suitable for the vehicle antilock braking system.

In order to improve the braking performance, the simulation results of the global sliding mode controller with an improved exponential reaching law are given in Figure 9. The braking performance results are shown in Table 3. As can be seen from Figure 9 (a), the vehicle velocity and wheel velocity are relatively smooth, which shows the proposed

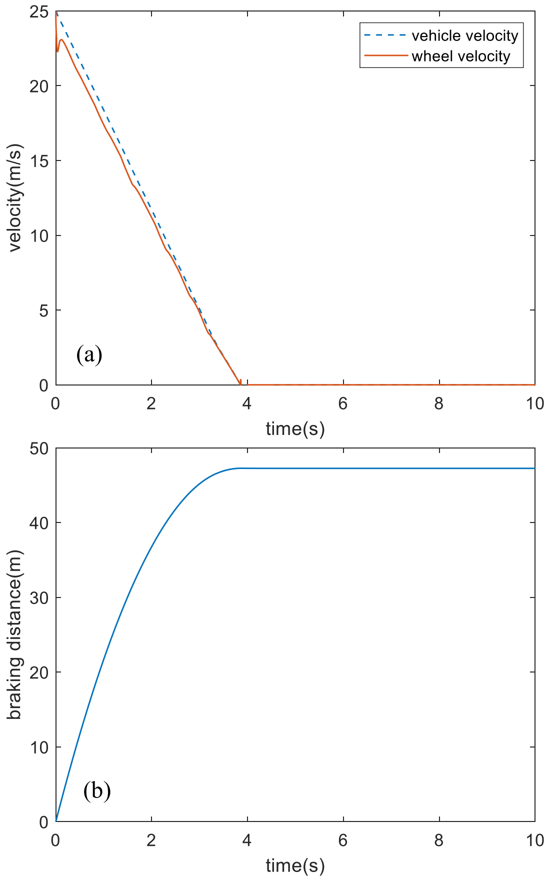


FIGURE 12. **Joint simulation results for wet asphalt with global sliding mode controller using traditional exponential reaching law: (a) velocity (b) braking distance.**

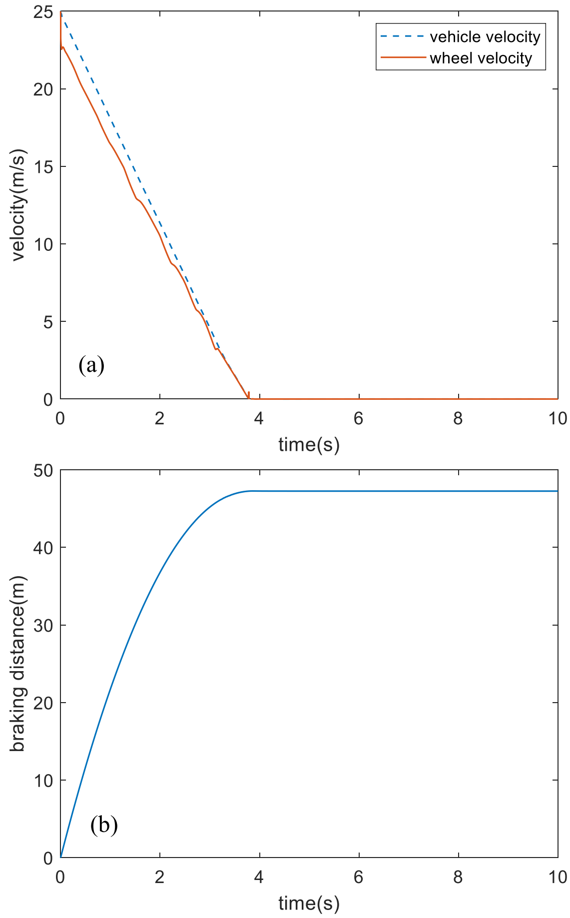


FIGURE 13. **Joint simulation results for wet asphalt with global sliding mode controller using an improved exponential reaching law: (a) velocity (b) braking distance.**

TABLE 3. **Comparison of braking distance and braking time of three different control methods.**

	braking distance (m)	braking time (s)
linear sliding mode controller	39.22	3.394
global sliding mode controller with traditional exponential reaching law	38.80	3.391
global sliding mode controller with an improved exponential reaching law	38.55	3.117

global sliding mode control scheme has good robustness. In Figure 9 (b), the proposed controller makes the wheel slip-ratio maintained at the desired slip-ratio. However, the other methods bring about the fluctuation of the slip-ratio. Simultaneously, the proposed scheme has a smaller braking distance and braking time and shows good braking performance. Therefore, the proposed controller has a better performance compared with the other controllers. It is very suited to the nonlinear antilock braking system.

V. JOINT SIMULATION USING MATLAB AND CARSIM

The quarter car model used for the simulation is a simplified model, ignoring the influence of pitch, roll and yaw motion, suspension, and tire dynamics. The actual braking situation of vehicle is more complicated than the theory. To further verify the practicability of the control method, MATLAB and CarSim will be used for joint simulation. CarSim is a vehicle simulation software for vehicle dynamics simulation research. It can define various vehicle parameters in detail in the database of its main interface and sub-interface, and flexibly set the simulation environment and simulation process. So joint simulation can further verify the practicability of the proposed control method.

The braking performances of three controllers are validated using a B-Class, Hatchback 2012 (No ABS) car running on wet asphalt road with an initial velocity of 25m/s. The main interface of CarSim is shown in Figure 10.

For traditional linear sliding mode control, traditional global sliding mode control, and improved global sliding mode controller, the curves including vehicle speed, wheel speed and braking distance are shown in Figures 11-13, respectively. The braking performance results of the three control methods are given in Table 4.

The joint simulation results show that the global sliding mode controller with improved exponential reaching law among the three control methods has the shortest braking

TABLE 4. Comparison of braking performance of three control methods using MATLAB and CarSim joint simulation.

	braking distance (m)	braking time (s)
linear sliding mode controller	47.81	3.894
global sliding mode controller with traditional exponential reaching law	47.25	3.862
global sliding mode controller with an improved exponential reaching law	46.39	3.806

distance and the braking time. It has the best braking performance. Compared with the traditional linear sliding mode controller, the braking distance is shortened by 1.42 m. The results are consistent with the MATLAB simulation results given in Section IV, which proves the feasibility of designed controller.

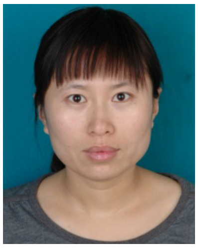
VI. CONCLUSION

A novel global sliding mode controller for the nonlinear ABS has been studied in this paper. First, we study the ABS on dry concrete and wet asphalt without a controller, considering the initial velocity of car is $25m/s$ with $T_b = 0$ and $T_b = 1000N \cdot m$, respectively. The effectiveness and accuracy of the system is verified by simulation research. It is found that there are a greater braking distance and braking time on the wet asphalt road. Then, the global sliding mode surface is designed for the ABS under a wet asphalt road. The traditional exponential reaching law is given to satisfy the sliding mode reaching condition. The control performance between the traditional linear sliding mode controller and the global sliding mode controller is compared and analyzed. The simulation results show that the traditional global sliding mode control scheme has a better braking performance. Finally, based on the traditional exponential reaching law, an improved exponential control law is proposed. The simulation results show that the effectiveness of the proposed global sliding mode control scheme has a better braking performance. Its wheel slip rate is maintained near the ideal wheel slip rate, which reduces the chattering problem. The proposed control scheme can obtain global robustness. It can be used effectively to control the ABS. The joint simulation using MATLAB and CarSim platform has obtained consistent results, further proving the practicability of the proposed global sliding mode control scheme. However, our research is only performed on wet asphalt pavements and not simulated on other pavements. The actual pavement is often more complicated, and the friction coefficient varies. In the future, we will consider pavements with variable friction coefficients for research.

REFERENCES

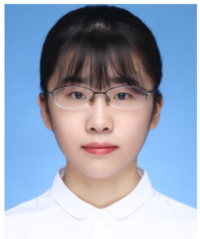
[1] F. Pretagostini, L. Ferranti, G. Berardo, V. Ivanov, and B. Shyrokau, "Survey on wheel slip control design strategies, evaluation and application to antilock braking systems," *IEEE Access*, vol. 8, pp. 10951–10970, 2020.
[2] H. B. Pacejka and E. Bakker, "The magic formula tyre model," *Vehicle Syst. Dyn.*, vol. 21, no. 1, pp. 1–18, Jan. 1992.
[3] C. Canudas de Wit, H. Olsson, K. J. Astrom, and P. Lischinsky, "A new model for control of systems with friction," *IEEE Trans. Autom. Control*, vol. 40, no. 3, pp. 419–425, Mar. 1995.
[4] U. Kiencke and L. Nielsen, *Automotive Control Systems: For Engine, Driveline, and Vehicle*. New York, NY, USA: Springer-Verlag, 2000.
[5] Q. Fu, L. Zhao, M. Cai, M. Cheng, and X. Sun, "Simulation research for quarter vehicle ABS on complex surface based on PID control," in *Proc. 2nd Int. Conf. Consum. Electron., Commun. Netw. (CECNet)*, Three Gorges, China, Apr. 2012, pp. 2072–2075.
[6] V. R. Aparow, F. Ahmad, K. Hudha, and H. Jamaluddin, "Modelling and PID control of antilock braking system with wheel slip reduction to improve braking performance," *Int. J. Veh. Saf.*, vol. 6, no. 3, pp. 265–296, 2013.
[7] A. Badie Sharkawy, "Genetic fuzzy self-tuning PID controllers for antilock braking systems," *Eng. Appl. Artif. Intell.*, vol. 23, no. 7, pp. 1041–1052, Oct. 2010.
[8] T.-L. Le, "Intelligent fuzzy controller design for antilock braking systems," *J. Intell. Fuzzy Syst.*, vol. 36, no. 4, pp. 3303–3315, Apr. 2019.
[9] C.-M. Lin and T.-L. Le, "PSO-self-organizing interval type-2 fuzzy neural network for antilock braking systems," *Int. J. Fuzzy Syst.*, vol. 19, no. 5, pp. 1362–1374, Oct. 2017.
[10] Y. Lee and S. H. Zak, "Designing a genetic neural fuzzy antilock-brake-system controller," *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 198–211, Apr. 2002.
[11] T. Sardarmehni, H. Rahmani, and M. B. Menhaj, "Robust control of wheel slip in anti-lock brake system of automobiles," *Nonlinear Dyn.*, vol. 76, no. 1, pp. 125–138, Apr. 2014.
[12] J. Zhang, W. Sun, and H. Jing, "Nonlinear robust control of antilock braking systems assisted by active suspensions for automobile," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 3, pp. 1352–1359, May 2019.
[13] H. Mirzaeinejad, "Robust predictive control of wheel slip in antilock braking systems based on radial basis function neural network," *Appl. Soft Comput.*, vol. 70, pp. 318–329, Sep. 2018.
[14] Y. He, C. Lu, J. Shen, and C. Yuan, "Design and analysis of output feedback constraint control for antilock braking system based on Burckhardt's model," *Assem. Autom.*, vol. 39, no. 4, pp. 497–513, Sep. 2019.
[15] Z. Wang, J. Zhu, L. Zhang, and Y. Wang, "Automotive ABS/DYC coordinated control under complex driving conditions," *IEEE Access*, vol. 6, pp. 32769–32779, 2018.
[16] J. Tan, Y. Fan, P. Yan, C. Wang, and H. Feng, "Sliding mode fault tolerant control for unmanned aerial vehicle with sensor and actuator faults," *Sensors*, vol. 19, no. 3, pp. 1–15, Feb. 2019.
[17] M.-J. Zhang and Z.-Z. Chu, "Adaptive sliding mode control based on local recurrent neural networks for underwater robot," *Ocean Eng.*, vol. 45, pp. 56–62, May 2012.
[18] X. Zhang, Y. Xu, M. Pan, and F. Ren, "A vehicle ABS adaptive sliding-mode control algorithm based on the vehicle velocity estimation and tyre/road friction coefficient estimations," *Vehicle Syst. Dyn.*, vol. 52, no. 4, pp. 475–503, Apr. 2014.
[19] S. B. Phadke, P. D. Shendge, and V. S. Wanaskar, "Control of antilock braking systems using disturbance observer with a novel nonlinear sliding surface," *IEEE Trans. Ind. Electron.*, vol. 67, no. 8, pp. 6815–6823, Aug. 2020.
[20] E. Kayacan, Y. Oniz, and O. Kaynak, "A grey system modeling approach for sliding-mode control of antilock braking system," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3244–3252, Aug. 2009.
[21] T. Shim, S. Chang, and S. Lee, "Investigation of sliding-surface design on the performance of sliding mode controller in antilock braking systems," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 747–759, Mar. 2008.
[22] J.-C. Wang and R. He, "Hydraulic anti-lock braking control strategy of a vehicle based on a modified optimal sliding mode control method," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 233, no. 12, pp. 3185–3198, Oct. 2019.
[23] Y. Chu, J. Fei, and S. Hou, "Adaptive global sliding-mode control for dynamic systems using double hidden layer recurrent neural network structure," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 31, no. 4, pp. 1297–1309, Apr. 2020.
[24] J. Zhang, Z. Ren, C. Deng, and B. Wen, "Adaptive fuzzy global sliding mode control for trajectory tracking of quadrotor UAVs," *Nonlinear Dyn.*, vol. 97, no. 1, pp. 609–627, Jul. 2019.
[25] S. Mobayen, "Fast terminal sliding mode controller design for nonlinear second-order systems with time-varying uncertainties," *Complexity*, vol. 21, no. 2, pp. 239–244, Nov. 2015.

[26] W. Liu, G. Xu, and X. Jiang, "Discrete global sliding mode control for time-delay carbon fiber multilayer diagonal loom," *IEEE Access*, vol. 5, pp. 15326–15331, 2017.
[27] C. Xiu, J. Hou, G. Xu, and Y. Zang, "Improved fast global sliding mode control based on the exponential reaching law," *Adv. Mech. Eng.*, vol. 9, no. 2, pp. 1–8, Feb. 2017.
[28] Y. Jing, Y.-E. Mao, G. M. Dimirovski, Y. Zheng, and S. Zhang, "Adaptive global sliding mode control strategy for the vehicle antilock braking systems," in *Proc. Amer. Control Conf.*, St Louis, MO, USA, 2009, pp. 769–773.
[29] X. Ping, L. Wei, and Z. Yan, "Robust and rapid control for ABS based on global sliding mode," in *Proc. 24th Chin. Control Decis. Conf. (CCDC)*, Taiyuan, China, May 2012, pp. 2195–2198.
[30] K. Han, B. Lee, and S. B. Choi, "Development of an antilock brake system for electric vehicles without wheel slip and road friction information," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5506–5517, Jun. 2019.



HONGWEI WANG was born in Tieling, Liaoning, China, in 1983. She received the B.S. degree in electrical engineering and automation from the Liaoning University of Technology, China, in 2004, and the B.S. and Ph.D. degrees in control theory and control engineering from Northeastern University, China, in 2006 and 2009, respectively. Since 2009, she has been an Assistant Professor with the School of Control Engineering, Northeastern University at Qinhuangdao. She has published about 40 articles, including 20 journal articles and one book chapter. Her research interests include vehicle safety control, sliding mode control, intelligent control, and prediction control.

SHAOWEN WU is currently pursuing the B.S. degree with Northeastern University at Qinhuangdao, Qinhuangdao, Hebei, China. He also works with Hongwei Wang, as a Student Researcher. His current research interests include robust control and intelligent control.



QIANYU WANG received the B.S. degree in electrical engineering from Shandong Agricultural University, China, in 2018. She is currently pursuing the master's degree with Northeastern University at Qinhuangdao, Qinhuangdao, Hebei, China. Her main research interests include vehicle fault diagnosis and fault tolerant control, and robust control.