Research Article

Evaluation on Braking Stability of Autonomous Vehicles Running along Curved Sections Based on Asphalt Pavement Adhesion Properties

Binshuang Zheng, Xiaoming Huang, Junyao Tang, Jiaying Chen, Runmin Zhao, Zhengqiang Hong, Tao Tang, and Meiling Han

1School of Modern Posts, Nanjing University of Posts and Telecommunications, Nanjing 210023, China
2School of Transportation, Southeast University, Nanjing 211189, China

Correspondence should be addressed to Meiling Han; meilinghan@njupt.edu.cn

Received 30 December 2021; Revised 30 March 2022; Accepted 19 April 2022; Published 29 May 2022

As the main objective influencing factor on the brake safety of autonomous vehicles, pavement texture information is directly related to road surface antiskid performance. However, in the brake system of autonomous vehicles, the influence of road surface adhesion characteristics on braking stability is seldomly considered. To study the braking stability of autonomous vehicles on curved sections under different road conditions, the advanced close-range photogrammetry system was utilized to extract the road surface texture information. Thereafter, the power spectral density (PSD) of the road surface was calculated by MATLAB to obtain the pavement adhesion coefficient curves based on the Persson friction theory model under different road conditions. Considering the pavement adhesion characteristics, the braking model of autonomous vehicles was built in Simulink, and then, the braking performance on curved sections was analyzed with CarSim/Simulink cosimulation. The results indicate that, according to the adhesion coefficient of different asphalt pavement types under different road conditions, the ranking order is open-graded friction course (OGFC) > stone matrix asphalt (SMA) > dense-graded asphalt concrete (AC). In addition, both the maximum lateral offset distances and the maximum lateral forces of the tires decrease as the curve radius gradually increases under different road conditions. It can also be found that there is a relatively uniform vertical forces distribution of the tire when the curve radius is no less than 100 m, and the limit speed of the vehicle varies parabolically with increasing in curve radius. Compared with dry road, the reduction of vehicle braking deceleration is more significant and the yaw rate is greater on wet road. Last but not least, the braking comfort with a radius of 200 m is the best according to the comfort index (CI) in International Standard ISO, in which the comfort level can be sorted into six levels.

1. Introduction

The National Highway Traffic Safety Administration [1] shows that about 90% of traffic accidents in the United States are caused by driver errors, followed by road information as the main objective factor. According to investigation of the World Health Organization [2], traffic accidents account for about 2.2% of the world deaths each year. Thereby, many research institutes studied the driving stability and road safety problem in terms of transportation energy conservation [3], multiple transport modes control [4, 5], traffic crash risk avoidance [6, 7]. However, these studies seldom take into account the factors that combine the supply and demand sides and rarely consider the feeling of passengers or drivers. In order to meet the development needs of traffic safety and driving safety, autonomous vehicles emerged and rapidly developed to meet society and economy requirements [8, 9]. Because of the high sensibility, low traffic pressure [10], low energy consumption [11], low traffic accident rate, and other advantages, autonomous vehicles will become the major traffic vehicle in the future, which can greatly improve traffic safety [12].
conditions, considering the driverless control of vehicles, it is necessary to use sensors to collect the driving environment information and apply braking pressure through an electronic control center ECU [13]. To be well known, the skid resistance performance of road surface is one of the main objective factors that affect the braking safety of autonomous vehicles. During the braking process, although antiskid braking system (ABS) and traction control system (TCS) play a role, rollover and slippage occur. It is indicated that the traditional braking system is unsuitable for the braking stability of autonomous vehicles. Therefore, it is necessary to explore the sensing parameters of road information during the braking process based on vehicle dynamics theory, providing real-time road texture information for autonomous vehicles.

In 1940, the concept of autonomous vehicles technology was firstly proposed by Norman Bel Geddes, an American industrial designer. In 1986, Europe launched PROM-ETHUS (Program for a European Traffic with Highest Efficiency and Unprecedented Safety) [14]. Subsequently, many European research institutes studied driving stability and safety in terms of the autonomous vehicle control system, such as a high-fidelity cosimulation platform for motion and control proposed by Wang [15], an advanced emergency braking controller by Guo [16], an adaptive fuzzy sliding mode controller by Boopathy [17], and relevant policy for automated driving [18, 19]. For example, Delageu developed a new vehicle braking model using MATLAB/Simulink to predict the braking distance under various braking conditions. With respect to this braking model, it considered the road properties, road gradient, wind resistance, and so forth [20]. In addition, considering the influence of road adhesion condition and road curvature on steering characteristics and stability of the vehicle, an equivalent dynamic model for autonomous vehicles at high speed was established [21]. Furthermore, combined with vehicle dynamics characteristics, a vehicle stability control strategy based on speed limitation control switch was built with MATLAB/Simulink cosimulation [22].

However, the previous research on braking stability of autonomous vehicles mainly focused on the development of braking control algorithms [23, 24] and electronic stability programs [25], ignoring the impact of different road information on the braking performance of vehicles [26]. Only with the consideration of the macro factors (e.g., road environment information and traffic capacity) was the vehicle-road coupling model established. Recently, few studies have investigated the braking behavior of autonomous vehicles in terms of the road surface skid resistance [27]. For instance, Du et al. [28] proposed a dynamic method to estimate pavement friction level using computer vision for enhancing the autonomous vehicle safety performance. Theoretically, the braking performance of autonomous vehicles is directly related to the traffic safety, such as the long braking distance and side slipping during emergency braking. Under wet road condition, the pavement adhesion coefficient decreases and braking performance of vehicles declines, which easily leads to traffic accidents during braking process [29]. Therefore, some researchers have contributed to the image processing technology of improving autonomous driving. For instance, Aldibaja et al. [30] proposed a frame accumulation strategy to enhance the representation of the road surface images for improving autonomous vehicle driving safety in wet road environment. According to the actual road conditions (e.g., pavement type, water film thickness, road geometry design, etc.), the comfort evaluation index of autonomous vehicles can be used to ensure braking safety [31]. It can provide reference for the sensor technology and the operation safety of autonomous vehicles, which furtherly contribute to saving time, improving road utilization, and fuel efficiency.

As we all know, typical braking scenarios include normal braking on straight road, emergency braking, steering braking on curved section, and braking on slope section on wet or dry pavement conditions. Due to the linear deformation and lateral unevenness generated on curve section, as running along curved sections, the wheel steering angle should be reasonably controlled and recognition of road conditions needs to be improved. In addition, due to the limited paper length, we just have discussed the driving scenario on a curved section in this study. Therefore, driving on a curved section was investigated to highlight the influence of road surface adhesion characteristics on the braking stability of autonomous vehicles in this study. In view of this, considering the braking characteristic and the perception requirements of autonomous vehicles, a novel braking model of the autonomous vehicle was proposed and built with MATLAB/Simulink according to the real-time texture information of different asphalt pavements. Then, CarSim/Simulink cosimulation was applied to analyze the braking characteristics of autonomous vehicles on curved sections for different road conditions. Furthermore, the braking comfort of autonomous vehicles under different working conditions was evaluated based on the comfort index in International Standard ISO. In this study, an evaluation system for braking stability and driving comfort of vehicles was established to provide theoretical guidance for braking strategies on curved sections and braking system design of autonomous vehicles. The research framework of this study is shown in Figure 1.

2. Friction Coefficient of Asphalt Pavement

2.1. Acquisition of Pavement Texture Information. Based on the automatic close-range photogrammetry system (ACRP system) developed by the research group [32, 33], the surface textures for three typical types of asphalt pavements (in Figure 2(a)) were collected firstly. After the preprocessing of collected images, reverse reconstruction technology was used to reconstruct the three-dimensional (3D) images of road surface texture, and the 3D model of asphalt pavement surface texture (Figure 2(b)) was established. Then, the GeoMagic and MeshLab 3D model software programs were adopted to preprocess the reverse reconstructed 3D model of asphalt pavement surface texture, including hole filling correction, leveling, and defining local coordinate axis attributes, to derive road surface texture 3D elevation data from 3D model, containing 3D coordinate points (x, y, z), as shown in Figure 2(c).
According to the above 3D elevation data, the surface morphology was reconstructed in MATLAB, as shown in Figure 3. Three types of asphalt pavement were selected in this study, AC pavement, SMA pavement, and OGFC pavement. The gradation curves of the three kinds of asphalt mixtures are drawn as shown in Figure 3(a). To generate a wet pavement surface, water was sprayed on the dry surface uniformly until the concave asperities were sealed with water [34].

2.2. Calculation of Friction Coefficient. Based on the 3D texture data \((x, y, z)\) obtained in Section 2.1, the power spectral distribution (PSD) solver was written in MATLAB using the PSD calculation model in the Persson friction theory [35, 36]. Since the random variables of the fractal road surface are discrete points, further filtering, windowing, and sampling window compensation of the coordinate data are needed in the process of solving the power spectrum [37]. The PSD of the road surface under wet and dry road conditions were both calculated (in Figure 4(a)).

Based on the calculated PSD, the friction coefficient curves of asphalt pavement were obtained by the Persson friction model (see Figure 4(b)). The variation trends of friction coefficient curves under different pavement conditions are basically similar; they both decrease significantly with the increase of the tire relative slipping speed. When the speed exceeds 40 km/h, the curve tends to be gentle, indicating that the actual contact area of the tire-road surface comes to a stable status when the speed is relatively high. The friction coefficient of the wet road surface is lower than that of dry pavement. In addition, the greater the speed, the greater the difference in friction coefficient between the two states (dry and wet pavement).

For both dry road and wet road conditions, the friction coefficients of the three types of asphalt pavements are sorted as OGFC pavement > SMA pavement > AC pavement, which indicates that the surface roughness has no change though the partial texture on wet road surface does not contribute to skid resistance for asphalt pavement caused by the film barrier between the tire and the pavement.
Figure 3: Pavement texture visualization: (a) gradation curves for three types of asphalt pavement; (b) AC-13 pavement, (i) dry condition and (ii) wet condition; (c) SMA-13 pavement, (i) dry condition and (ii) wet condition; (d) OGFC-13 pavement; (i) dry condition and (ii) wet condition.
3. Braking Theory of Autonomous Vehicles

Theoretically, the desired braking deceleration for autonomous vehicles is obtained based on the road surface peak adhesion coefficients identified in real time. Then, the reverse braking system converts the desired braking deceleration into the desired brake pressure threshold. Meanwhile, the electronic control unit (ECU) system of autonomous vehicles calculates brake pressure through the brake pedal simulator. Furthermore, the brake actuator confirms the current braking condition and sends a brake signal to the pressure controller. With rapid response, the braking system outputs the actual braking force to the tires in real time, thereby to realize the automatic braking process.

3.1. Braking Characteristic under Typical Scenarios.

Under no driver operation, the autonomous vehicles should monitor the road traffic condition in real time by equipped sensors and adopt different braking modules to perform braking behavior. In general, there are certain differences in braking behavior between autonomous vehicles and non-autonomous vehicles under different braking scenarios. The braking characteristics on curved sections and on rainy days are specifically described as follows.

3.1.1. Braking on Curved Section. Due to the linear deformation and lateral unevenness generated on curved sections, the vehicle body may have offset distance. As a result, the driving path may deviate from the curve center line and the vehicle may lose control. In particular, the side slip and rollover may occur in this situation. During the braking process, the wheel steering angle should be reasonably controlled and recognition of road conditions needs to be improved. Therefore, the distance and speed of the vehicle can be maintained within a safe range, and the braking force of the wheels can be balanced. Furthermore, the lateral displacement of the vehicle can be regarded as an index to evaluate the vehicle’s dynamic stability.

3.1.2. Braking on Rainy Days. Due to the change of the tire-pavement contact area and the road surface adhesion coefficient on rainy days, the vehicle is prone to have side slip and tire hydroplaning risk during the braking process. The lateral deviation of the vehicle body is the main factor, which should be considered for evaluating the vehicle braking stability. Based on the road surface adhesion characteristics, the safe following distance and driving speed are synthetically determined by the relative position of the front vehicle speed, the relative driving speed, and the braking performance.

To highlight the superiority of autonomous vehicles, the passenger’s comfort is a vital index assessing the maneuverability of autonomous vehicles under the assurance of braking safety. Generally, on rainy days, the braking comfort demand of vehicles is quite prominent driving on the curved sections.

3.2. Evaluation Indices for Braking Performance. In terms of autonomous vehicles, the current road surface friction characteristics and the relative state of surrounding vehicles need to meet the limitations under an emergency braking state, such as the shortest braking distance, the maximum braking deceleration, and the vehicle braking stability. In the EU Brake Regulation 71/320/EWG, the reaction time of the driver is ignored for braking distance. That is,

\[ s = v_A \left( t_a + \frac{t_s}{2} \right) + \frac{v_A^2}{2 \left( -\Delta \mu \right)} \]  

where \( s \) is braking distance, \( v_A \) is tested speed, \( t_a \) is the coordination and response time of braking system, \( t_s \) is the
growth time of braking force, and \( \ddot{x}_v \) is the braking deceleration.

Under dry road condition, the side sliding will not occur with the adhesion condition of \( \mu_h = 0.80 \). With a low adhesion coefficient \( \mu_h \), the relative deceleration of two vehicles is specified by EU regulations (equation (2)). The EU brake regulations also list specific limits for passenger vehicles, trucks, and other vehicles.

\[
a \geq 0.1 + 0.85(\mu_h - 0.2), \quad 0.2 \leq \mu_h \leq 0.8.
\]

The comfort index (CI) is specified in International Standard ISO 2631-1 [38]. Without considering the lateral offset distance, the calculation model of CI can be simplified as

\[
CI = \left[ \frac{1}{m} \sum_{i=0}^{m} a_i^2 \right]^{1/2},
\]

where \( a_i \) is the \( i \)th acceleration value obtained statistically and \( m \) is the total amount of statistics. For the subsequent simulation experiment, the acceleration value is calculated at an equal time interval (\( \Delta t = 1 \) s), which is in accordance with the statistical frequency of comfort (within 0.5 Hz~80.0 Hz).

According to the range of comfort index, six levels of braking comfort are defined in line with the International Standard ISO 2631-1, as shown in Table 1. When the ranges of CI value overlap, the driving comfort of the vehicle lies between two comfort levels.

### 3.3. Braking Model for Autonomous Vehicles

Under good road condition, a mathematical model of forward braking dynamics is established, assuming that the vehicle decelerates on a horizontal road and the gradient resistance \( F_i \) is ignored. Thereafter, the air resistance and the rolling resistance are both considered in the built braking model, while the slope resistance, a small proportion of the acceleration resistance, and the internal friction are neglected [39]. With Newton’s second law, the reverse braking model for autonomous vehicles is formed:

\[
P_{\text{des}} = \frac{ma_{\text{des}} + (1/2)C_D\rho v^2 + mgf}{(T_{bf} + T_{br})/r_f P_b},
\]

where \( a_{\text{des}} \) is desired braking deceleration, \( T_{bf} \) and \( T_{br} \) are the braking torque for front and rear wheel, \( r_f \) is the tire rolling radius, and \( P_b \) represents tire braking pressure. In addition, \( a_{\text{des}} = \mu_b g \), where \( g \) denotes the gravitational constant, \( \rho \) is the density of air, \( C_D \) represents the aerodynamic resistance coefficient, \( A \) is the front vehicle area, and \( f \) is the wheel rolling resistance coefficient.

According to the reverse braking model (as expressed in equation (4)) of autonomous vehicles, the desired braking pressure \( P_{\text{des}} \) of the wheel cylinder can be calculated. Then, the unit module of the reverse braking model of autonomous vehicles is established in MATLAB/Simulink, as shown in Figure 5(a). Furthermore, the vehicle relative speed \( v \) with respect to the road surface and pavement adhesion coefficient \( \mu_h \) obtained above are imported in the braking model, where \( \mu_h \) equals to the peak adhesion coefficient value \( \mu_{\text{max}} \) as the vehicle drives at desired braking deceleration. In the case of safety braking, the desired braking pressure \( P_{\text{des}} \) of the wheel cylinder can be calculated in real time. Then, the built braking model is imported into CarSim to replace the original braking model of traditional vehicles. In order to simulate the automatic steering behavior of autonomous vehicles close to human operation, the adaptive braking control method was adopted to adjust the vehicle state in real time, ensuring that the vehicle drives at optimal speed and preset travel path through the curved section (in Figure 5(b)).

### 3.4. Validation of the Braking Model

Based on the proposed braking system of autonomous vehicles, the brake control algorithm model was built in Simulink. Then, the cosimulation was conducted with CarSim to validate the accuracy of the braking system compared with the traditional ABS braking system. In simulation, a good road condition was adopted, and the peak adhesion coefficient of the AC-13 asphalt pavement under dry road condition was selected as 0.90. At the beginning of braking, the initial speed of the vehicle is set as 120 km/h with the throttle percentage of 0° and simulation time step of 20 s.

In order to reflect the maximum braking efficiency of the vehicle, a constant braking pressure of 10 MPa was applied to the traditional ABS braking vehicle. An adaptive braking control system based on the road surface adhesion characteristics was used for the autonomous vehicle to brake with the expected braking pressure. According to the simulation results, the braking performance curves of the vehicle under two conditions are obtained, as shown in Figures 6(a) and 6(b). It can be seen that the braking performance of the autonomous vehicle is better than that of the traditional ABS system. The braking time is shortened by 10.95%, and the corresponding braking distance is reduced by 10.92%. Comparing the lateral acceleration-time curves under the two conditions (in Figure 6(c)), it can be seen that traditional ABS vehicle has fluctuating lateral acceleration, while the

### Table 1: Comfort evaluation level for autonomous vehicles.

| Levels | CI range (m/s²) | Description for vehicle comfort |
|--------|----------------|-------------------------------|
| 0      | >2.0000        | Extremely uncomfortable        |
| 1      | 1.2500~2.5000  | Very uncomfortable            |
| 2      | 0.8000~1.6000  | Uncomfortable                 |
| 3      | 0.5000~1.0000  | Fairly uncomfortable           |
| 4      | 0.3150~0.6300  | A little uncomfortable         |
| 5      | <0.5000        | Comfortable                   |
autonomous vehicle has approximately stable lateral acceleration during the braking process.

During braking process, to control the tire slip rate within the optimal range of 10% - 20%, the traditional ABS vehicle frequently switches solenoid valves without considering the road characteristics, which leads to extremely bad passenger experience. According to the road surface adhesion characteristics acquired in real time, the desired braking pressure at the real-time position can be calculated and applied to the tires, where the vehicle can obtain the optimal braking deceleration. Hence, the tire slip rate of autonomous vehicles remains around 12.0% without significant fluctuation.

Figure 5: Braking system of autonomous vehicles: (a) reverse brake control algorithm based on MATLAB/Simulink; (b) schematic diagram for steering braking control system.

autonomous vehicle has approximately stable lateral acceleration during the braking process.

During braking process, to control the tire slip rate within the optimal range of 10% - 20%, the traditional ABS vehicle frequently switches solenoid valves without considering the road characteristics, which leads to extremely bad passenger experience. According to the road surface adhesion characteristics acquired in real time, the desired braking pressure at the real-time position can be calculated and applied to the tires, where the vehicle can obtain the optimal braking deceleration. Hence, the tire slip rate of autonomous vehicles remains around 12.0% without significant fluctuation.

For the braking system of the autonomous vehicle taking into account the actual tire-road contact characteristics, it can reflect the vehicle braking stability requirements more explicitly. Obviously, the braking performance of autonomous vehicles is better than that of traditional ones. In other words, the proposed braking system in this study is suitable for autonomous vehicles, which has high reliability.

4. Modeling Parameters’ Setting in CarSim

4.1. Asphalt Pavement Modeling. In simulation, the reference travel path, pavement geometry, and roughness properties are major components of pavement model. To reduce the workload for data input, the segmentation method was used to convert the generated reference path into \((x, y)\) coordinate, as shown in Figure 7(a). The reference travel path of the vehicle can be divided into three parts as follows:

(i) Firstly, a straight line from point 1 to point 2 is defined by distance \(S\) from the starting point 1 and the direction angle \(\theta\).

(ii) Secondly, an arc from point 2 to point 3 is defined by radius \(R\) and angle \(\theta\).

(iii) Thirdly, a straight line starting at point 3 is similarly defined by distance \(S\) from the starting point and the direction angle \(\theta\).

Based on the above three processes, the generated reference path was converted into \((x, y)\) coordinate finally; that is, the input of coordinate data of pavement linear key points was completed.

With respect to the pavement model database in CarSim, the pavement geometry properties (e.g., road width, number of lanes, elevation, etc.) were mapped to the corresponding coordinates \((x, y)\), respectively. Moreover, the adhesion coefficient of the continuous points on road surface collected in real time was also imported to the pavement model, as shown in Figure 7(b).
4.2. Vehicle Model Parameters. In this study, the typical SUV vehicle in urban area was selected as vehicle model, and vehicle body parameters are shown in Table 2. As the air resistance has a significant effect on vehicle braking performance, the aerodynamics parameters obtained through a large number of wind tunnel tests presented in CarSim database were directly adopted in braking simulation. The specific aerodynamic parameters include the windward surface area of the vehicle (the SUV vehicle is taken as 3.3 m²) and air density (taken as 1.206 kg/m³).

Theoretically, the tire-pavement interaction determines braking safety of the vehicle. To make simulation results consistent with the practical situation, the tire-pavement adhesion coefficient calculated by the research group [40, 41] was imported in CarSim.

4.3. Sensor Parameters’ Setting. The CarSim interface was applied to write the POP-UP Windows subroutine for showing the vehicle driving data through MATLAB; simulation results can be dynamically visualized as shown in Figure 8(a). The driving data includes the engine speed, vehicle speed, throttle, and braking percentage. Thereinto, the braking percentage is the ratio of the current brake pressure to the effective maximum brake pressure of the wheel cylinder. In addition, the long-range laser radar is utilized to detect the traffic condition within a long distance, and the short-range laser radar is adopted to detect vehicles and pedestrians in front of the vehicle within a short distance. The effective distances of the two radars are 150 m and 30 m, respectively, with the horizontal viewing angles set as 9 deg and 80 deg, respectively. Furthermore, the vertical viewing angles of the two radars are both 9 deg, as shown in Figure 8(b).

5. Evaluation on Braking Performance of Autonomous Vehicles

In accordance with the above built autonomous vehicle model and pavement model, the braking simulation of autonomous vehicles on curved section (under wet and dry road conditions) was conducted in CarSim. Meanwhile, the written model in Simulink was imported to replace the initial braking model (in Figure 9).

5.1. Braking Process Analysis. In simulation, a 700 m long road with both straight and curved sections was built with the simulation time set as 30 s. There were speed limit signs, safety warning signs, and lane change signs on both sides of
the simulated road. The simulated vehicle was given a constant initial speed of 100 km/h. At the same time, traffic signs recognition module, radar, camera, and other sensors were added to the simulated vehicle. With equipped sensors, road environment can be dynamically recognized during braking process (see Figure 10).

Moreover, the automatic optimal cornering speed was adopted to adjust the brake cylinder pressure in real time combining the identification of road environment by equipped sensors. In particular, the lateral acceleration should not exceed 0.35 g to ensure the vehicle braking stability during the steering process. The visual interface for

![Figure 7: Pavement properties setting in CarSim: (a) reference travel route setting; (b) input interface for road surface adhesion coefficient.](image)

| Table 2: Parameters setting of vehicle body. |
|---------------------------------------------|
| **Items**             | **Value**             | **Items**             | **Value**             |
| Vehicle mass          | 2257 kg              | Distance between centroid and front axis | 1330 mm             |
| Vehicle length        | 4475 mm              | Axle spacing          | 3140 mm              |
| Vehicle width         | 2029 mm              | Roll inertia $I_{xx}$ | 846.6 kg-m$^2$      |
| Vehicle height        | 1966 mm              | Pitch inertia $I_{yy}$| 3524.9 kg-m$^2$     |
| Centroid height       | 780 mm               | Yaw inertia $I_{zz}$  | 3524.9 kg-m$^2$     |
braking simulation is shown in Figure 10. In addition, based on Section 2.2, the adhesion coefficient under dry road condition is set as 0.90, while on wet road it is 0.60 in this study. On dry road, the vehicle speed varied with time was analyzed according to the simulation results (in Figure 11(a)). It can be seen that the braking process of the autonomous vehicles on curved section can be divided into four stages; that is,

(i) firstly, decelerate evenly nearby the curve;
(ii) secondly, automatically adjust the wheel cylinder pressure in real time, and decelerate to the center of the curve;
(iii) thirdly, drive away from the curve section with variable acceleration;
(iv) finally, accelerate evenly to the initial speed.

When the vehicle passes the curve, there is a nonlinear variation of vehicle speed. That is, from the initial speed of
100 km/h at \( t = 1.0 \) s, the vehicle starts to brake with a deceleration of \(-2.992 \text{ m/s}^2\) until it approaches the curve. At \( t = 7.0125 \text{ s}\), the wheel cylinder brake pressure is automatically adjusted to go through the curve section at a variable speed according to sensing the road alignment. Then, the vehicle drives at an acceleration of \(2.865 \text{ m/s}^2\) (\( t = 11.5125 \text{ s}\)) until it reaches the initial speed, which indicates that the braking phase lasts 7.575 s (from \( t = 1.0 \) s to \( t = 8.4875 \text{ s}\)) as vehicle speed reduces to 28.71 km/h. From Figure 11(b), we can calculate the braking distance of the vehicle as 128.92 m, that is, the distance of 156.68 m at the end of braking was subtracted by the distance of 27.76 m at speed 100 km/h as the vehicle starts to decelerate.

5.2. Tire Vertical Force Distribution. According to the vehicle speed curve (in Figure 11(a)), it can be seen that second stage and third stage belong to steering process, in which the vehicle dynamic characteristics are strongly nonlinear. The vertical forces of the tires suddenly change as the brake pressure of 10 MPa is applied. The vertical forces of the front and rear tires frequently oscillate and the amplitude of variation is large (as shown in Figure 12). When the vehicle drives away from the curve section, the vertical forces of the tires are redistributed and reach equilibrium state.

Compared with dry road condition, the tire vertical forces have a higher oscillation frequency on wet road and need more time to reach an equilibrium state. Moreover, under the same braking pressure, the vehicle gets smaller braking deceleration and slip easily occurs in tires. It is mainly because the adhesion coefficient on dry road is larger than that on wet road.

Similarly, adjust the curve radius and use the same vehicle dynamics model to simulate the braking behavior of autonomous vehicles. The vertical forces of the tires with different radius are obtained as shown in Figure 13. The simulation results show that when the radius is less than 50 m, the magnitudes of the tire vertical forces are listed as \( F_{z,L2} > F_{z,R1} > F_{z,R2} > F_{z,L1} \), while the vertical force of each tire is \( F_{z,R1} > F_{z,L1} > F_{z,L2} > F_{z,R2} \) as the radius is no less than 100 m. When the vehicle accelerates to 100 km/h, the vertical force of each tire is redistributed again, and the corresponding maximum vertical forces are \( F_{z,R1} > F_{z,L1} > F_{z,L2} > F_{z,R2} \). When the radius is less than 100 m, the difference between the tire vertical forces of the left and right wheels gradually decreases with the increase of curve radius.
During the steering process, the vehicle body tilts to the outside of the curve. Thereafter, a certain amplitude swing occurs because of the uneven tire vertical forces distribution. As the curve radius is larger than or equal to 100 m, the tire vertical forces of left and right wheels are linearly distributed. Moreover, when the radius is 100 m, the tire vertical force of the right front wheel increases sharply to the maximum. Above all, during the vehicle steering process, pavement adhesion characteristics and curve radius both have a significant effect on the distribution of the maximum tire vertical forces. Moreover, the road surface conditions (dry or wet road) have little effect on the braking stability of autonomous vehicles.

5.3. Vehicle Limit Speed. According to the vehicle speed-time curves under different road conditions during the braking process (in Figure 14), the speed limits at different radius are summarized as shown in Table 3. It can be seen that as the curve radius gradually increases, the speed limit of the vehicle driving through the curved section improves.

Figure 15 shows that there is a good parabolic relationship between the speed limit and the curve radius, and the correlation coefficients are both greater than 90% under dry road and wet road conditions.
Figure 16: Tire lateral force curves with curve radius of 10 m: (a) on dry road; (b) on wet road.

Figure 17: Tire lateral force curves on dry pavement: (a) $R = 15$ m; (b) $R = 20$ m; (c) $R = 30$ m; (d) $R = 50$ m; (e) $R = 100$ m; and (f) $R = 200$ m.
Figure 18: Tire lateral force curves on wet pavement: (a) $R = 15$ m; (b) $R = 20$ m; (c) $R = 30$ m; (d) $R = 50$ m; (e) $R = 100$ m; and (f) $R = 200$ m.

Figure 19: Tire lateral offset distance with different curve radius: (a) on dry road; (b) on wet road.
different road conditions. In addition, the speed limit on dry road is greater than that on wet road. This results from the larger adhesion between the tire and pavement on dry road condition, which allows the vehicle to drive at a higher speed on curved sections. Thereby, it can save braking time and reduce tire friction or fuel consumption.

Compared with wet road condition, the maximum speed that the vehicle on dry road can achieve is relatively larger, indicating that there is a positive correlation between the tire-pavement adhesion coefficient and the vehicle safety brake speed. In addition, the relative increase rate reaches a peak when radius $R$ is 100 m, which is about 13.47%. It indicates that as the radius of the curve is 100 m, the vehicle has better braking stability and is more eco-friendly.

5.4. Tire Lateral Force Distribution. The lateral force curves of the tires with the curve radius of 10 m are simulated, as shown in Figure 16. Taking into account the difference between the recognition accuracy of the vehicle perception system and the blind spots during the monitoring process, the vehicle braking deceleration significantly reduces and the yaw rate is larger on wet road compared with dry road condition. For different curve radius, the
The excessive lateral force produced in the steering forces should be adjusted automatically in time to ensure the vehicle in real-time under the large curve radius. In order to simulate results, the maximum lateral force and the allowed lateral offset distance of the tires on the curved section are extracted, as shown in Table 4.

From Table 4, it can be seen that road adhesion characteristics have a significant effect on the lateral offset distance and lateral force of the tires with different curve radius. Keeping the curve radius constant, as the road adhesion coefficient is lower on wet road, the braking performance of the vehicle declines, while the allowable lateral offset distance and speed limit of the vehicle tires both decrease. For example, when the road adhesion coefficient is reduced from 0.90 to 0.60 with the curve radius of 10 m, the allowable lateral offset distance of the tire decreases by about 47.4 mm and the speed limit of driving declines by 1.56 km/h. Similarly, with a certain road adhesion coefficient, the maximum lateral offset distance and the maximum lateral force of the tire both gradually decrease as the curve radius increases. Meanwhile, the falling rates of the maximum lateral offset distance and lateral force of the tires become greater as the curve radius gets smaller. In addition, the vehicle’s speed limit is gradually improved with the increase of the curve radius, and the growth rate increases continuously.

It can also be found that when the curve radius is no larger than 50 m, the lateral offset distance curves of the tires are similar on the whole (the lateral acceleration $a \leq 0.30 \, g$). At the center of the curved section, the vehicle begins to accelerate and the vehicle tire laterally inclines to the outside of the travel path. The lateral offset distance curve fluctuates greatly with radius of 100 m and 200 m. The primary cause is that the automatic braking system should adjust the lateral acceleration ($a \leq 0.35 \, g$) of the vehicle in real time under the large curve radius. In order to adapt to the change of road alignment, the tire vertical forces should be adjusted automatically in time to ensure that the vehicle will not rollover or overturn, considering the excessive lateral force produced in the steering process.

| Time interval (s) | Radius R of curved section (m) | Comfort index (CI) |
|------------------|-------------------------------|-------------------|
|                  | 10               | 15               | 20               | 30               | 50               | 100              | 200              |
| $\Delta t_1$     | 0.1460           | 0.0479           | 0.0460           | 0.0460           | 0.0460           | 0.0107           | 0.0107           |
| $\Delta t_2$     | 0.5596           | 0.5769           | 0.4442           | 0.0758           | 0.0466           | 0.0037           | 0.0037           |
| $\Delta t_3$     | 0.5547           | 0.5543           | 0.5541           | 0.5537           | 0.5621           | 0.0012           | 0.0012           |
| $\Delta t_4$     | 0.5636           | 0.5818           | 0.5634           | 0.5557           | 0.5547           | 0.1651           | 0.0006           |
| $\Delta t_5$     | 0.5600           | 0.5858           | 0.5594           | 0.5648           | 0.5655           | 0.3395           | 0.0352           |
| $\Delta t_6$     | 0.5206           | 0.5887           | 0.5980           | 0.5608           | 0.5536           | 0.5323           | 0.1988           |
| $\Delta t_7$     | 0.5256           | 0.5154           | 0.5042           | 0.4878           | 0.4201           | 0.6287           | 0.2414           |
| $\Delta t_8$     | 0.2833           | 0.2799           | 0.2347           | 0.2859           | 0.2122           | 0.6137           | 0.2017           |
| $\Delta t_9$     | 0.1691           | 0.0119           | 0.0610           | 0.1608           | 0.1041           | 0.1870           | 0.1466           |
| $\Delta t_{10}$  | 0.4730           | 0.0012           | 0.1070           | 0.0300           | 0.1506           | 0.0142           | 0.0857           |
| $\Delta t_{11}$  | 0.0736           | 0.0569           | 0.4362           | 0.6020           | 0.0401           | 0.4154           | 0.1694           |
| $\Delta t_{12}$  | 0.7241           | 0.6660           | 0.5331           | 0.0334           | 0.1270           | 0.3549           | 0.0673           |
| $\Delta t_{13}$  | 0.3884           | 0.4678           | 0.4807           | 0.6597           | 0.5679           | 0.0948           | 0.0333           |
| $\Delta t_{14}$  | 0.6412           | 0.5324           | 0.5325           | 0.5081           | 0.4237           | 0.0403           | 0.0163           |
| $\Delta t_{15}$  | 0.4889           | 0.5318           | 0.5320           | 0.4453           | 0.5983           | 0.0217           | 0.0080           |
| $\Delta t_{16}$  | 0.5500           | 0.5248           | 0.5257           | 0.5713           | 0.5374           | 0.3498           | 0.0039           |
| $\Delta t_{17}$  | 0.5200           | 0.5207           | 0.5221           | 0.5219           | 0.3974           | 0.0019           | 0.0019           |
| $\Delta t_{18}$  | 0.4840           | 0.0201           | 0.0833           | 0.6797           | 0.5914           | 0.5647           | 0.0009           |
| $\Delta t_{19}$  | 0.0451           | 0.0754           | 0.0729           | 0.0683           | 0.0724           | 0.5109           | 0.1250           |
| $\Delta t_{20}$  | 0.0360           | 0.0733           | 0.0760           | 0.0241           | 0.0841           | 0.3371           | 0.4052           |
| $\Delta t_{21}$  | 0.0131           | 0.0657           | 0.0727           | 0.0055           | 0.0994           | 0.0729           | 0.3339           |
| $\Delta t_{22}$  | 0.0222            | 0.0557           | 0.0674           | 0.0270           | 0.0684           | 0.0109            | 0.0734           |
| $\Delta t_{23}$  | 0.0532           | 0.0457           | 0.0609           | 0.0416           | 0.0328           | 0.1141           | 0.0749           |
| $\Delta t_{24}$  | 0.0716           | 0.0341           | 0.0520           | 0.0477           | 0.0064           | 0.1017           | 0.0666           |
| $\Delta t_{25}$  | 0.0649           | 0.0163           | 0.0418           | 0.0490           | 0.0428           | 0.0776           | 0.0415           |
| $\Delta t_{26}$  | 0.0352           | 0.0053           | 0.0263           | 0.0470           | 0.0478           | 0.0862           | 0.0064           |
| $\Delta t_{27}$  | 0.0094           | 0.0259           | 0.0055           | 0.0316           | 0.0471           | 0.0318           | 0.0031           |
| $\Delta t_{28}$  | 0.0209           | 0.0469           | 0.0204           | 0.0036           | 0.0429           | 0.0158           | 0.0015           |
| $\Delta t_{29}$  | 0.0400           | 0.0640           | 0.0495           | 0.0323           | 0.0260           | 0.0078           | 0.0007           |
| $\Delta t_{30}$  | 0.0466           | 0.0593           | 0.0651           | 0.0551           | 0.0039           | 0.0037           | 0.0004           |
| $\Delta t_{31}$  | 0.0486           | 0.0280           | 0.0216           | 0.0665           | 0.0195           | 0.0026           | 0.0002           |

Table 6: Comfort levels with different curve radius under wet road condition.

Note: CI is the comfort index of the corresponding curve radius R.
5.5. Braking Comfort Evaluation. Based on the comfort levels in Section 3.2, the comfort level of autonomous vehicle was evaluated for different road conditions, as shown in Tables 5 and 6.

From Tables 5 and 6, it can be seen that the comfort with curve radius of 200 m is the best as all of the comfort levels are all no less than 4. Furtherly, the matrix heatmaps were drawn to clearly reveal the relationship between curve radius $R$ and comfort index (in Figure 20). The color map of CI under each road condition has the same color range. It clearly shows that the comfort index is no more than 0.35 m/s$^2$ as the vehicle runs along the curve section (from $t = 7.0125$ s to $t = 11.5125$ s). As mentioned in Section 5.1, the brake pressure of the vehicle wheel cylinder can be adjusted automatically when passing the curve section at a variable speed according to sensing the road alignment. Results indicate that the comfort of the vehicle meets the passenger requirement, and the advantage of autonomous vehicles is also reflected.

Compared with wet road condition, it can provide greater lateral friction due to the good adhesion on dry road condition, which mostly counteracts the centrifugal force generated by the vehicle on curved sections. Thus, the ride comfort during the steering process can be greatly improved, so the duration time of the “curve balance state” on dry road lasts longer, increasing by about 57.14% compared with wet road condition, as shown in Figure 21. In addition, the “curve balance state” is defined as the duration time of ride comfort at Level 5 during the steering process. As the radius of the curve increases, the braking comfort of the vehicle during cornering is relatively good. This is because the curve length increases with increasing the radius of the curved section. The autonomous vehicle adopts an adaptive control system through the curved section at the optimal speed, in which there is a certain speed buffering process on the curve with a larger radius. The results of comfort evaluation can provide a basis for road alignment design.

![Matrix heatmaps of the comfort evaluation results](image(a))

![Matrix heatmaps of the comfort evaluation results](image(b))

**Figure 20**: Matrix heatmaps of the comfort evaluation results: (a) on dry road; (b) on wet road.

![Duration time of “curve balance state”](image)

**Figure 21**: The duration time of “curve balance state” with different radius.

From Figure 21, the “curve balance state” duration time slightly increases with the radius increase when the curve radius $R \leq 100$ m, but the variation is not significant. When the radius $R > 100$ m, the “curve balance state” duration time increases significantly. It is shown that the curve radius is a significant factor that affects the ride comfort of autonomous vehicles during the steering process. To improve the ride comfort of the vehicle, it is recommended that the curve radius $R \geq 100$ m, and the brake deceleration starts at least 100 m from the entrance of the curved section.

The simulation results of braking comfort evaluation can provide a reference for road alignment design. Furthermore, the research results verify the accuracy of the built autonomous braking model indirectly, which can be applied to conduct the following research on braking strategies under typical driving scenarios.
6. Conclusions

In this paper, with the consideration of asphalt pavement adhesion characteristics, a novel braking model for autonomous vehicles was proposed and built in Simulink. Thereafter, the braking performance of autonomous vehicles on curved sections was analyzed with CarSim/Simulink cosimulation. In addition, based on the comfort index in International Standard ISO, the comfort level of autonomous vehicles was evaluated to investigate the braking strategies of autonomous vehicles running along curved sections under different road conditions. The main conclusions drawn from this study are as follows:

1. For both dry and wet road conditions, the friction coefficient of OGFC asphalt pavement is the largest, followed by SMA pavement and AC pavement. The change rules of adhesion coefficient curves under different road conditions are similar, which significantly decrease with the increase of tire slip rate. As tire speed exceeds 40 km/h, the adhesion coefficient curve tends to be gentle.

2. When the curve radius is no less than 100 m, the tire vertical forces distribution is relatively uniform. It shows that the road surface adhesion characteristics have little effect on the braking stability of autonomous vehicles. Compared with dry road condition, the tire vertical forces have higher oscillation frequency on wet road and need more time to reach an equilibrium state.

3. As the curve radius increases, the speed limit of the vehicle safely driving through the curved section gradually improves. On wet road, the vehicle braking deceleration significantly declines and the yaw rate is greater than that on dry road. There is a good quadratic parabolic relationship between the speed limit and the curve radius. Moreover, the speed limit of the vehicle on dry road is greater than that on wet road for different curve radius.

4. Based on the comfort index in International Standard ISO, the comfort level can be sorted into six levels. In addition, the braking comfort with a curve radius of 200 m is the best at a vehicle speed of 100 km/h because the comfort levels during the braking process are no less than 4. It indicates that the comfort meets the passenger requirement and the advantage of autonomous vehicles is also reflected.

Results show that the curve radius is a significant factor influencing the ride comfort of autonomous vehicles during the steering process. It is recommended that the actual speed limit among vehicles running along curved sections should be 0.85–0.95 times the average simulated speed limit under different curve radius. To improve the ride comfort of the vehicle, it is recommended that the curve radius $R \geq 100$ m, and the brake deceleration starts at least 100 m from the entrance of the curved section. In this paper, the simulation method is suitable for different types of tire and vehicle. Due to the limited paper length, a typical SUV vehicle was selected as the vehicle model. However, there is obvious difference of tire-pavement contact mechanical characteristics for different types of tires (e.g., smooth tire, longitudinal pattern tire, transverse pattern tire, and cross-country tread pattern tire) and asphalt pavement. In addition, the braking principles for different types of autonomous vehicles (e.g., bus, truck, especially, and long-distance truck) are also different. Thus, the specific braking strategies for different types of tires and vehicles under unmanned condition will be furtherly investigated in the future research.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Binshuang Zheng mainly engaged in texture information, AVs braking theory research, and draft manuscript preparation. Xiaoming Huang mainly engaged in supervision and checking the research method. Junyao Tang and Meiling Han mainly engaged in data processing and analysis. Jiaying Chen mainly engaged in texture information research. Runmin Zhao mainly engaged in data collection of pavement friction. Zhengqiang Hong mainly engaged in braking process research for autonomous vehicles. Tao Tang mainly engaged in checking English writing and revising grammatical issues. All authors reviewed the results and approved the final version of the manuscript.

Acknowledgments

This study was supported by Natural Science Research Startup Foundation of Recruiting Talents of Nanjing University of Posts and Telecommunications (Grant nos. NY221150 and NY219167) and the National Natural Science Foundation of China (Grant no. 51778139).

References

[1] National Highway Traffic Safety Administration, National Motor Vehicle Crash Causation Survey: Report to Congress, National Highway Traffic Safety Administration, Washington, DC, USA, 2008.
[2] World Health Organization, World Health Statistics 2008: Report of WHO Scientific Group, WHO, Geneva, Switzerland, 2008.
[3] Y. Yang, Z. Yuan, J. Chen, and M. Guo, “Assessment of oscillating value method based on entropy weight to transportation energy conservation and emission reduction,” Environmental Engineering and Management Journal, vol. 16, no. 10, pp. 2413–2423, 2017.
[4] S. Q. Cheng, Z. Q. Liao, and Y. Zhu, “Dynamic changes in community deprivation of access to urban green spaces by...
multiple transport modes,” Frontiers in Public Health, vol. 9, Article ID 615432, 2021.

[5] Y. S. Ci, H. L. Wu, Y. C. Sun, and L. Wu, “A prediction model with wavelet neural network optimized by the chicken swarm optimization for on-ramps metering of the urban expressway,” Journal of Intelligent Transportation Systems, Article ID 1890670, 2021.

[6] Z. Z. Yuan, K. He, and Y. Yang, “A roadway safety sustainable approach: modeling for real-time traffic crash with limited data and its reliability verification,” Journal of Advanced Transportation, Article ID 1570521, 2022.

[7] Y. Yang, K. He, Y.-P. Wang, Z.-Z. Yuan, Y.-H. Yin, and M.-Z. Guo, “Identification of dynamic traffic crash risk for cross-area freeways based on statistical and machine learning methods,” Physica A: Statistical Mechanics and its Applications, vol. 595, Article ID 127083, 2022.

[8] L. Ye and T. Yamamoto, “Modeling connected and autonomous vehicles in heterogeneous traffic flow,” Physica A: Statistical Mechanics and its Applications, vol. 490, pp. 269–277, 2018.

[9] J. Guanetti, Y. Kim, and F. Borrelli, “Control of connected and automated vehicles: state of the art and future challenges,” Annual Reviews in Control, vol. 45, pp. 19–40, 2018.

[10] R. F. Stern, Y. Chen, M. Churchill et al., “Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic,” Transportation Research Part D: Transport and Environment, vol. 67, pp. 351–365, 2019.

[11] A. Vahidi and A. Scarinetta, “Energy saving potentials of connected and automated vehicles,” Transportation Research Part C: Emerging Technologies, vol. 95, pp. 822–843, 2018.

[12] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, and T. Oluwatola, “Autonomous vehicle technology: how to best realize its social benefits,” in Proceedings of the 22nd ITS World Congress, Bordeaux, France, December 2015.

[13] P. F. Zhang, “Research on vision navigation technology of intelligent vehicle,” Post-Doctorate Reports, Tsinghua University, Beijing, China, 2004.

[14] A. Broki, Intelligent Vehicles: Key Technologies for Intelligent Transportation Systems, China Communication Press, Beijing, China, 2002.

[15] D. Wang and M. Pham, “A high-fidelity co-simulation platform for motion and control research for vehicle platooning,” International Journal of Vehicle Autonomous Systems, vol. 6, no. 1/2, pp. 104–121, 2008.

[16] L. Guo, Z. Ren, P. Ge, and J. Chang, “Advanced emergency braking controller design for pedestrian protection oriented automotive collision avoidance system,” The Scientific World Journal, vol. 2014, Article ID 218246, 11 pages, 2014.

[17] A. M. Boopathi and A. Abudahair, “Adaptive fuzzy sliding mode controller for wheel slip control in antilock braking system,” Journal of Engineering Research, vol. 2, no. 4, pp. 1–19, 2016.

[18] D. Milakis, B. Van Arem, and B. Van Wee, “Policy and society related implications of automated driving: a review of literature and directions for future research,” Journal of Intelligent Transportation Systems, vol. 21, no. 4, pp. 324–348, 2017.

[19] S. Wang and J. Zhao, “Risk preference and adoption of autonomous vehicles,” Transportation Research Part A: Policy and Practice, vol. 126, pp. 215–229, 2019.

[20] P. Delaigue and A. Eskandarian, “A comprehensive vehicle braking model for predictions of stopping distances,” Proceedings of the Institution of Mechanical Engineers-Part D: Journal of Automobile Engineering, vol. 218, no. 12, pp. 1409–1417, 2004.

[21] K. Liu, H. Y. Chen, J. W. Gong, S. P. Chen, and Y. Zhang, “Adaptive Cruise Control: A Research on handling stability of high-speed unmanned vehicles,” Automotive Engineering, vol. 41, no. 5, pp. 514–521, 2019.

[22] H. Jin and S. J. Li, “A research on vehicle stability control based on limited speed,” Automotive Engineering, vol. 40, no. 1, pp. 48–56, 2018.

[23] J. M. Bae, S. Y. Yoo, J. H. Kim, and G. H. Kang, “Immune landscape and biomarkers for immuno-oncology in colorectal cancers,” Journal of Pathology and Translational Medicine, vol. 54, no. 5, pp. 351–360, 2020.

[24] A. M. Boopathi and A. Abudahair, “Firefly algorithm tuned fuzzy set-point weighted PID controller for antilock braking systems,” Journal of Engineering Research, vol. 3, no. 2, pp. 1–16, 2015.

[25] Z. Wang, M. Wang, Y. Zhang et al., “Driverless simulation of path tracking based on PID control,” IOP Conference Series: Materials Science and Engineering, vol. 892, no. 1, Article ID 12050, 2020.

[26] H. G. He, Z. P. Sun, and X. Xu, “Autonomous driving techniques under intelligent transportation conditions: review and outlook,” Bulletin of National Natural Science Foundation of China, vol. 30, no. 2, pp. 106–111, 2016.

[27] J. Ni and J. Hu, “Dynamics control of autonomous vehicle at driving limits and experiment on an autonomous formula racing car,” Mechanical Systems and Signal Processing, vol. 90, pp. 154–174, 2017.

[28] Y. Du, C. Liu, Y. Song, Y. Li, and Y. Shen, “Rapid estimation of road friction for anti-skid autonomous driving,” IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 6, pp. 2461–2470, 2019.

[29] J. Peng, L. Chu, and T. F. Fwa, “Determination of safe vehicle speeds on wet horizontal pavement curves,” Road Materials and Pavement Design, vol. 2020, Article ID 1772350, 13 pages, 2020.

[30] M. Aldibaja, N. Suganuma, and K. Yoneda, “Robust intensity-based localization method for autonomous driving on snow-covered road surface,” IEEE Transactions on Industrial Informatics, vol. 13, no. 5, pp. 2369–2378, 2017.

[31] J. Khoury, K. Amine, and R. Abi Saad, “An initial investigation of the effects of a fully automated vehicle fleet on traffic stability,” Journal of Advanced Transportation, vol. 2019, Article ID 6126408, 10 pages, 2019.

[32] S. I. Granshaw, “Close range photogrammetry: principles, methods and applications,” Photogrammetric Record, vol. 25, no. 130, pp. 203–204, 2010.

[33] J. Chen, X. Huang, B. Zheng et al., “Real-time identification system of asphalt pavement texture based on the close-range photogrammetry,” Construction and Building Materials, vol. 226, pp. 910–919, 2019.

[34] H. Tanaka, K. Yoshimura, R. Sekoguchi et al., “Prediction of the friction coefficient of filled rubber sliding on dry and wet surfaces with self-affine large roughness,” Mechanical Engineering Journal, vol. 3, no. 1, pp. 1–16, 2016.

[35] B. N. J. Persson, “On the fractal dimension of rough surfaces,” Tribology Letters, vol. 54, no. 1, pp. 99–106, 2014.

[36] C. Michele, “A simplified version of Persson’s multiscale theory for rubber friction due to viscoelastic losses,” Journal of Tribology, vol. 140, no. 1, pp. 1–20, 2018.

[37] P. Johansson and I. Rycklik, “Laplace processes for describing road profiles,” Procedia Engineering, vol. 66, pp. 464–473, 2013.
[38] G. S. Paddan and M. J. Griffin, “Evaluation of whole-body vibration in vehicles,” *Journal of Sound and Vibration*, vol. 253, no. 1, pp. 195–213, 2002.

[39] Y. Wang, K. Chen, Y. G. Zhang, and X. Song, “Aerodynamic drag features on automobile with non-smooth surface,” *Journal of Tongji University*, vol. 41, no. 4, pp. 571–576, 2012.

[40] X. Y. Liu, Q. Q. Cao, J. Chen, and X. Huang, “Simulation of vehicle braking behavior on wet asphalt pavement based on tire hydroplaning and frictional energy dissipation,” *Journal of Southeast University*, vol. 34, no. 4, pp. 500–507, 2018.

[41] S. Zhu, X. Liu, Q. Cao, and X. Huang, “Numerical study of tire hydroplaning based on power spectrum of asphalt pavement and kinetic friction coefficient,” *Advances in Materials Science and Engineering*, vol. 2017, Article ID 5843061, 11 pages, 2017.