Determination of Allowable Rutting Depth Based on Driving Safety Analysis

Leilei Chen, Ph.D.[1]; Gang Liu[2]; Zhengdong Qian, Ph.D.[3]; and Xiangfei Zhang[4]

Abstract: To evaluate the effect of different rutting depths on driving safety as well as determine the allowable rutting depth, an evaluation model is established based on a simulation program of the vehicle–road interactions. Firstly, a vehicle–road coupling model consisting of a general vehicle assembly model and a pavement model with different rutting depths was prepared through the vehicle dynamics method. The vehicle steering angle was selected as the simulation output, by analysis of which it can be found that the rutting depth has a great influence on vehicles without front-wheel steering suspension and steering assist systems. Then, the vehicle model was improved, and an advanced numerical simulation was conducted as a comparison. Lastly, the evaluation model of different rutting depths was established based on steering wheel difference angle value by the Delphi method. In addition, the determination method of allowable rutting depth was given through an example, which provides a quantitative method to evaluate the influence of different rutting depths. **DOI: 10.1061/JPEODX.0000180.** © *2020 American Society of Civil Engineers.*

Author keywords: Allowable rutting depth; Driving safety; Vehicle dynamics method; Evaluation model; Delphi method.

Introduction

Rutting is a traditional distress of asphalt pavement, which significantly affects the pavement performance and service life. For the permanent deformation accumulation in different layers of the pavement, rutting maintenance has always been one of the most difficult problems in pavement engineering (Coleri et al. 2012; Goh et al. 2011). Apart from the great damage to the pavement structure, rutting also has significant influences on driving safety for both vehicles and drivers. For example, when a vehicle is turning or changing lanes, rutting may affect the driver's operation, causing vehicles to run out of control. This may greatly affect the driving stability and threaten traffic safety (Start et al. 2013; Yeganeh et al. 2019). In recent years, with the development of road infrastructures, driving comfort and safety gained more and more focus. In this situation, a method to assess the impact of rutting damage on driving safety was needed.

In order to reduce rutting damage and maintain the pavement in good condition, many studies have been conducted on the criteria of rutting depth. In China, the evaluation methodology of the rutting condition has been included in the *Technical Specifications for Maintenance of Highway Asphalt Pavement*, JTJ073.2-2001 (Chinese Standard 2001), relating to pavement quality evaluation. However, a rut was merely characterized as deformation-type damage in the specification, and any effects on driving safety have not been considered. This method cannot reflect the actual severity of ruts, and the induced damage will be definitely underestimated. Moreover, in the latest Chinese regulation, the *Highway Performance Assessment Standards*, JTG5210-2018 (Chinese Standard 2018), only two rutting grades were specified: light and weight with a threshold of 15 mm, and the rutting evaluation index model is adopted fully based on the empirical method. Similarly, in the US, Japan, and the UK, definitions of allowable rutting depths for rutting maintenance were also put forward through engineering experience and take rare consideration of impact on driving safety (Mohammad et al. 2017). This empirical determination method of a threshold lacks theoretical support.

In order to solve these problems, several studies were carried out in highway engineering field. Laboratory and virtual experiments were conducted to predict rutting depth in pavements made with conventional asphalt mixes (Malysz et al. 2012; Bakhshi and Arabani 2018; Walubita et al. 2019). For the rutting development process prediction, models under various temperatures and loads were developed using both accelerated pavement testing (APT) and full-scale tests (Epps Martin et al. 2003; Suh et al. 2012; Suh and Cho 2014). Moreover, a resurfacing plan was recommended to resist rutting with the implementation of perpetual pavements (Tarefder and Bateman 2012). Overall, it can be concluded that research on rutting mainly focused on rutting prediction and antirutting design. However, quantitative study on the influence of rutting depth on driving safety has not been found, and quantitative evaluation of rutting damage is needed. Therefore, it is of great necessity to investigate the impact of rutting depth on driving safety in a more specific and quantitative way.

To evaluate the effect of different rutting depths on the driving safety, numerical simulations were adopted as the main research method in this study, which have been widely adopted in simulating vehicle–road coupling behaviors (Qiu and Griffin 2003; Hu et al. 2017; Shen et al. 2016). Due to the complicated mechanical system and related tedious process of modeling, errors always occurred due to varied parameters and heavy load. Thus, most studies simplify the auto structure to concentrate the research scope on vehicle driving stability (Geng et al. 2009). In order to establish

[1]Associate Professor, Intelligent Transportation System Research Center, Southeast Univ., Nanjing 210000, China (corresponding author). ORCID: https://orcid.org/0000-0001-8447-1667. Email: chenleilei@seu.edu.cn

[2]Graduate Student, Intelligent Transportation System Research Center, Southeast Univ., Nanjing 210000, China. Email: 220173083@seu.edu.cn

[3]Professor, Intelligent Transportation System Research Center, Southeast Univ., Nanjing 210000, China. Email: Qianzd@seu.edu.cn

[4]Ph.D. Candidate, Intelligent Transportation System Research Center, Southeast Univ., Nanjing 210000, China. ORCID: https://orcid.org/0000-0002-8213-5210. Email: zhang_xf@seu.edu.cn

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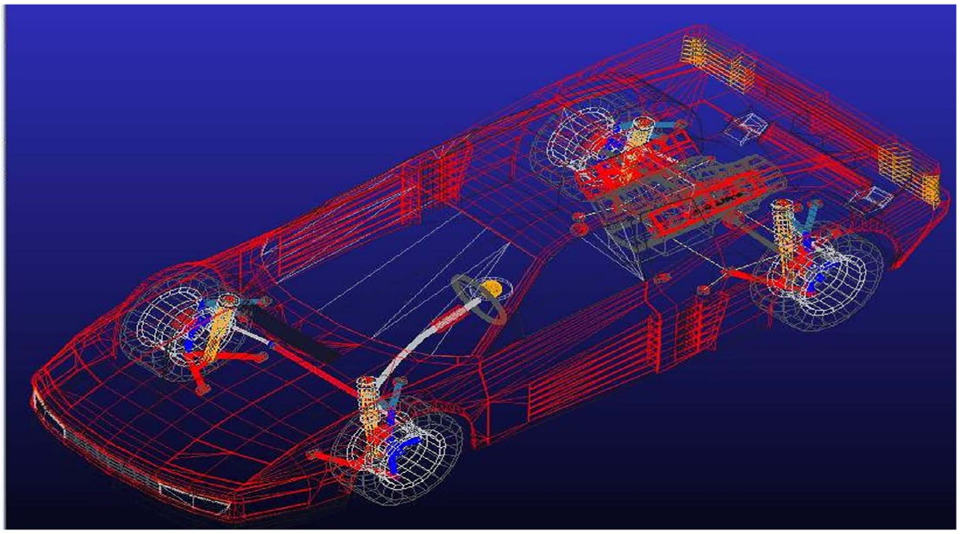


Fig. 1. Vehicle assembly model.

a considerably effective model, Sapietova and Lukac (2014) adopted the vehicle dynamics method to build the virtual prototype of vehicle, which proved to be a credible approach. It can be found that most of these vehicle–road models were aimed to simulate the dynamic response of the vehicle caused by pavement roughness or cracking. Regarding the impact of different rutting depths on driving safety, no literature using this methodology could be found.

The main objective of this paper is to provide a quantitative method to evaluate the influence of different rutting depths. Firstly, a vehicle–road coupling model was established to simulate the vehicle status while driving across a rut with different rutting depths. Secondly, the results of the driving stability were analyzed to reveal the general influence of rutting depths on driving safety. Thirdly, an advanced numerical simulation of vehicle–road coupling was conducted, and the results were analyzed for commonly used vehicles. Finally, an evaluation model of driving safety under different rutting depths was established based on the Delphi method to quantify the impact of rutting depth on driving safety.

Numerical Simulation

As mentioned previously, in the existing studies, the dynamic response of the vehicle relied on the pavement roughness. Compared with the pavement roughness, rutting is a large deformation along the longitudinal direction of the road. When travelling straight along the direction of the rutting, vehicles may experience little effect from rutting. However, in the case of changing lanes or directions, rutting may have great influence on vehicles, just like if the vehicle traveled across a hole. This situation is more critical to driving safety due to the large height difference of ruts compared with roughness. Therefore, it is significantly meaningful to investigate the interaction between vehicle and pavement rutting.

As a characteristic value reflecting driving safety and stability (Kim et al. 2016), steering wheel angle was employed as the key parameter to predict lane changes through a mathematical model. In order to simulate the general impact of vehicle steering on a pavement with rutting on driving stability, basic parameters of the general vehicle were used to establish the vehicle model assembly, and a general pavement model with different rutting depths was also utilized according to different working conditions. Based on the aforementioned preparation, the simulation of the vehicle steering on a pavement with a rut was implemented.

Vehicle Modeling

In this section, a vehicle virtual prototype is established by assembling different parts, including suspension, engine, steering system, and tires. Most modern cars consists of independent suspensions. Thus, the front and rear ones were both designed to be independent, which means wheels on each side were suspended separately under the frame through elastic suspension. For the front suspension, the commonly used McPherson suspension was employed (Suh and Yoon 2018). For the rear suspension, the engine was placed at the rear, and the rear wheel was utilized as the driving wheel. For the steering system, the rack and pinion steering structure was adopted, which is often used in vehicle engineering (Geng et al. 2009). For tires, the Magic Formula, as a classical theory of tire models, was selected in this assembly (Maclaurin 2011). Parameters of the vehicle mass were commonly defined according to those of generally used vehicles (Sapietova and Lukac 2014). Mass of the vehicle body was set to 995 kg, engine was 300 kg, and each tire was 25 kg. Various subsystems of the vehicle model were established and assembled through standard vehicle dynamics software, as shown in Fig. 1.

Pavement Modeling

Factors such as rutting depth and driving speed have significant effects on vehicle driving safety and steering stability. However, compared with rutting depth and driving speed, other factors such as geometry of rutting and stern sidewall inclination angle are not as important when it comes to the driving stability (Dmitriev 2013). Therefore, the rutting geometry (Fig. 2) was simplified as trapezoid with lower bottom length of 80 cm, side inclination angle α of arctan $1/15$, and depth of h.

Apart from the function of vehicle modeling, a general flat pavement model can be established through the pavement creation function (Shakhlavi et al. 2018). Consequently, the generated pavement property file was modified according to the geometry of the

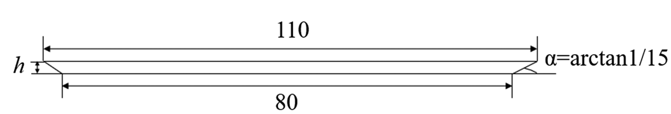


Fig. 2. Geometry of rutting.

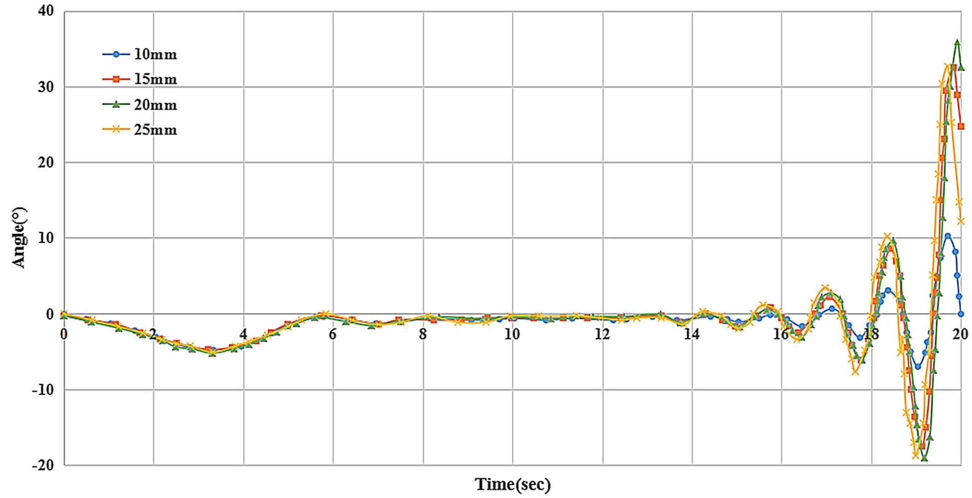


Fig. 3. Steering wheel angle under different rutting depths.

pavement with ruts. Finally, the pavement property file was imported, and a pavement model with different rutting depths was generated.

Vehicle–Road Coupling Simulation

Considering the actual scenario that wheels on one side are usually in the center of the rut, the right tires were selected to move in the rut and the left tires to move on the flat pavement at a given speed. In this case, the tires bear the yawing force, which will motivate the wheel to steer at a certain angle (Guo et al. 2014). In the vehicle–road coupling model, the contact between tires and pavement was primarily considered. A four-wheel model was established, and classical tire model Fiala was chosen due to its advantage in reflecting the actual contact conditions (Senabre and Valero 2012). After importing the vehicle model, road model, driver control file, and generation of the vehicle–road coupling model, the numerical simulation can be performed.

Simulation Results and Analysis

In this simulation, the vehicle was driving straight on an asphalt pavement with different rutting depths (10, 15, 20, and 25 mm). The angle between vehicle travel direction and rutting longitudinal direction was 0°. According to the investigation of the design speed in different countries, 120 km/h is mostly adopted (Choi et al. 2013; Zhang et al. 2017). Thus, the driving speed of 120 km/h was used in this simulation. The wave of the steering wheel angle is shown in Fig. 3.

Fig. 3 illustrates that when the vehicle ran in the rutting area for a time of about 15 s, the steering wheel started to shake from side to side owing to the reaction force from sidewall of the rutting. The peak and bottom points of each curve represent the rotation degree of the steering wheel. The considerably large maximum values of positive and negative steering wheel angles indicate that ruts have a great influence on vehicles without a steering assist system. Although such old-fashioned vehicles are quite rare nowadays, special attention still should be paid to the impact of rutting on their driving safety. Moreover, the maximum values of positive and negative steering wheel angles under different rutting depths were obtained (Table 1).

Table 1. Maximum output values for different steering wheel angles (degrees)

Steering wheel angle	Rutting depth (mm)			
	10	15	20	25
Positive (degrees)	10	32	35	33
Negative (degrees)	7	17	18	18

Table 1 indicates that the steering wheel angle rose as the rutting depth increased from 10 to 20 mm and reached the maximum of 35° when the rutting depth was about 20 mm. After that, when the rutting depth reached 20 mm and then continued to grow, it did not increase. Considering that the steering wheels were not equipped with a steering assist system, it can be inferred that the vehicle has already jumped and the steering wheel may be out of control. Therefore, when the rutting depth reached around 20 mm, the vehicle was in an unsafe state.

For comparison, another travel angle (9°) was also simulated. The general rutting depth (15 mm) was selected, and results are shown in Fig. 4. The opposite variation tendency of steering wheel angles under different travel angles of 0°and 9° can be attributed to the fact that the side wall of the rut has great reverse effect on the travel direction of the vehicle without a steering assist system. The travel direction of 9° had the maximum positive steering wheel angle of about 27° and a negative angle of 57°, which was about 1.5 times that of angles under 0°.

From the preceding analysis of simulations for the simplified vehicle model, the general influence of different rutting depths can be obtained, and it can be concluded that different angles between the travel direction of the vehicle and the direction of the rut also have different extents of impact on driving safety. However, because the vehicle without a steering wheel assist system was adopted, the output value of the steering wheel angle is considerably larger compared with that under actual driving conditions, which is obviously unsuitable for assessing the actual influence of different rutting depths on driving safety. Consequently, an improved numerical simulation should be performed.

Improved Numerical Simulation

Considering the actual driving conditions, Heinzl et al. (2016) implemented additional steering on the stability control of a

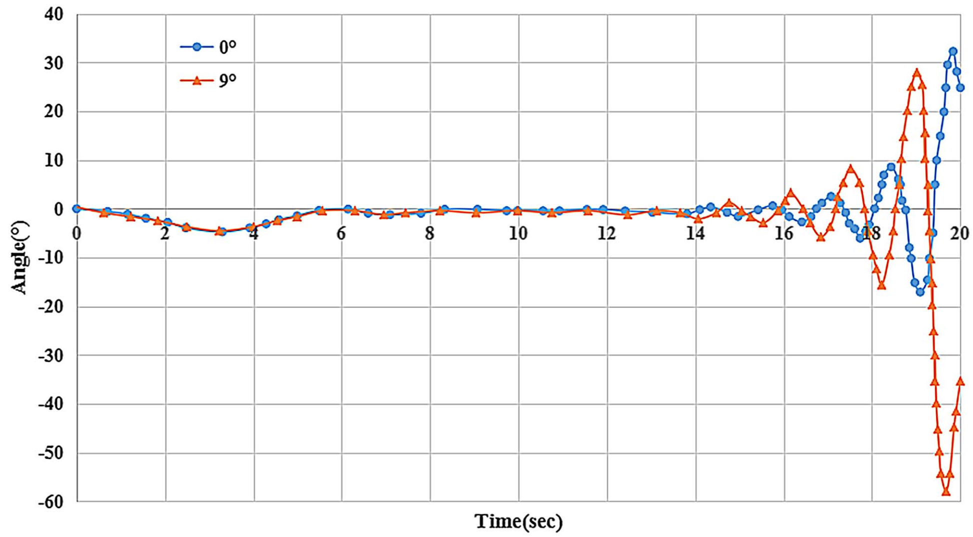


Fig. 4. Steering wheel angle under a travel angle of 0° and 9°.

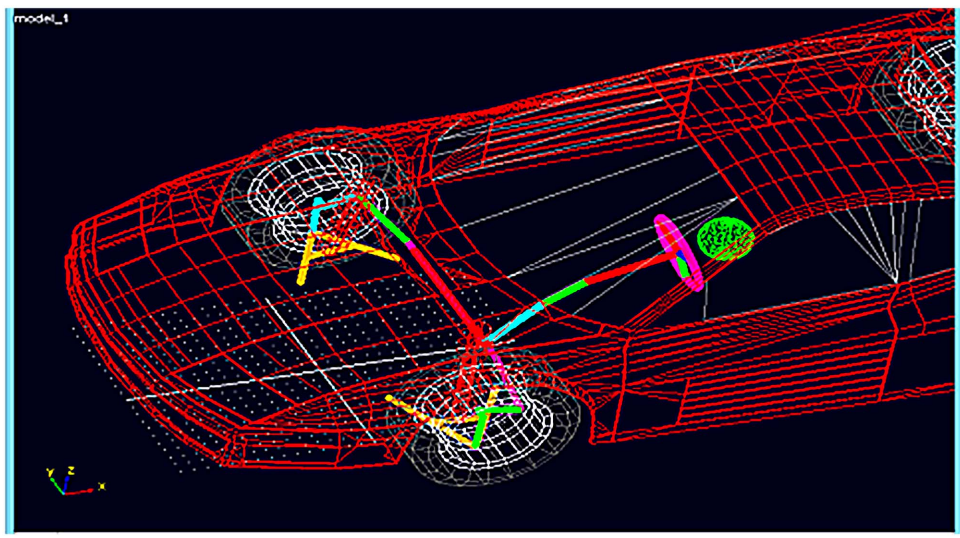
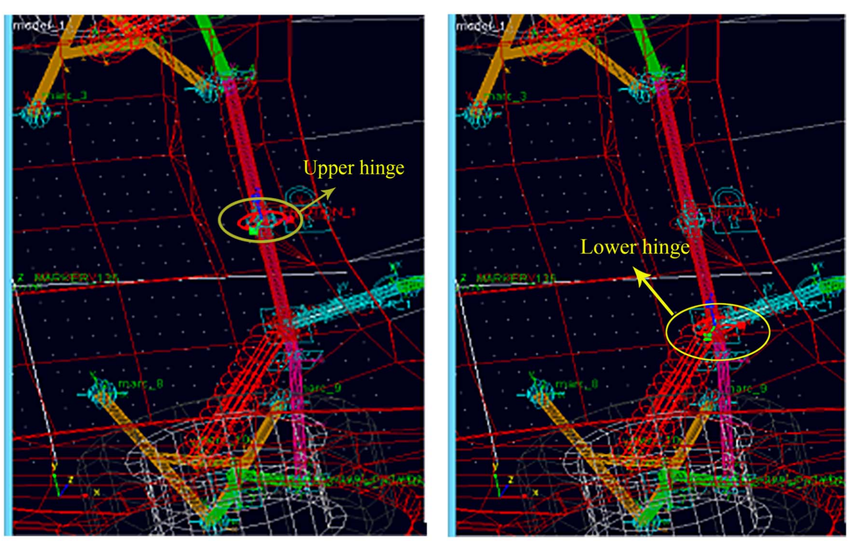


Fig. 5. Front-wheel steering suspension.



(a) (b)

Fig. 6. Steering wheel returning assist: (a) Friction 1; and (b) Friction 2.

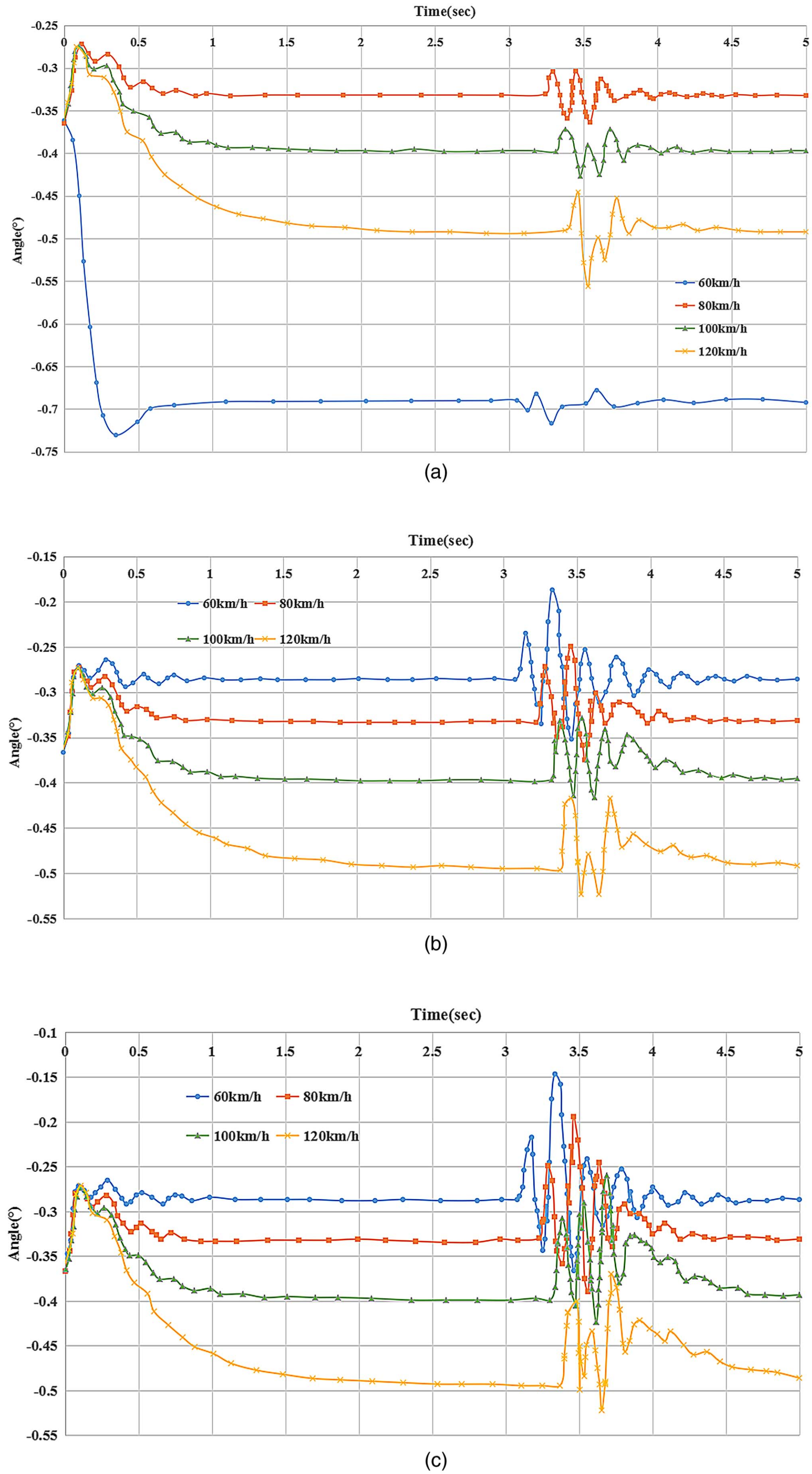
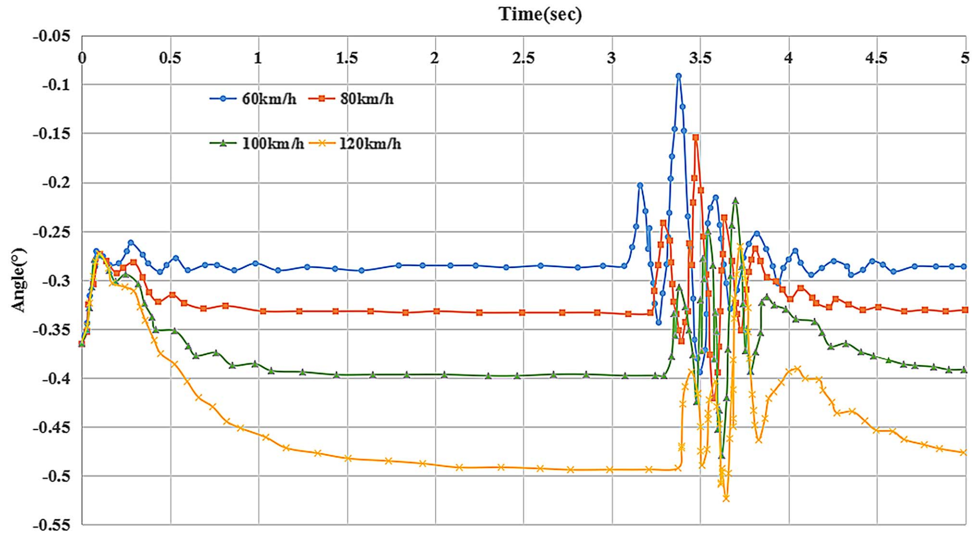


Fig. 7. Steering wheel angles under different driving speeds and rutting depths: (a) $h = 10$ mm; (b) $h = 15$ mm; (c) $h = 20$ mm; and (d) $h = 25$ mm.



(d)

Fig. 7. (*Continued.*)

passenger car. Concerning this, the following improvements were achieved based on original vehicle model.

Optimization of Vehicle Model

The front-wheel steering suspension was supplemented, as shown in Fig. 5. The returning assist simulation was approximately replaced by the frictional resistance of the two hinges, as shown in Fig. 6.

Simulation Results and Analysis

Simulation test of driving in straight line was conducted on asphalt pavement with different driving speed V (60, 80, 100, and 120 km/h) and different rutting depths h (10, 15, 20, and 25 mm). The angle between travel direction of the vehicle and the rutting direction was 0°.

Fig. 7 shows that the steering wheel angles of the vehicle with front-wheel steering suspension and a steering assist system motivated by different rutting depths were considerably smaller than those of without them. Curves in the figure have two fluctuations. The first fluctuation occurred when the vehicle runs into the rutting. The absolute value of the curve grew as the driving speed increased except for the 60 km/h curve in Fig. 7(a), which is consistent with the steering-wheel angle analysis result of vehicle–road coupling simulation without a steering assist system. The second fluctuation indicates the instability of driving when the vehicle was running across the rut. Therefore, special attention was paid on the peak points of each curve marked in the figure, which represent the rotation degree of steering wheel. The differences of angle values between the second-stage fluctuation peak and valley can reflect the driving stability of the vehicle, as indicated in Table 2, where V is the driving speed and h is the rutting depth.

Table 2. Steering wheel difference angle (degrees)

Rutting depth, h (mm)	Driving speed, V (km/h) 60	80	100	120
10	0.0166	0.0301	0.0358	0.0527
15	0.0762	0.0809	0.0719	0.0742
20	0.1399	0.1388	0.1388	0.1341
25	0.1752	0.1717	0.1712	0.1803

Table 2 demonstrates that although the rutting depth increased from 10 to 25 mm, the steering wheel angle output at different driving speeds significantly went up, and the fastest growth appeared between the rutting depths of 15 and 20 cm. When the rutting depth was 10 cm, the steering wheel angle output differences between different speeds were the largest, and the angle at 120 km/h was four times that at 60 km/h. When the rutting depth was greater than 15 cm, angles at different driving speeds were very close. Besides, the angle output of the high driving speed driving had a lower angle than that of the low driving speed in some parts, which is the consequence of the steering wheel returning assist to ease the input from the pavement.

Evaluation Model

Definition of Steering Wheel Rotation Value and Driving Safety Characterization Value

Because the output value of the steering wheel angle is small, for the convenience of research and statistics processing, the steering wheel rotation value (SWRV) is redefined as presented in Eq. (1)

$$\mathrm{SWRV} = 2\pi r\alpha \tag{1}$$

where r = radius of the steering wheel (cm); and α = steering wheel difference angle (degrees).

The diameter of general steering wheel can be 36, 38, or 40 cm; thus the average value (38 cm) was selected in this research. Results of SWRV are given in Table 3, and the cubic polynomial trend line is illustrated in Fig. 8.

There is no relevant regulation to estimate the steering wheel angle for driving safety. Therefore, the driving safety characterization value (DSCV) is scored from 5 to 0 points, representing driving

Table 3. SWRV under different rutting depths and driving speed

Rutting depth, h (mm)	Driving speed, V (km/h) 60	80	100	120
10	1.9807	3.5915	4.2717	6.2882
15	9.0922	9.6530	8.5791	8.8535

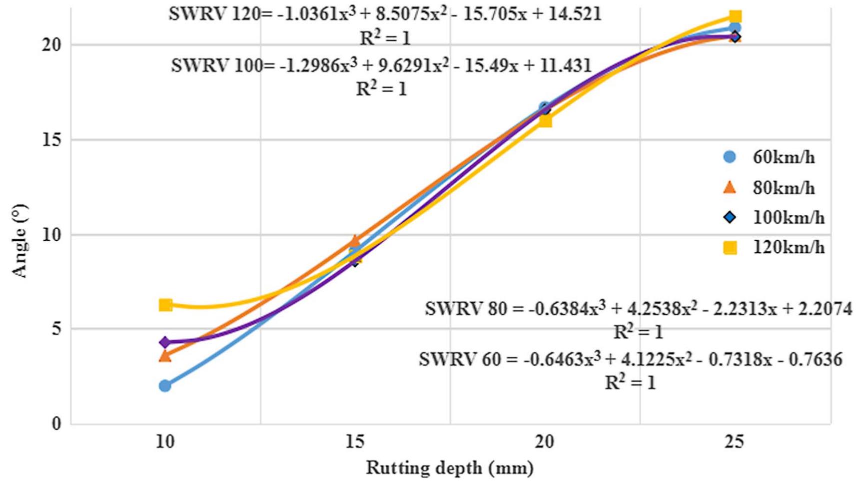


Fig. 8. Cubic polynomial trend curve of steering wheel rotation.

Table 4. Assigned score of different influence levels

Impact level	DSCV
No	5
Slight	4.5
Great	2.5
Severe	0.5

safety from high to low. It corresponds to 5 points when rutting depth is 0. The DSCV is assigned to the impact level, as indicated in Table 4.

Model Development

In this section, different intervals of SWRV were first scored with DSCV through the Delphi method. Consequently, through regression analysis, the functional relationship between SWRV and DSCV was obtained. Finally, the driving safety characterization model of DSCV under different rutting depths was built.

Delphi method, as an evaluation method that seeks expert opinions through anonymous methods, is commonly employed for the estimation of driving safety. Scores given by experts are summarized, analyzed, and classified in the first period. Then, the actual objective experience and subjective judgment of many experts are comprehensively considered, which can be adopted for estimating steering wheel rotation (Steurer et al. 2011). The procedure of its application in the driving safety characterization model under different rutting depths is as follows:

1. Expert selection: according to the requirements of the evaluation method, experienced experts from different occupations need to be selected. In this study, 12 experts were selected. The occupation and the working years are presented in Tables 5 and 6, respectively.
2. The impact degree table corresponding to different steering wheel rotation ranges was designed.
3. Experts were provided with the background information of this research, and scores were obtained anonymously.
4. The results of the scores given by experts were summarized statistically and then reported to experts. The experts corrected their scores based on the feedback of the results.
5. After several rounds of anonymous consultation and feedback, the final analysis conclusion was formed. In this study, three rounds of marking were designed.

Table 5. Occupation

Job type	Number
Researchers	6
Manager	3
Driver	3

Table 6. Working years

Working years	Number
≤2	2
2–5	4
≥5	6

Table 7. Score of steering wheel rotation value

SWRA group (°•cm)	(0,10)	(10,20)	(20,30)	(30,40)	(40,50)
	5	15	25	35	45
Score	3.952	1.657	1.400	0.854	0.415

6. Scores of different steering wheel rotation ranges are given in Table 7. In order to clarify the relationship between DSCV and SWRV, the middle value of each range was taken as the representative score. The exponential regression curve between DSCV and SWRV is illustrated in Fig. 9.

Combined with the relationship between SWRV and rutting depth, a quantitative relationship between DSCV and rutting depth at different driving speeds can be established as shown in Eq. (2)

$$\mathrm{DSCV} = 4.7824\exp\{-0.053(\delta h^3 + \gamma h^2 + \varepsilon h + \phi)\} \tag{2}$$

where h = rutting depth (mm); and δ, γ, ε, and ϕ = coefficients related to driving speed, the values of which can be found in Table 8.

The evaluation model of different rutting depths established using the Delphi method can be used in the control of rutting damage efficiently and conveniently. For example, taking the dangerous situation and the general safety level into consideration, if the driving speed 120 km/h and driving safety characterization value = 4 were selected (e.g., 120 km/h and 4), then 6 mm could be recommended as the allowable rutting depth.

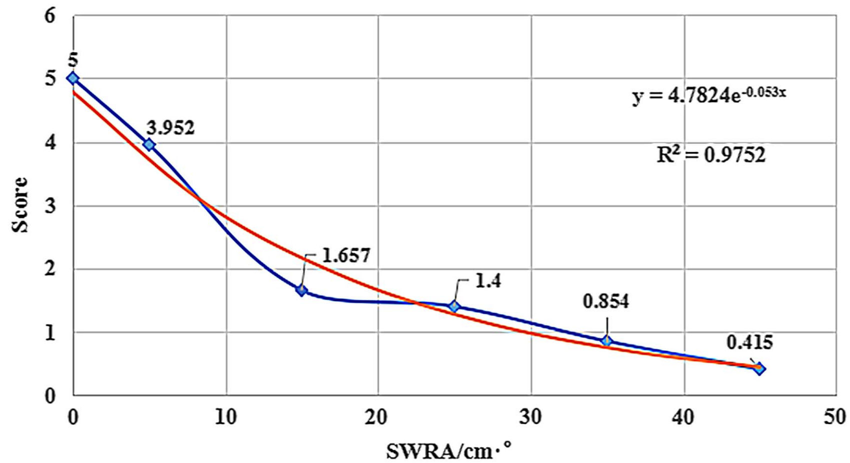


Fig. 9. Exponential regression curve between DSCV and SWRV.

Table 8. Coefficients related to driving speed

	Driving speed (km/h)			
Coefficient	60	80	100	120
δ	0.6463	0.6384	1.2986	−1.0361
γ	4.1225	4.2538	9.6291	8.5075
ε	−0.7318	−2.2313	−15.49	−15.705
ρ	−0.7636	2.2074	11.431	14.521

Conclusions

The influence of different rutting depths on driving was investigated through general and improved numerical simulations using a vehicle dynamics method. Then, an evaluation model was established based on steering wheel difference angle through the Delphi method. The following conclusions are drawn from the study:

- The steering wheel angle caused by a rut is considerably large for vehicles without front-wheel steering suspension and a steering assist system. It rises as the rutting depth increases, and when the rutting depth reaches a certain value, the vehicle has already jumped and the steering wheel may be out of control. Therefore, special attention should be paid to the impact of rutting depth on this type of old-fashioned vehicle. In addition, the angle between the travel direction of the vehicle and direction of the rut also has great influence on driving.
- The steering wheel angle motivated by the rutting depth is much smaller for vehicles with front-wheel steering suspension and a steering assist system compared with vehicles without these features.
- SWRV and DSCV were defined, which give quantitative and intuitive expression for driving stability and its evaluation method, respectively.
- The evaluation model of different rutting depths was established by the Delphi method, providing a quantitative and effective method to evaluate the influence of different rutting depths.

Data Availability Statement

Some data, models, or code generated used during the study are available from the corresponding author by request: (1) vehicle model file; (2) pavement model file; and (3) detailed scores of steering wheel rotation values from experts.

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