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Original Paper

Review of Multi-dimensional Rut Index Threshold Method Based on Driving Comfort and Safety

Qiangqiang Feng[1,2] & Kaijia Fu[1,2]

[1] Xi'an Highway Research Institute Co., Ltd., Xi'an, Shaanxi Province, China,

[2] Shaanxi Xigongyuan Engineering Testing Co., Ltd., Xi'an, Shaanxi Province, China

[*] Qiangqiang Feng, E-mail:·379676429@qq.com

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Abstract

Rutting, one of the typical distresses in asphalt pavement, is known to be a potential hazard to driving comfort and safety when considering driving performance. The cost of different treatment plans varies greatly, which directly affects the allocation and use of maintenance funds and the formulation of maintenance investment plans. The safety and comfort evaluation and maintenance threshold of rutting have an important role in determining the timing of rutting maintenance and the allocation of maintenance funds. At present, the research on rutting based on driving safety/comfort only considers the one-dimensional rut depth. It is difficult to carry out in-depth discussion on the influence of traverse and longitudinal features from the three-dimensional perspective, thus cannot establish a vehicle driving safety/comfort theory system based on real multi-dimensional rut morphological features. With the introduction of high-efficiency, high-density and high-precision advanced 3D laser technology, it is possible to break through the bottleneck of effective extraction and construction/reconstruction of high-resolution three-dimensional rutting features. This paper gives a detailed overview of the rut maintenance threshold standard and multi-dimensional rut indexes, rut comfort and safety evaluation, and maintenance threshold methods; and finally discuss the current problems and proposes future research recommendations. Future research will not only construct the multi-dimensional morphological of the rut with high resolution and with the cross and vertical slopes of the road considered, but also establish a multi-dimensional rut evaluation method and maintenance standard considering driving safety/comfort with comprehensive high precision, which can be used for the refining and revising of rut maintenance specification.

Keywords

rut maintenance, multi-dimensional rut index, safety and comfort evaluation, maintenance threshold, 3D laser

1. Introduction

As the length of roads open to traffic jumped from 1.4 million kilometers at the beginning of 2000 to 4.7 million kilometers at the end of 2017, China is moving from a peak period of road construction to a period dominated by maintenance and repair. Therefore, the road management department will face long-term arduous task of maintenance and management. The purpose of road maintenance and repair is to provide drivers with conditions for high-speed and safe driving. However, as the operation period of the road grows, the road surface will deform under the influence of load, temperature and environment. For one thing, ruts affect the flatness of the road surface, leading to the decrease of vehicle comfort when driving straight or changing lanes. For another, water in ruts in rainy days causes vehicles to drift, affecting driving safety (Fwa, Chu, & Tan, 2016).

Many experts both at home and abroad have conducted much research on the driving comfort and safety evaluation of ruts, and according to different mathematical models, they proposed the evaluation criteria of one-dimensional rut depth maintenance. However, the maintenance threshold value (allowable rut depth) of rut depth evaluation index of different institutions is different. For one thing, due to the different measuring equipment and methods adopted by different road management departments and the different definitions of rut depth, there can be different rut depths measured at the same rut section. For another, as the formation of ruts is influenced by the road structure, traffic load and climatic environment, the complexity of ruts causes that the same maximum rut depth corresponds to several different cross-sectional forms, resulting in the fact that the maximum rut depth is insufficient to reflect the true impact of ruts on driving performance.

When the vehicle is running on the rut, the non-uniformity of the rut longitudinal section is the key factor causing the vehicle to lose control, so the horizontal and longitudinal characteristics of ruts are also important indicators for the evaluation of driving performance. Therefore, it is of great significance to study the rut-pavement interaction and correlation based on the form and geometric characteristics of the rut. The key to solve these problems is to obtain high resolution 3D topography data of the real rut, which poses a great problem for the highway maintenance departments at home and abroad.

All these problems may be attributed to a core, that is, the existing rut detection technology. Whether it is measured with a ruler manually, ultrasonic rangefinder, or multi-point shared-beam laser, the results are all restricted by the density of transverse data point, which makes it difficult to accurately characterize the two-dimensional cross-sectional form of the rut, let alone obtain its three-dimensional topography information. In recent years, with the development of laser technology, especially when the emerging 3D laser technology has been introduced into the field of rut detection, a foundation is laid for constructing intuitive, comprehensive, accurate and reliable 3D models of the pavement rut. 3D laser technology can extend the study of rut from a single depth to two-dimensional features such as cross-sectional form, and even introduce near-real three-dimensional views such as longitudinal length and volume. With advanced 3D laser technology, high-density and high-precision laser-point cloud data can be obtained, which also provides a scientific platform for evaluation of rut maintenance and analysis of driving performance. To adapt to the development needs of fine maintenance management, and in view of the fact that the current rut detection technology for expressway and the characteristic indexes cannot meet the scientific maintenance decision, this paper mainly summarizes the rut maintenance threshold standards and multi-dimensional rut indexes, the rut comfort and safety evaluation, and maintenance threshold methods, analyzes existing problems and proposes suggestions for future research.

2. Rut Maintenance Threshold Standards and Multi-dimensional Rut Indexes

2.1 Rut Maintenance Thresholds and Criteria

At present, domestic and international road agencies generally adopt the one-dimensional rut depth as the maintenance evaluation index of the rut. As shown in Table 1, the Ministry of Transport of the People's Republic of China and the US Federal Highway Administration have evaluated the different severity levels of rut depth. Pavement rutting with the same maximum rutting depth, however, may correspond to several different kinds of rutting profiles, which is caused by the complexity of pavement structures, traffic loads and weather conditions during the rut deterioration process. Thus, the one-dimensional rutting depth index is insufficient to reflect the rutting's effects on vehicle driving performance. Moreover, it is not a reasonable practice to classify the ruts into low or high severity levels when considering rut safety evaluation. For example, the rut of 14.9mm is evaluated as low; while the rut of 15.1mm will be evaluated as high. While these two kinds of rutting's influence on vehicle safety evaluation is almost the same.

Table 1. Rutting Maintenance Evaluation Criteria of Different DOTs in China and U.S.

Road Agency	Rutting maintenance evaluation criteria
Department of Transportation Highway Performance Assessment Standards [2]	Rutting depth 10 - 15mm Low Rutting depth ＞15mm High
U.S. Federal Highway Administration FHWA [3]	5 - 6 mm Light 6 - 13 mm Low 13 - 25 mm Medium ＞25 mm High

Table 2 lists the evaluation criteria for rut depth maintenance of different interstate transportation departments in the United States (Fwa, Chu, & Tan, 2016). The department of transportation in each state divides the rut into the grades below according to road condition surveys and subjective experience. So, there exist the same problems mentioned above.

Table 2. Examples of Rut Maintenance Threshold Standards Adopted in Different U.S. DOTs

Highway Agency	Low (mm)	Medium (mm)	High (mm)
Washington State Department of Transportation (WSDOT 1999)	6.3 - 12.7	12.7 - 19.1	> 19.1
Ohio Department of Transportation (ODOT 2006)	3.2 - 9.5	9.5 - 19.1	> 19.1
Massachusetts Highway Department (CMRPC 2006)	6.3 - 12.7	12.7 - 38.1	> 38.1
Texas Department of Transportation (TDOT 2001)	6.35 - 12.67	12.68 - 25.15	> 25.15
MnRoad in Minnesota (MDOT 2003)	6.35 - 12.7	12.7 - 25.4	> 25.4
California Department of Transportation (Caltrans 2006)	Schedule corrections when rut depth> 25.4		

As can be seen in the above study, two institutions think that ruts with the depth greater than 20 mm are enough to be classified as severe type; four institutions believe that only ruts with the depth greater than 25 mm can be considered as serious type; one institution classifies ruts with the depth only greater than 50.8 mm as severe type. The facts above clearly indicate that there are differences in engineering judgments between institutions on the severity of rutting.

In addition, the division of the severity of the above-mentioned ruts does not take into account factors such as road grade, speed limit, etc. which may cause the maintenance threshold to be too large or too small, resulting in waste of maintenance funds or an increase in driving safety risk evaluation. In the above specification, the rut is divided into deeper and shallower divisions with a depth of 15 mm. This division is obviously rough. Xu of Tongji University (1994) gave a relatively detailed recommended value of rut depth maintenance threshold according to different road grades, see Table 3.

Table 3. Rut Maintenance Threshold under Different Road Grades

Road grade	Expressway	Other grade roads	
		Non-intersection section	Intersection section
Rutting depth(mm)	10-15	15-20	20-25

The difference in the basis for above classification of rutting severity and formulation of maintenance standards leads to difference in the maintenance standard and severity. Some standards are based on the pavement structure design, or based on the experience of maintenance personnel, and some others are based on the drift safety analysis and driver comfort analysis. The impact of ruts on road safety and comfort is a complex and controversial issue (Cenek et al., 2014; Ihs, 2004), resulting in conflicting conclusions about comfort and safety. Therefore, to study the basis for the formulation of the above standards, the research on safety and comfort of ruts is reviewed below.

2.2 Multi-dimensional Rut Indexes

Before reviewing the literature on driving comfort and safety, this paper first reviews the multi-dimensional evaluation index of ruts, since is not only the depth of the rut that affects the tires of the vehicle, but the entire section of the road. Complete road profiles contain valuable information, such as cross slopes, rutting shapes and other associated pavement distresses. However, it is impractical to use the full road profile (every point) directly for engineering decision-making. Consequently, maintenance personnel and researchers put forward evaluation indexes such as rut depth and width to evaluate rut, and infer the deformation mechanism and safety risk of rutting.

For a long time, the research on rut characteristic indexes at home and abroad mainly focuses on one-dimensional depth. The concept of two-dimensional characteristic indexes of ruts was first proposed by Oteng Seifah and Manke in 1976 (Oteng-Seifah & Manke, 1976). In recent years, researchers at home and abroad have proposed many new rutting characteristic indexes (Wang, 2017; Li, 2007; Wu, 2007; Hui, 2013; Qu, 2005) from the aspects of distress type identification, driving safety and maintenance requirements (see Table 4). It is an extension and supplement to the existing evaluation indexes of pavement rutting depth, which can reflect the rutting characteristics more intuitively and stereoscopically. To a great extent, it can improve the understanding and judgment of road engineers to the rutting condition of pavement, and thus guide the maintenance and management of expressway more effectively. However, due to the high requirements of these new indexes for testing equipment and the limited accumulated historical data and experience, people still lack intuitive understanding of its numerical range and change law. Moreover, due to the complexity of rut water accumulation process, relevant indexes of rut water accumulation depend on the drawing of complete rut cross section, and continuous sections interact with each other, resulting in the lack of analysis and research on safety based on rut water accumulation indexes. In addition, in the past, the maximum rut depth was often used to represent the depth of rut water to calculate the dangerous degree of the road section with ruts, but obviously the two are different. Therefore, it is necessary to employ advanced detection technology to further study these new indexes, and gradually establish the safety evaluation standards that meet the indexes.

Table 4. Multi-dimensional Rut Indexes and Applications

Multi-dimensional rut index		application
1D parameter	Rut depth (maximum 、average 、water-filled rutting depth 、left and right rut depth	severity of the rut, driving safety
	Rut width	severity of the rut , driving safety
	Rut length	severity of the rut , driving safety
	Rut height in the middle of the rut	severity of the rut , driving safety, rut shape
2D parameter	Positive-Negative Area	cause of the rutting.
	Positive-Negative Area Ratio	cause of the rutting.
	Fill area	volume of material required in rehabilitation
3D parameter	Concave convex volume deformation	volume of material required in rehabilitation

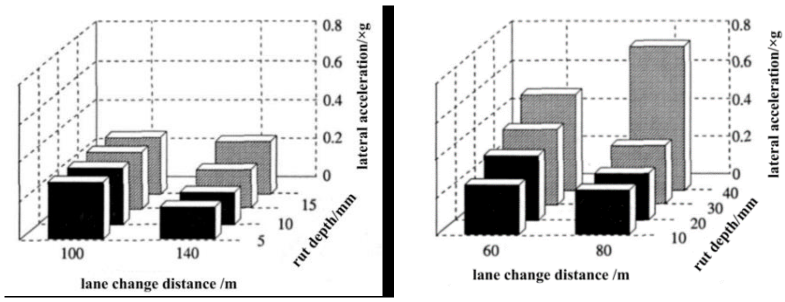
3. Rut Comfort and Safety Evaluation and Maintenance Threshold Methods

Long before the structural condition of a rutted pavement becomes a concern, maintenance or rehabilitation of the pavement would have to be carried out to restore the functional condition of the pavement for safe traffic operations. Pavement ruts affect the functional operation of a highway because they can cause steering instability of vehicles, especially for lane changing or overtaking operations of vehicles. More important, they present a safety risk to vehicles because they collect water during wet weather, which can lead to reduced skid resistance along the rutted wheelpaths because of the presence of water. However, most highway agencies today rely on experience and engineering judgment in setting the rut depth maintenance threshold for activating rut repair from the perspective of road managers (Fwa, Chu, & Tan, 2016). For road users, what is directly felt is not the strength and stability of the pavement structure, but the functional performance related to road roughness, ride quality, slip, noise, etc. The user is more concerned about the ease of handling the vehicle and the stability of the vehicle when driving on the road. The following is an overview of current comfort and safety related rutting research for the rut with and without water.

3.1 Comfort Evaluation of Dry-state Rutting

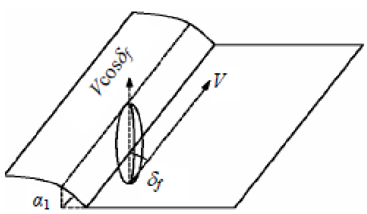
The research on drying ruts currently considers indexes such as rut depth, rut sidewall inclination and rut shape, and qualitatively or quantitatively analyzes the influence of dry ruts indictors on vehicle comfort evaluation by using lateral acceleration, roll angle, yaw angle etc. The Japan Institute of Civil Engineering and Construction (2004) (Cong & Yang, 2009) measured the lateral acceleration of a vehicle when it changed lanes. According to different driving speeds, the lane change distance of the vehicle is 100m and 140m (100km/h), 80m and 60m (60km/h) respectively. The relationship between lateral acceleration and rut depth is shown in Figure 1: the deeper the rut, the greater the lateral acceleration.

When the rut depth is 40mm, the lateral acceleration exceeds 0.4g, which exceeds the exposure limit of the human body to vibration response. As shown in Figure 2, Cong (2010), Xie (2007) simplified the rut profile into a triangle as the lateral excitation of the rut to the vehicle. Compared with the above actual rut shape, the research hypothesis is relatively simple.



a) General lane b) G408

Figure 1. The Relationship between Lateral Acceleration and Rut Depth When Vehicle Changing Lanes



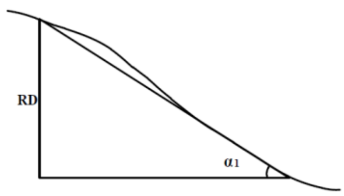


Figure 2. Vehicle Tire Passing the Rutting **Triangle Shaped Rutting Model**

Kazuya (2010) believes the conventional index - the rut depth, simply depends on the maximum displacement in the measured profile with unlimited wavelengths, cannot show the wavy characteristics of rutting profile, and has a drawback in which influence of vehicle behavior on riding quality. The article filtered the rut by a band-pass difference filter, as shown in Figure 3: the dotted line is the original road surface, and the solid line is the filtered rut profile. It is concluded that the adjusted rut depth is more correlated with the ride quality rating value HRD (half-car-based index for rutting distress based on the semi-car model).

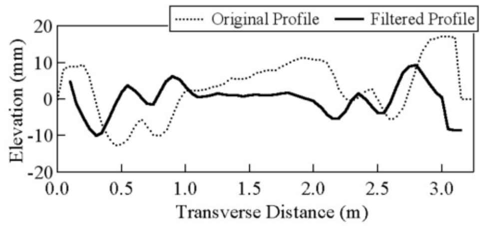
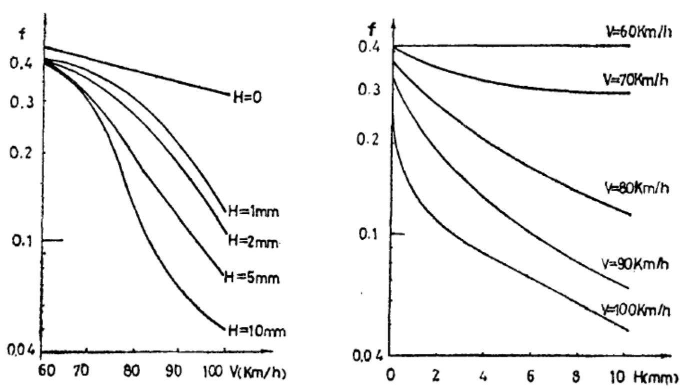


Figure 3. An Example of the Filtering of a Rut Profile

Even so, the current research on the influence of the rut on the vehicle is not accurate. It's because of the rutting model is too simplified or the testing equipment cannot detect the high-precision rut profile. Although Kazuya considered the influence of rutting shape on vehicle stability, the detection equipment is relatively backward (data were collected in 1998), and the collection interval of each point on the rutting profile is 30cm, which does not represent the real rut profile. Nevertheless, Kazuya's research proves that the lateral detection point spacing affects the lateral rolling characteristics of the vehicle when changing lanes. Therefore, it is necessary to collect a continuous and accurate rut profile and to perform vehicle analysis based on the safety and comfort of the vehicle.

3.2 Safety Evaluation of Water-filled Rutting

The research on the water-filled rutting is mostly based on the study of water-filled pavement (Ji, Huang, & Liu, 2003; Ji, Huang, & Liu, 2004; 19. Ji, Gao & Chen, 2010; Qiu, 2013). The current water-filled pavement research conclusions are uniform and mature (the effect of water film thickness on hydroplaning) and are adopted by the driver's manuals. Figure 4 shows the influence of vehicle speed and water film thickness on pavement friction established by the Field Hydroplaning Experiment (1967). Fwa (2007, 2008) established and validated the 3D finite element simulation model. Based on the model, the effects of water film thickness, wheel load, tire inflation pressure, tire tread pattern and vehicle speed on critical hydroplaning speed were analyzed.



The relationship between pavement friction and water film thickness under different vehicle speeds

The relationship between pavement friction and vehicle speed under different water film thickness

Figure 4. The Relationship between Pavement Friction and Vehicle Speed, Water Film Thickness

Based on the above conclusions of the water film thickness, researchers have tried to convert the water film thickness in the road without rut into the water-filled rutting depth in the road with rut. For example, Japan's "Road Maintenance and Repair Outline" (1978) put forward that the water film thickness must be less than 7mm in order to prevent cars from hydroplaning on the expressway. To ensure that the water film thickness is less than 7mm, if the cross slope is considered, the rut should be less than 20 mm; if the influence of other problems in actual management is to be considered, the critical depth of the rut is finally set to 25 mm.

Xu (1994) and Lei (2008) considered the rut depth maintenance threshold of expressways from the perspective of driving safety. The shape of the rut is simplified to a parabola (left of Figure 5) and a triangle (right of Figure 5), respectively. The former uses the method of mathematical integration to explore the relationship between the water film thickness H and the rut depth RD according to the area equivalence principle. As shown in the figure, the area of the parabola (AOB) is the same as the area of the rectangle (ABCD) formed by the dotted line. The latter considers the cross slope of the road. It is considered that when the c-point elevation at the bottom of the rutting is greater than or equal to the d-point of the outer edge of the rutting, no water will accumulate in it. It is calculated that the critical rut depth (rut depth maintenance threshold) RD of the rut that does not accumulate water is 9 mm. However, the influence of the rut shape, which has been reduced into parabolas and triangles, on the calculation of rut water depth is overly simple.

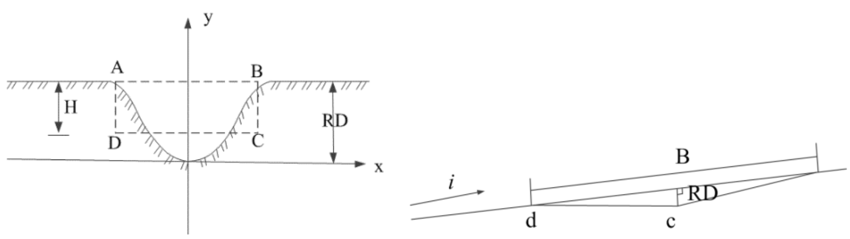


Figure 5. Parabola-shaped Rutting Model Triangle Shaped Rutting Model

Fwa (2011) presented a method to determine the critical rut depth threshold for pavement maintenance considering the risk of hydroplaning and the required safe braking distance. This is an improvement method for the classification of rutting severity using engineering judgment and experience. The critical rut depth analysis clearly shows that if the frictional properties and maximum allowed vehicle speed along different pavement sections of a highway are different, their critical rut depths would also be different (as shown in Figure 6). It is a more accurate classification of the severity of the rut depth for road safety and pavement management.

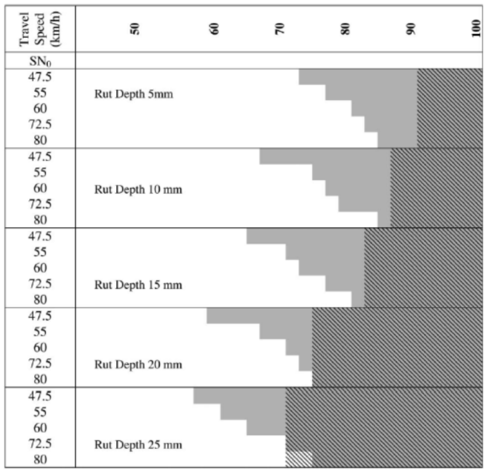


Figure 6. Governing Criterion for Safety Assessment at Different Rut Depths

The above studies rarely consider the cross slopes and grades of the rutted roads that affect the water-filled rutting depth. Mingxuan Lei considered the cross slope of the road, but only considered the critical rut depth where the water could not accumulate. In addition, the influence of the rut shape reduced to parabola and triangle on the calculation of the water-filled rutting depth is too simplified. Simpson (2013) believes that cross slope is a known factor contributing to the safety impacts of rutting on asphalt pavements. In addition, the potential water entrapment depth was suggested to be collected (calculated) in the new released AASHTO standard practice (2014a), however, research on the safety of water - filled rutting is still rare. VTI (Swedish National Road and Transport Research Institute) has done some work looking at the correlation between accident rate, speed, cross slope and rutting and the relationships are not clear (His et al., 2011). It is speculated that driver behavior changed on rutted roads so this impacted the resulting accident rate.

Gallaway (1971), Luo (2015), Guo (2013) considered the impact of the road environment where the rut is located on the water film thickness and hydroplaning speed. Gallaway and FHWA collaborated to study the effects of pavement cross slope, pavement texture, and drainage length and rainfall intensity on the water film thickness through laboratory experiments. For a rainfall intensity of 1.5 in/hr, a surface texture of 0.03 in., and a drainage length of 24ft., increasing the cross slope from 1/16 in/ft (1/192) to 1/4 in/ft (1/48) decreased water depths by 62 percent in the outside wheel path (approximately 21 feet from the top of the drainage area). Correspondingly, increases in surface texture decreased water depths; whereas, increases in rainfall intensity and drainage length increased water depths. Luo believes the presence of longitudinal and cross slopes would decrease the wheel load of vehicles perpendicular to the pavement surface. And results show that hydroplaning speed at pavement segments with large slopes are lower than that with no grades. Guo applied the finite element simulation software Fluent to simulate the theoretical variation and distribution law of the dynamic water pressure of the vehicle tire under different cross slopes. According to the analysis, the impact of the cross slope on the vehicle driving safety is not obvious during rainy days. When the cross slope is 2%, the velocity of water of transverse direction on the road surface is much lower than the velocity of tire, the transverse tire tread grooves can timely drain most of the water.

Finally, the longitudinal characteristic water length of the rut is also less studied for driving safety. The length of the water determines the travel time of the vehicle in the water-filled rut. Xu (2009) pointed out that the longer the car travels in the water-filled area, the greater the difference in the grounding speed of the tires on both sides of the car, which are the main reasons for the side slip of the car.

4. Conclusions and Recommendations

4.1 Conclusions

From the review of the above literature, it can be seen that the current research on rut safety at home and abroad, including the formulation of maintenance thresholds, only considers the one-dimensional depth index, but does not take into account the multi-dimensional characteristics of rut and the longitudinal and traverse slope of the rut profile.

At present, the research on the relationship between dry ruts and vehicle lateral stability (comfort) is not accurate. At present, factors such as rut depth, rut sidewall inclination and rut shape are taken into account. The effects of dry ruts on vehicle comfort (lateral acceleration, roll angle and yaw angle) are qualitatively or quantitatively analyzed, but they inaccurate as the rutting model is too simplified, or the detection equipment cannot detect high-precision rutting section. Therefore, it is necessary to collect information on continuous and accurate rutting sections, and dynamically analyze vehicle stability and comfort based on real rutting cross sections (3D reconstruction model).

In addition, the relationship between hydroplaning and water-filled rutting at home and abroad is still based on one-dimensional rutting depth index, which cannot truly and comprehensively represent the impact of ponding in ruts on driving safety. In fact, besides the one-dimensional rutting depth index, the maximum depth of rut, the characteristics of rut cross sections (rut shape, rutting area, rut volume, rut width, etc.) and the longitudinal characteristics of rut (rut length) can also be key factors affecting ponding capacity in ruts.

Therefore, although there are a lot of rut researches based on traffic safety at home and abroad, there is still no complete multi-dimensional maintenance evaluation system based on traffic safety mechanism, so it cannot accurately make scientific maintenance decisions for road ruts.

4.2 Future Research Recommendations

The following two aspects provide research ideas and suggestions for future rut maintenance evaluation system based on vehicle safety/comfort evaluation: high-precision 3D rut morphological reconstruction and the impact of multi-dimensional rut index on vehicle dynamic; and the determination of multi-dimensional rut maintenance threshold based on vehicle hydroplaning analysis and considering the horizontal and longitudinal gradients of road.

4.2.1 High-precision 3D Rut Morphological Reconstruction and the Influence of Multi-dimensional Rut Index on Vehicle Dynamic

Step 1. Data acquisition and processing of high-precision 3D model

High-precision 3D line laser system is used to detect the full-lane coverage of transverse pavement profile, combined with two line laser detection systems with the detection width of 4m. In terms of the detected pavement profile, each profile contains intensive data points with X-direction resolution of 1mm, Y-direction resolution of 1-5mm and Z-direction resolution of 1 mm, from which high-precision and high-density point cloud data of rutting profile are obtained. The acquisition equipment meets the requirements of the new AASHTO *PP 70-14 Standard Practice for Collecting Traverse Pavement Profile*(2014b).

Step 2. 3D pavement reconstruction based on LiDAR and high-precision rut profile

Before data reconstruction and analysis, the 50 mm moving average method recommended in *AASHTO PP 69-14 Standard Practice for Determining Pavement Deformation Parameters and Cross Slopes from Collected Transverse Profiles* (2014a) is used to denoise and smooth the collected profiles. The transverse profile data includes the shape of rut, and the location data includes the geographic coordinates of the profile point cloud data where the rut is located. The cross slope can be calculated by the geographic coordinates of the left and right points on the lane markings.

Step 3. Dynamic accuracy verification of 3D reconstructed rutting model

On the basis of precise 3D pavement, effective points are selected with equal spacing (determination of spacing between transverse points and longitudinal sections), and 3D pavement model is reconstructed by using pavement units with different spacing between transverse and longitudinal sections. Based on vehicle dynamics simulation software-Carsim, the effects of 3D road surface models with different longitudinal and lateral intervals on simulation results (vehicle response: lateral, longitudinal and vertical accelerations) are analyzed and compared with the actual data collected. On the premise of ensuring dynamic accuracy and validity of detection points, there exist an optimal pavement unit which can reduce detection costs and running time of vehicle safety/comfort analysis.

Step 4. Comfort/safety dynamics analysis based on 3D reconstructed rut model

The correlation between multi-dimensional rut indexes and vehicle dynamics is analyzed, and the maintenance threshold based on comfort/safety analysis of multi-dimensional rutting indexes is analyzed. Support Vector Machines or Pattern Recognition/Pattern Category are proposed to establish the relationship between rut morphological indexes and hazards.

4.2.2 Determination of Multi-dimensional Rut Maintenance Threshold Based on Vehicle Hydroplaning Analysis and Considering the Longitudinal and Horizontal Gradients of Road

Step 1. Analysis of the influencing factors in the study of maximum water film depth

$$water\_depth = f(texture, length, cross\_slope, rainfall\_intensity)$$

Among them, water_depth represents the ponding depth; texture represents the depth of texture; length represents the ponding length; rainfall_intensity represents the intensity of rainfall; and cross_slope represents the cross slope of road.

After rutting formulated on the road surface, the direction of runoff flow, the depth, area and volume of ponding have changed, which lead to the change of ponding depth in the rutting section.

$$waterfilled\_rut\_depth = f(texture, length, cross\_slope, rainfall\_intensity, longitudinal\_slope, water\_area, water\_volume)$$

In the formula, waterfilled_rut_depth represents the depth of waterfilled rut, water_area represents the ponding area, and water_volume represents the ponding volume.

Step 3. Optimization of critical speed formula for vehicle hydroplaning

$$hydroplaning\_speed = f(tire\_tread\_depth, load, inflation\_pressure, waterfilled\_rut\_depth)$$

In the formula, hydroplaning_speed represents the speed when vehicle hydroplanes, tire_tread_depth represents the tread depth, load represents vehicle load, and inflation_pressure represents tire pressure.

Step 4. Determine the maintenance threshold of rut depth, length, area and volume.

Safety maintenance thresholds considering rut depth, length, area and volume are proposed.

This paper reviews the research from above two aspects: current rut maintenance threshold standards and multi-dimensional rut indexes; rut comfort and safety evaluation and maintenance threshold methods. At present, the research on rut evaluation has developed from the one-dimensional rut depth to a multi-dimensional one. However, due to the limitation of detection technology, the research on the impact of multi-dimensional rut index on vehicle safety/comfort is still not well developed. Based on high-precision and high-density 3D laser detection system, this paper provides research ideas and suggestions for improving the evaluation system of rut maintenance threshold method.

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