

EVALUATION OF PAVEMENT RUNOFF AND DRIVING SAFETY ON HIGHWAY CURVE SEGMENT

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Abstract. Runoff depth distribution on the concave and circular curve sections is obtained from a two-dimensional numerical simulating model in order to analyze the temporal and spatial variation of the pavement runoff on the curve section. The two-dimensional model verified by the field data can depict the alignment of pavement more accurately as compared to the empirical equation and a one-dimensional model. The runoff on the concave section and circular curve section is compared for the free water drainage and centerline drainage. Results show that a two-dimensional model is essential for the analysis of the centerline drainage. The runoff depth can be controlled by a reasonable curb height and location interval. The drainage type affects the variation of the runoff depth on the nearside lane, and the maximum water depth can be up to more than 80 mm on the concave section and nearly 60 mm on the circular curve section under centerline drainage. Besides the existing hydroplaning results, the runoff depth difference of the wheel trace should be considered to evaluate driving safety. Sideslip will occur when the depth difference becomes more than 6 mm under condition that the runoff depth is less than the tread

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depth (7 mm). When the runoff depth is more than the tread depth, sideslip will occur once the depth difference exceeds 4 mm.

Keywords: road engineering, asphalt pavement, runoff distribution, curve segment.

Introduction

Presence of excessive rainfall remaining on the pavement may cause hydroplaning, since water decreases friction between the tire and pavement surface (Mayora & Piña, 2009). Accurate depiction of the pavement runoff behavior, such as depth, velocity, and flow direction, is essential for ensuring driving safety (Luo & Li, 2019). Compared with the straight-line section described by a one-dimensional laminar flow model, the runoff distribution of the curve segment should be reflected by the three-dimensional terrain. Moreover, traffic safety should also be evaluated. The runoff variation on the pavement is mainly influenced by a number of factors, such as rainfall intensity, pavement width, slope, and drainage types (Ma et al., 2017). Among them, pavement slope is one of the most important factors affecting pavement runoff behavior. For example, the cross slope may be up to 8% at superelevation, and the longitudinal gradient may be even higher. Therefore, it is necessary to analyze the runoff distribution on the curve segment in order to ensure efficient drainage design and provide for the driving safety.

The research methods used in the analysis of the runoff can be grouped into three categories based on the calculation algorithm, i.e., the empirical regression, hydraulic, and hydrodynamic model. Empirical regression requires a large amount of data, and multiple factors cannot be considered to ensure accurate prediction (Anderson, 1995; Ji et al., 2004). The hydraulic models are also frequently used for runoff behavior forecasting (Anderson et al., 1998; Cristina & Sansalone, 2003). Pavement generally is simplified as a one-dimensional section along the resultant gradient (William & Stuart, 2000). The depth distribution can be simulated by taking the precipitation and pavement resultant gradient into account. However, the traditional simplification of the runoff depth distribution as a one-dimensional section along the resultant gradient is not sufficient (Ji et al., 2004; Escarameia et al., 2006; Maxwell et al., 2015; Jeong & Charbeneau, 2010). The numerical modeling proved to be a more efficient tool for pavement runoff simulation as compared to the methods of empirical regression and hydraulic modeling (Ma et al., 2017; Charbeneau et al., 2008; Wang & Geng, 2013). Two-dimensional shallow water equations based on the hydrodynamic factors are currently accepted to mathematically describe

a wide variety of free-surface flows under the effect of gravity. Several studies have evaluated the benefits of two-dimensional shallow water equations. According to Wolff (2013) and Chen (2017), in contrast to one-dimensional models, two-dimensional shallow water equations can accurately characterize the flow field of pavement runoff considering the influence of multiple factors, such as pavement width, slope and drainage types (Geng et al., 2019). Ressel et al. (2019) pointed out that traditional one-dimensional models describing the flow on the one-dimensional drainage paths have certain limitations, because most hydrological processes on the pavement surface occur in the two-dimensional space with a temporal variation. High-performance computers may help in the simulation of fluid behavior, such as dam-break waves, propagation of flood waves in rivers, flood plain inundations, etc. (Dawson et al., 2009). A two-dimensional flow field can better describe the runoff variation considering the influence of the pavement slope, specifically, it may help avoid the numerical instability caused by small water depth and discontinuity (Wolff, 2013; Chen et al., 2017; Costabile et al., 2017). Furthermore, the backwater phenomenon caused by irregular bottom and curbs can also be depicted (Wang & Geng, 2013; Cea et al., 2010). It has become a widely accepted practice to mathematically simulate the free surface flows on the pavements using the hydrodynamic model based on the two-dimensional shallow water equations.

Previous studies on the impermeable pavement drainage mainly focused on the depth distribution on the straight segment, there are still considerably fewer studies dedicated to the analysis performed on the curve segment (Geng et al., 2019; Ma et al., 2019). In this paper, the data on depth variation on the pavement surface have been obtained using a two-dimensional numerical simulating model in order to develop a better understanding of the runoff distribution on the curve segment. The two-dimensional model, which has been verified by field data, can depict the alignment of pavement more accurately than the empirical equation and a one-dimensional model. Runoff on the concave section and circular curve section is compared for the free water drainage and centerline drainage. Moreover, besides drawing conclusions on hydroplaning, the differences in water depths between wheel traces have also been compared in order to evaluate driving safety.

1. Method

Pavement runoff variation can be described by the empirical regression, one-dimensional and two-dimensional models. In contrast to the empirical regression, the simulation models, especially the

two-dimensional model demonstrating high degree of effectiveness and accuracy, are widely used to depict the pavement alignment. The two-dimensional models have been successfully applied in many studies (Dawson et al., 2009; Costabile et al., 2017). Based on the two-dimensional shallow water equations, pavement water depth can be simulated when it is necessary to design pavement drainage and provide for driving safety. Two-dimensional shallow water equations contain the continuity equation (Equation (1)) and the momentum equations in x and y directions, respectively (Equation (2) and (3)) (Ma, et al., 2020). By combining the above-mentioned equations, the finite-volume method is implemented on the unstructured grids to obtain the depth variation (Wang & Geng, 2013).

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = q(t) \quad (1)$$

$$\frac{\partial(uh)}{\partial t} + \frac{\partial\left(u^2h + \frac{1}{2}gh^2\right)}{\partial x} + \frac{\partial(uvh)}{\partial y} = ghS_{0,x} - ghS_{f,x} \quad (2)$$

$$\frac{\partial(vh)}{\partial t} + \frac{\partial(uvh)}{\partial x} + \frac{\partial\left(v^2h + \frac{1}{2}gh^2\right)}{\partial y} = ghS_{0,y} - ghS_{f,y} \quad (3)$$

where u and v are the horizontal velocity components in x and y directions, m/s; h is the water depth, m; g is the gravitational acceleration, m/s²; $q(t)$ is the rainfall intensity, mm/h; $S_{0,x}$, $S_{0,y}$ are the slope source terms in x and y directions, and $S_{f,x}$, $S_{f,y}$ are the friction source terms in x and y directions.

2. Verification

The above model has been verified within a practical engineering project in the northeast area of China (Geng et al., 2019). In order to verify that the two-dimensional model can also be applied to curve sections, the part of Shanghai-Nanjing Expressway from Zhongshanmen to Maqun Interchange was taken as an example. It is a section of S-shaped superelevation transition that connects a straight section and a curve. The length of this section is 6.6 km and the width is 24.5 m. The longitudinal gradient is 1.1% and the cross-slope changes from -2.0% to 3.6%. In this part, the pavement runoff depth was simulated by empirical equation, one-dimensional motion wave equation, and two-dimensional shallow water equations, respectively. The design rainfall intensity is 150 mm/h, referring to the specifications for the drainage design of

highways (JTG/T D33-2012) and local meteorological condition data (Ministry of Transport of the People's Republic of China, 2013; Yao et al., 2009; Zhi, 2012; Fu, 2012).

The theoretical value of the maximum water film depth can be obtained by the following empirical Equation (4), which was suggested by Ross and Russam (1968) based on the experimental data. The calculated maximum water film depth is 6.5 mm.

$$d = 0.017 \cdot (L \cdot I)^{0.47} \cdot S^{-0.2} \quad (4)$$

where L is the length of drainage path (310.5 m); I is the rainfall intensity (150 mm/h); and S is the slope (1.1%).

Based on the simulation results, in case of the one-dimensional model, the maximum water film thickness on the section of zero cross slope was 7.2 mm. It was greater than the results obtained using the empirical method. Besides, the one-dimensional model assumes that the water flows along an unchanged section, but the assumptions that may be valid for the straight segment may not be easily confirmed on the curve section.

Based on the two-dimensional model (Ressel et al., 2019), the flow field (Figure 1) showed the flow direction variation on the pavement. Due to the existence of zero cross slope, it is more likely to be inundated during the transition. It could be observed that the runoff changed in the two-dimensional space. The maximum water depth on the location of fast lane was 6.6 mm (Figure 2). The temporal and spatial variation is shown in Figure 3 (Chen et al., 2017). Although the empirical method is widely used, it usually yields valid results only on the basis of analysis of a large amount of data. As a result, the two-dimensional model not only demonstrates a good agreement with the empirical equation, it can also describe the influence of the pavement alignment on the runoff. The two-dimensional model has proved to be more suitable in simulation of the road surface runoff on the curve sections.

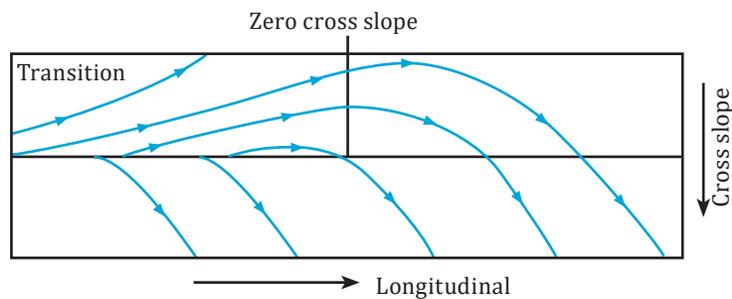


Figure 1. Flow field on transition

In this study, the proposed model is used to analyze the water depth distribution on the pavement. Taking a two-way six-lane pavement (cross slope is 2%) with the design speed of 120 km/h as an example, pavement runoff distribution is analyzed when the rainfall intensity is 86 mm/h at the recurrence interval of 1 year (1a). In the following section, the simulation results concerning water distribution on the concave and circular curve sections obtained based on the two-dimensional model are compared. The impact of water depth variation on the driving safety is also analyzed.

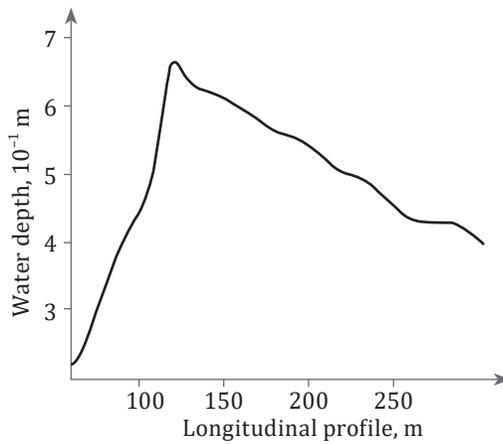


Figure 2. Pavement water depth in the fast lane

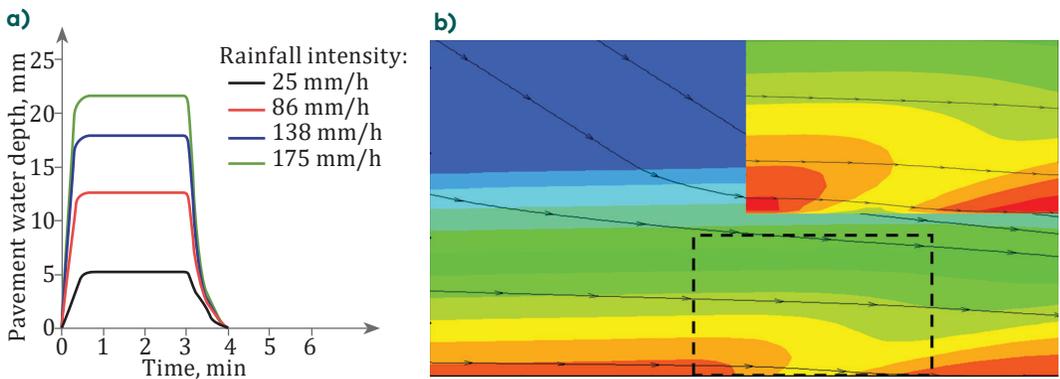


Figure 3. Pavement surface flow: a – Temporal variation; b – Spatial variation (Chen et al., 2017)

3. Results and discussion

3.1. Runoff distribution in the curve

3.1.1. Concave section

Figure 4 demonstrates the pavement surface flow on the concave section in case of the centerline drainage and free water drainage. Inundation occurred at the bottom of the vertical curve; it became more pronounced when the centerline drainage was adopted. For the free water drainage, the contour line of the pavement water depth was basically consistent with the direction of the longitudinal gradient. The direction of water flow was mainly affected by the cross slope. When adopting the centerline drainage, an obvious backwater occurred in the nearside lanes due to the presence of curbs. Near the curbs, the water flow converged toward the bottom of the vertical curve resulting in an extension of the inundation at the bottom. The depth did not exceed 17 mm when the free water drainage was adopted, while in the case of the centerline drainage, the depth increased and exceeded 120 mm due to the presence of curbs. Given that the outlets were placed at the interval of 25 m, the backwater width reached nearly 3 m and the length - nearly 50 m.

As the rainfall continued, pavement water depth reached a steady state in a certain period of time. The time to steady state depended on the distance to the median strip. Within the road range, pavement water depth gradually became steady from the fast lane (left-hand lane) to the nearside lane (right-hand lane). In addition, irrespective whether

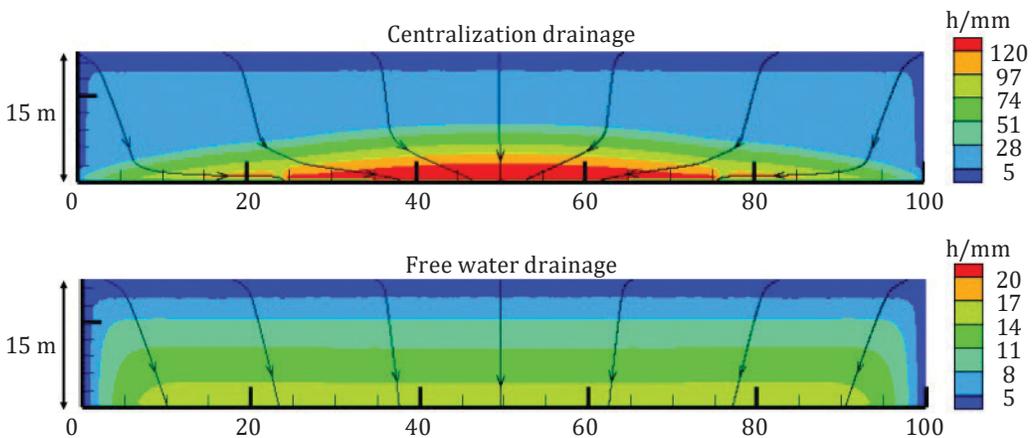


Figure 4. Pavement surface flow on the concave section

the centerline or free water drainage was adopted, the maximum water depth was always observed on the nearside lane. An obvious increase of pavement water depth would specifically occur in the nearside lane when the centerline drainage is adopted, and the depth might be up to over 80 mm (Figure 5). In Figure 5, Lanes 1, 2, and 3 are named on the pavement from the median strip to the nearside lane, and the observation points are the wheel traces of each lane along the driving direction. While in other lanes, the water depth was basically lower than 10 mm, which was almost the same as the condition under free water drainage. It can be concluded that the nearside lane should not be ignored when the outlets are adopted, so a reasonable curb height is significant for preventing inundation in the nearside lane, which depends on the rainfall, pavement width, and slope.

3.1.2. Circular curve section

The pavement runoff of the circular curve section is shown in Figure 6. Along the direction of the cross slope, the volume of water remaining on the pavement increased along with the increase of the distance to the median strip. Along the longitudinal gradient, it was obvious that the downstream inundation situation might be worse. The streamline of the pavement water depth was in line with the direction of the longitudinal gradient under free water drainage. In case of the centerline drainage affected by the curbs outside, backwater could occur in nearside lanes. The overall variation of pavement water flow was similar to the condition for the concave section because of the same

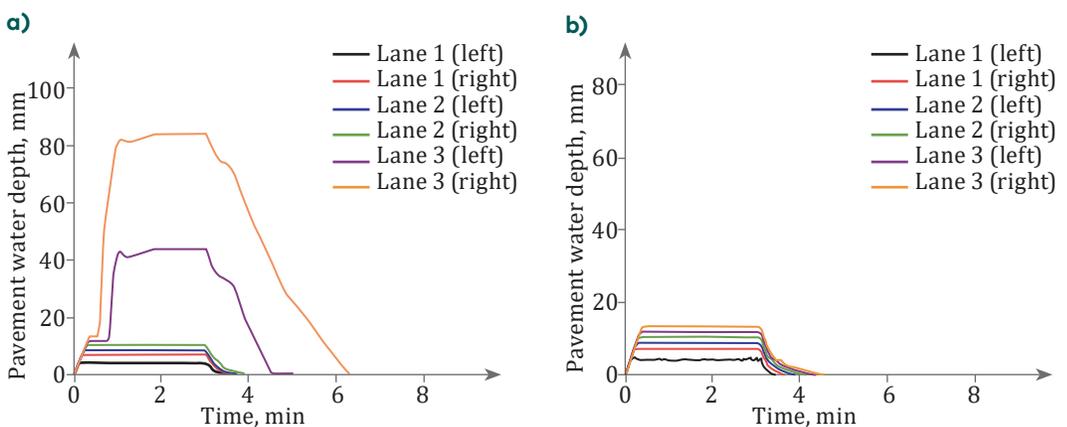


Figure 5. Pavement water depth of the concave section: a – Centerline drainage; b – Free water drainage

cross slope and longitudinal gradient. It should be noted that the water does not flow outside the pavement from the nearest outlet, but may flow into the outlet downstream under the influence of the longitudinal gradient. Therefore, the outlet size, width and location interval should be considered for effective pavement drainage.

As it could be seen in Figure 7, characteristics of the pavement water depth variation of the circular curve section were the same as those of the concave section. The comparison of water depth under free water drainage and centerline drainage showed that the drainage type only influenced the pavement water depth variation in the nearside lane,

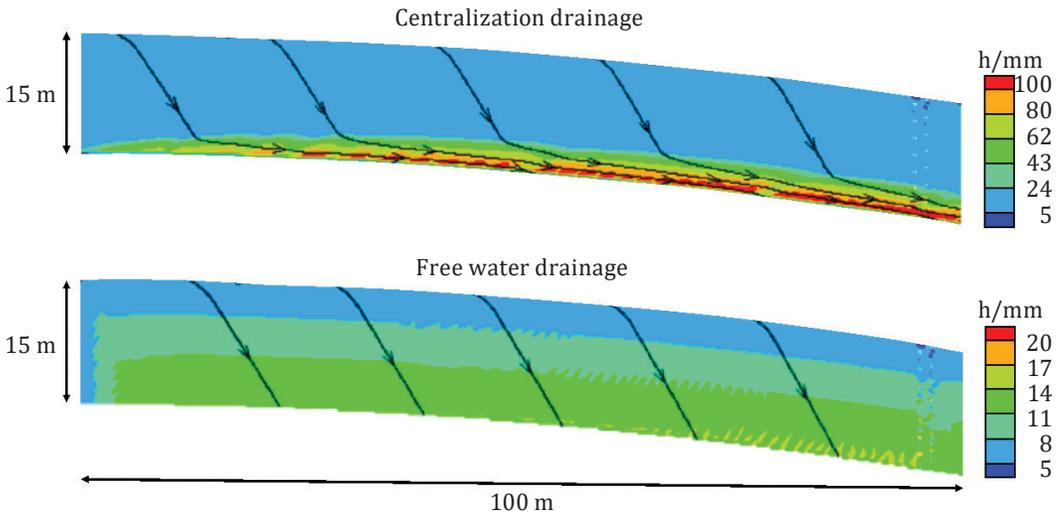


Figure 6. Pavement surface flow on the circular curve section

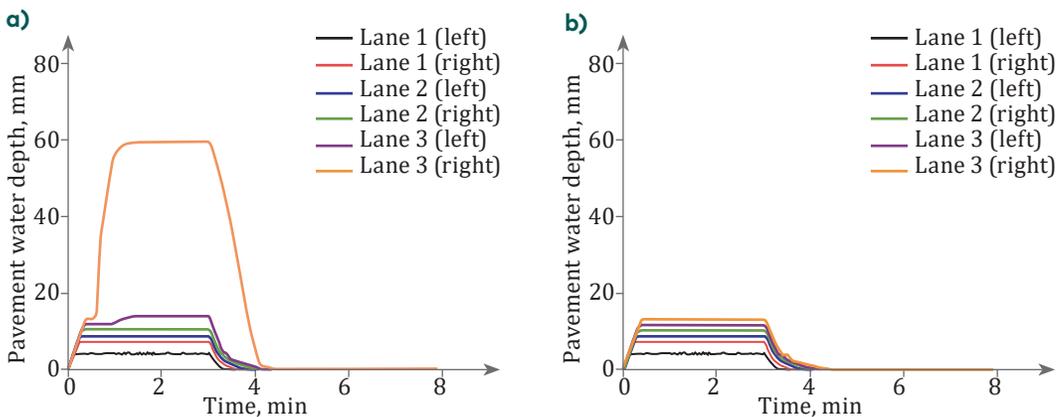


Figure 7. Pavement water depth of circular curve section: a – Centralization drainage; b – Free water drainage

no matter which drainage type was adopted. However, in case of the centerline drainage, the road surface runoff in the nearside lane could easily reach the maximum depth. The pavement water depth in each lane was below 20 mm for free water drainage, while the maximum water depth in the nearside lane could be almost 60 mm for centerline drainage. The increment of depth (more than 40 mm) will inevitably have impact on the driving safety.

3.2. Driving safety

Hydroplaning depth is usually used to evaluate the pavement driving safety on rainy days. The notion of hydroplaning depth implies that the lifting force of the runoff under the tire is greater than the gravity of the vehicles. The presence of the water film leads to insufficient contract between the tire and the pavement. Thus, sufficient friction cannot be provided on an inundated road surface. The hydrodynamic pressure will lift the tire from the pavement surface for an instant when high speed is reached (Lantieri et al., 2015). As a result, vehicle stability inevitably decreases. It is important to consider not only stability in the vertical, but also the horizontal plane. The runoff depth in the fast lane is small, but the water depth under left and right wheels of the vehicle may greatly differ. It is likely to cause sideslip of the vehicles when the difference in water depth is great (Zhang, 2016). So, in this part, the difference of the runoff depth between two tires is considered.

The angle difference $\Delta\alpha$ can represent stability of the driving vehicle (Zhang et al., 2014), it can be defined by equation (5):

$$\Delta\alpha = \frac{L_1 - L_2}{d}, \quad (5)$$

where,

$$L_1 = V_{t,x} \cdot t - \frac{1}{2}a_1t^2, \quad (6)$$

$$L_2 = V_{t,x} \cdot t - \frac{1}{2}a_2t^2, \quad (7)$$

$$a_1 = \frac{F_1}{m}, \quad (8)$$

$$a_2 = \frac{F_2}{m}. \quad (9)$$

So, according to equations (6-9), the angle difference $\Delta\alpha$ can be calculated by equation (10):

$$\Delta\alpha = \frac{F_2 - F_1}{2md} \cdot t^2, \quad (10)$$

where L_1 is the displacement of the left tire, m; L_2 is the displacement of the right tire, m; d is the distance between the front wheels, m; $V_{t,x}$ is the speed of the wheel, km/h; t is time, s; a_1 is the longitudinal acceleration of the left tire, m/s²; a_2 is the longitudinal acceleration of the right tire, m/s²; F_1 is the friction between the left tire and pavement, N; F_2 is the friction between the right tire and pavement, N; and m is the mass of the vehicle, kg.

It is generally believed that the vehicle can be controlled to ensure safety when the steering wheel is rotated by less than 90°, meaning that a certain duration (1–2 s) is needed. Therefore, when the vehicle enters the watered area, the relative lateral angle in the first two seconds should be calculated. The distance between the front wheels and such tire parameters as its type and dimensions have been discussed in the study carried out by Zhang et al. (2014), who analyzed the relationship between the vehicle speed and tire-pavement friction. The average tread depth (7 mm) is calculated based on the statistical data (8–10 mm for new tires) (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2015; Zhang, 2014; Dong et al., 2012). As shown in Table 1 and Table 2, the variation of relative lateral angle difference corresponding to water depth difference between the left and right tires at different driving speeds was calculated according to equation (5).

In order to improve the driving stability, the angle of the left and right deflection of the vehicles should be kept within 25°. This means that the driving safety is sufficiently good without the influence of the runoff on the pavement surface when the vehicle is driven into the inundation area 1 s later. Considering Table 5, it may be concluded that sideslip would occur when the depth difference became more than 6 mm under condition that the runoff depth was less than the tread depth (7 mm). Table 6 illustrates that sideslip would occur when the depth difference became more than 4 mm under condition that the runoff depth was more than the tread depth (7 mm).

According to the specifications for highway alignment (JTG D20-2017) (Ministry of Transport of the People's Republic of China, 2017) and engineering practice, the values of alignment indexes for the concave section and circular curve section were set in Table 3. Based on the simulation results of different cases, the difference in water depth at the observation points in each lane was shown in Figure 8. It has been demonstrated that for both concave section and circular curve section, the water depth difference in three lanes was less than 4 mm, satisfying the safety requirements. Comparing different lanes, the difference in

water depth under left and right wheels of the vehicle in the fast lane was always the largest, and the difference gradually decreased from the fast lane to the nearside lane. For the concave section, the difference in water depth of the fast lane in Case 1 could be more than 3 mm, which was the largest among three cases. While for the circular curve section, the largest water depth difference was in the fast lane of Case 6. That means hydroplaning is more likely to occur in the fast lane than in other lanes.

Table 1. Deflection angle when the runoff depth is less than 7 mm

Time	Vehicle speed, km/h	Difference in water depth between the left and right tires, mm					
		2	3	4	5	6	7
1 s	V<100	4.8°	7.2°	9.5°	11.9°	14.3°	16.7°
	later	100<V<120	7.2°	10.7°	14.3°	17.9°	21.5°
2 s	V<100	19.1°	28.6°	38.2°	47.7°	57.3°	66.8°
	later	100<V<120	28.6°	43.0°	57.3°	71.6°	85.9°

Table 2. Deflection angle when the runoff depth is more than 7mm

Time	Vehicle speed, km/h	Difference in water depth between the left and right tires, mm						
		2	3	4	5	6	7	
1 s	V<90	7.2°	10.7°	14.3°	17.9°	21.5°	25.1°	
	later	90<V<100	9.5°	14.3°	19.1°	23.9°	28.6°	33.4°
	100<V<120	11.9°	17.9°	23.9°	29.8°	35.8°	41.8°	
2 s	V<90	28.6°	43.0°	57.3°	71.6°	85.9°	100.3°	
	later	90<V<100	38.2°	57.3°	76.4°	95.5°	114.6°	133.7°
	100<V<120	47.7°	71.6°	95.5°	119.4°	143.3°	167.1°	

Table 3. Values of different alignment indexes (width: 15 m)

Case	Cross slope, %	Radius of the vertical curve, m	Longitudinal gradient difference, %
1	1	4000	10
2	2	6000	3
3	3	5000	5
Case	Cross slope, %	Curve radius, m	Longitudinal gradient, %
4	3	650	2
5	4	1000	0.3
6	2	1500	0.8

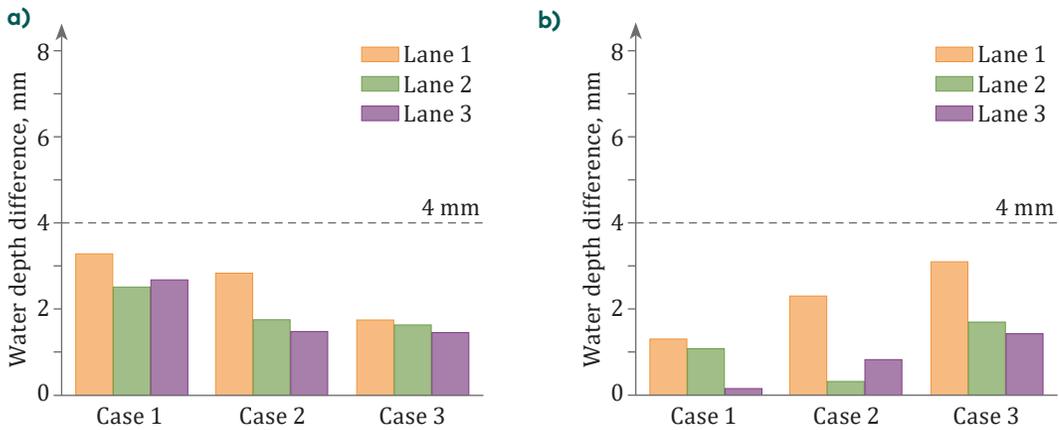


Figure 8. Water depth difference at the observation points in each lane:
a – Concave section; b – Circular curve section

Conclusions

Pavement water distribution on the concave section and circular curve section has been compared for the free water drainage and centerline drainage. According to the variation of water depth, driving safety has been evaluated considering the difference of the runoff depth between two tires. The following conclusions can be drawn.

Depending on the slope of the road, pavement inundation tends to persist in the downstream locations. The drainage type affects the variation of the runoff depth in the nearside lane, and the maximum water depth can be up to more than 80 mm in the concave section and nearly 60 mm in the circular curve section in case of the centerline drainage. When the curbs are installed, the direction of the runoff flow is not consistent with the resultant gradient. This fact also proves that a two-dimensional model is essential for the analysis of the centerline drainage. The runoff depth can be controlled by a reasonable curb height and location interval.

In order to ensure the driving safety on rainy days, the difference in water depth under the left and right wheels of the vehicle should be taken into consideration. Sideslip will occur when the depth difference becomes more than 6 mm under condition that the runoff depth is less than the tread depth (7 mm). When the runoff depth is more than the tread depth, sideslip will occur once the depth difference becomes more than 4 mm. Besides the existing hydroplaning results, the runoff depth

difference of the wheel trace should be considered to evaluate driving safety.

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Disclosure Statement

The authors declare no conflict of interest.

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