Journal of Urban Development and Management
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An Analytical Investigation into the Water Film Dynamics at the Connection Lines of Highways and Urban Roadways

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Received: 11-07-2023 **Revised:** 12-09-2023 **Accepted:** 12-15-2023

Citation: S. Shao, P. Tian, H. H. Zhang, H. Zhang, H. Zhang and L. Li, "An analytical investigation into the water film dynamics at the connection lines of highways and urban roadways," *J. Urban Dev. Manag.*, vol. 2, no. 4, pp. 181–194, 2023. https://doi.org/10.56578/judm020402.

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Abstract: This study uses BIM software and fluid simulation finite element analysis software to investigate the impact of the water film effect on the surfaces where highways connect with urban roads. The analysis indicates that the drainage length (L), road surface slope (i), rainfall intensity (I), and road surface construction depth (T) are significant factors affecting the thickness of the water film (H) generated by the said effect. The thickness of the water film grows with an increase in drainage length and rainfall intensity; however, it decreases with an increase in road surface slope and road surface construction depth. The approximate relationship between the water film thickness and these four influencing factors is $\mathrm{H} \propto \mathrm{L}^{4.02655} \mathrm{i}^{-1.65562}(0.87\mathrm{I}+1.26)\left(4.07-0.17\,\mathrm{T}-0.13\,\mathrm{T}^2\right)$. When the water film is thin, the area occupied by the water film in front of the car tires is small; as the thickness of the water film increases, the area it occupies gradually increases, and the tires are gradually lifted by the water film. When lifted to a certain height, the "hydroplaning" phenomenon occurs, which can lead to traffic safety issues. The results of this study are expected to provide a reference for related research on connection lines.

Keywords: BIM; Influencing factors; Fitting equation; Finite element analysis

1 Introduction

To avoid issues such as unclear functionality, mismatched connections, and abrupt cross-sectional changes when highways merge with urban roads, a connection line is needed to facilitate this transition. In rainy weather, a thin layer of water accumulates on the road surface, forming a water film of certain thickness, which reduces the friction between the tires and the road surface, leading to the phenomenon of "hydroplaning". The thickness of the water film is an important factor affecting road traffic safety. Analyzing the dynamics of the water film on the road surface is fundamental for studying various issues from road safety to urban drainage, and is also crucial for both drivers and autonomous driving systems of vehicles [1–5]. The thickness of the water film is influenced by many factors, such as tire tread design, load, speed, road surface slope, and road surface construction depth [6, 7]. In recent studies, BIM is used as a digital tool in the infrastructure field, providing digital support in areas such as asphalt pavement design and management decisions for roads, intersection design and traffic analysis, and planning, modeling, analysis, and flood management of water supply and drainage networks [8–11]. CFD-related software, capable of providing multiphase flow models based on the finite volume method, can simulate and analyze fluid dynamics problems. Therefore, this paper builds upon previous research and considers using software like Open Roads Designer (ORD), Revit, and Fluent for simulation, to study the relationship between different drainage lengths, road surface slopes, rainfall intensities, and road surface construction depths with the thickness of the water film effect on the connection line, as well as the distribution of water flow around patterned tires at different water film thicknesses, to provide theoretical support and methodological guidance for the design of the connection line.

2 Highways, Urban Roads, and Connection Lines

2.1 Definition of Highways and Urban Roads

As defined by the *Design Specification for Highway Alignment* and *Technical Standard of Highway Engineering* [12, 13], highways can be classified into five technical grades: expressways, first-class highways, second-class highways, third-class highways, and fourth-class highways, among which expressways are the highest grade, characterized by segregated lanes, directional separation, and fully controlled entry and exit points in terms of form and quantity. In the *Code for Design of Urban Road Alignment* and *Code for Design of Urban Road Engineering* [14, 15], urban roads are divided into four technical grades: expressways, arterial roads, secondary arterial roads, and branch roads. Urban expressways are the highest grade of urban roads, providing large-capacity, long-distance, and fast transportation services within the city. Both highways and urban roads serve the function of transportation, with highways handling the external transportation of the city and urban roads managing the internal transportation process. With rapid economic development and the continuous improvement of people's living standards, the frequency of personnel and material exchanges within and between cities has increased. Therefore, the effective and smooth connection of highways and urban roads is a prerequisite for completing the city's external transportation.

2.2 Definition of Connection Lines

Connection lines are the transitional sections between highways and urban roads, also known as connecting roads. In the *Guideline for the Connection Planning and Design of Highway and Urban Road* [16], connecting roads refer to the transitional roads between highways and urban roads. This guideline provides relevant information on the planning and design of networks, sections, nodes, and signs for the connecting part, offering guidance for new or reconstructed connecting road projects. At the same time, connecting roads must consider the standards of both highways and urban roads. Typically, connecting roads near the urban end are planned and designed based on the demands of urban roads in terms of cross-sectional design, drainage methods, etc. For connecting roads at the far end from the city, the aforementioned aspects should meet the requirements of highways in the short term while also considering the potential expansion of the city in the long run, leading to the transformation of highways into urban roads.

3 The Phenomenon of Water Film Effect

The phenomenon of the water film effect refers to the formation of a thin layer of accumulated water on the road surface during rain, snowmelt, or road washing, resulting in the creation of a water film with a certain thickness on the road surface. This film reduces the friction between the tires and the road surface, leading to instability and safety issues during driving. When there is water on the road surface, the wheels compress the water during movement, forming a friction area mediated by the liquid water. This liquid water film can reduce the friction coefficient between the tires and the road surface, causing the wheels to lose some of their grip, and thus reducing the driver's control during turning, accelerating, braking, or changing lanes. On highways, cars travel at high speeds, and when the driver needs to leave the highway and enter urban roads through a connection line, the car will reduce its speed. If during rain, snowmelt, or road washing, the road has poor drainage or flooded areas, and the driver reduces speed excessively or brakes suddenly, the water film effect can occur, eventually leading to the so-called "hydroplaning", a phenomenon likely to occur in areas of super-elevation, especially in regions where the longitudinal slope is relatively flat.

In summary, the water film effect is the least known yet one of the most dangerous situations. In traffic accident statistics, wet road surfaces dominate, far exceeding all other weather-related factors. Therefore, it is necessary to study the water film effect on connection lines and analyze its influencing factors. On the one hand, this provides theoretical support for the design of connection lines, and on the other hand, it helps to avoid traffic accidents caused by the water film effect on these lines.

4 Analysis of the Impact of Water Film Effect on Connection Line Surfaces

If a water film is formed on the connection line between highways and urban roads, it will separate the car tires from the road surface, significantly reducing the friction coefficient between the tire and the road, eventually leading to the so-called "hydroplaning" phenomenon. The road water film is influenced by various factors, including the degree of road surface slipperiness, tire condition such as tire type and tread depth, vehicle speed, rainfall intensity, drainage length, and road conditions such as road surface slope and road surface construction depth. Therefore, this section studies the relationship between different drainage lengths, road surface slopes, rainfall intensities, road surface construction depths, and the thickness of the water film produced by the water film effect on the connection line, as well as how different water film thicknesses affect the distribution of water flow around the tires, to determine the impact of the water film effect on the surfaces of connection lines.

This study of the relationship between the aforementioned four factors and water film thickness uses the 3D terrain model of the Southeast Lake Avenue project, specifically the newly constructed junction of Southeast Lake Avenue and the Ring Expressway, as shown in Figure 1. The road 3D model is established using the information in Table 1 about the width of connecting road lanes in the form of a plane-connected road embankment, as well as partial information from the Southeast Lake Avenue project.

Table 1. Lane width information

Connection Form	Road Category	Number of Bidirectional Lanes	Width per Lane (m)	Total Width of Single Direction Lanes (m)
Plane Connection	Highway	8	3.75	15
	Urban Arterial Road	10	3.5	17.5
	Connecting Road	22	5.4[Note]	59.4

Note: The width of the connecting road needs to consider the size of the toll islands. Therefore, the lane width in this table refers to the distance between the centerlines of two adjacent toll islands, including the width of a single lane.

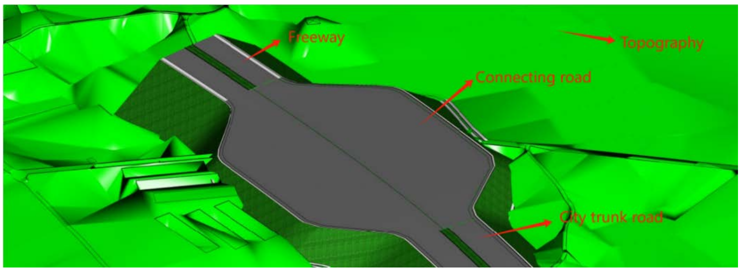


Figure 1. 3D terrain and road model

4.1 Relationship Between Drainage Length and Water Film Thickness

This study specifically focuses on the calculation and distribution of road surface water film thickness along the cross slope direction of the road arch. Therefore, the consideration of drainage length is limited to the width of a single driving lane [17]. In terms of the connection between highways and urban roads, whether it is a plane connection or an interchange connection, the biggest difference in the connecting road section is the number of connection lanes: the number of lanes in plane connection is more than that in interchange connection, which ultimately leads to different drainage lengths. Therefore, this study chooses the plane connection method, which has a larger number of lanes, to discuss the relationship between drainage length L and water film thickness H.

Based on the aforementioned 3D terrain and road model, the water film effect feature of ORD is utilized, and the controlled variable method is adopted for exploring the relationship between drainage length and water film thickness. The road surface slope (i) is set at 1.5%; the rainfall intensity (I) is calculated using the formula for a 3-year recurrence period of heavy rainfall in Changchun city, which is 3.033mm/min or 181.98mm/h; the interval of water flow is 5m; and the road surface texture depth (T), or construction depth, is 0.7mm.

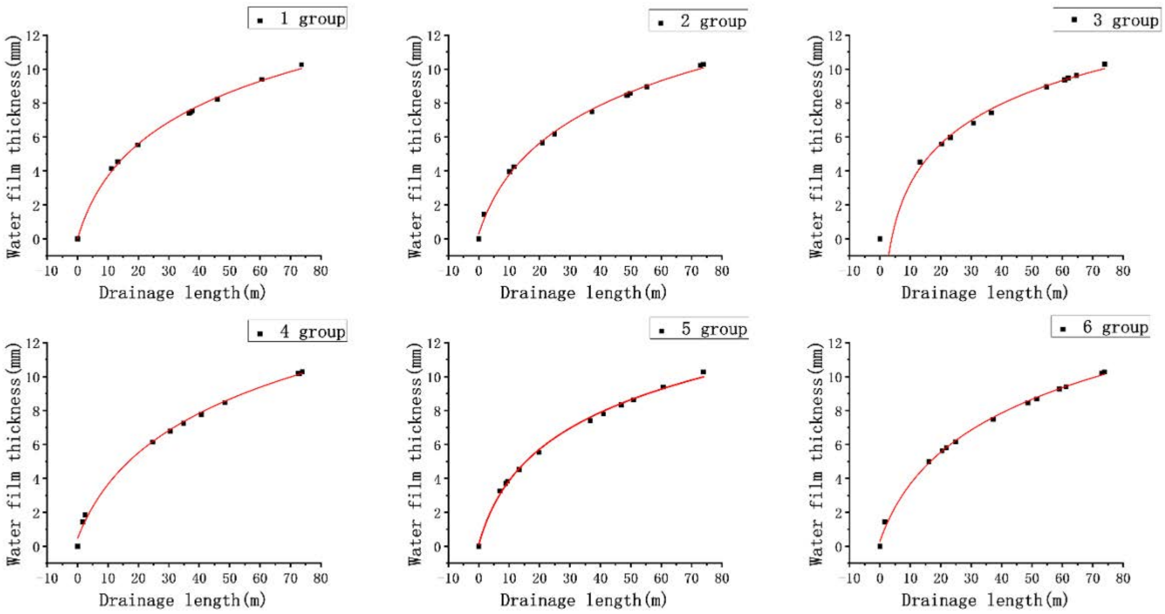


Figure 2. Relationship between drainage length and water film thickness in plane connection

As shown in Figure 2, six different flow lines were selected to explore the relationship between road surface drainage length and water film thickness in the form of plane connection. Regression analysis of the above data yields a series of formulas:

$y = 4.02128\ln(x + 6.63928) - 7.60214, R^2 = 0.9988,$ Significance $= 0.003$

$y = 4.09101\ln(x + 7.43728) - 7.91703, R^2 = 0.99696,$ Significance $= 0.0005$

$y = 3.39546\ln x - 4.57799, R^2 = 0.99162,$ Significance $= 0.000009$

$y = 4.54036\ln(x + 9.81395) - 9.90719, R^2 = 0.9968,$ Significance $= 0.0003$

$y = 3.78606\ln(x + 5.85651) - 6.59475, R^2 = 0.99728,$ Significance $= 0.001$

$y = 4.32515\ln(x + 8.44169) - 8.93407, R^2 = 0.99753,$ Significance $= 0.00008$

Summarizing the above six formulas, the approximate relationship between the water film thickness (H) and drainage length (L) in the plane-connected form can be expressed as $\mathrm{H} \propto \mathrm{L}^{4.02655}$.

From Figure 2, selecting any set of water film thickness and drainage length data for nonlinear curve fitting, such as set 1, yields an R^2 of 0.9988, close to 1, indicating a good fit; the significance value of 0.003 is less than 0.05, indicating significance. Under certain conditions of rainfall intensity, road surface slope, and road surface construction depth, the water film thickness increases nonlinearly with the increase in drainage length. This is mainly because an increase in drainage length means an increase in the dispersion area of the water flow, which reduces the flow rate of the water and increases the thickness of the water film. Also, an increase in drainage length extends the time water flows on the surface, allowing water to stay on the road surface longer, forming a thicker water film. The variation in water film thickness with drainage length follows a pattern from large to small, especially within the 0-20m range of drainage length, where the change in water film thickness is greatest. This phenomenon may be due to water loss during road surface flow; initially, water loss is small, but as water flows on the road surface, it increases due to evaporation, percolation, etc., although not enough to offset the increasing trend of water film thickness, eventually slowing down the increase. To effectively prevent a significant increase in water film thickness, it is necessary to ensure that the drainage length on the connection line is kept small. Therefore, drainage length is an important factor affecting water film thickness and can be a measure to improve the water film effect, that is, appropriately reducing the drainage length of the connection line.

4.2 Relationship Between Road Surface Slope and Water Film Thickness

Highways and urban roads may adopt different cross-slope values, leading to significant changes in cross-slope when connecting roads are integrated, ultimately affecting the thickness of the water film.

Road surface slope includes longitudinal slope, cross-slope, and composite slope. In reality, the impact on water film thickness is influenced by all three types of slopes. However, to qualitatively study the impact of road surface slope on water film thickness, and based on analysis by Zhang and Zhang [18] of the impact of road surface slope on water film thickness, it shows that the impact of cross-slope on water film thickness is greater than that of longitudinal slope. Therefore, cross-slope should be considered as the main influencing factor. Thus, in this study, road surface slope is considered as the cross-slope, with the impacts of longitudinal slope and composite slope on water film thickness to be further researched and analyzed.

To better study the relationship between the cross-slope of the connecting road and the thickness of the water film, the range of cross-slope values is set between 0.5%-4.5%. The research method for road surface slope is consistent with that of drainage length, using the controlled variable method. First, other influencing factors are set to fixed values, namely drainage length L at 31.5m; rainfall intensity I at 3.033mm/min; flow interval at 5m; road surface construction depth T at 0.7mm. Then, by changing the road surface slope values in the simulation model, the results of water film thickness are obtained, and finally, the relationship between road surface slope and water film thickness is analyzed.

As shown in Figure 3, six sets of data are selected to explore the relationship between road surface slope i and water film thickness H. Regression analysis of the above data yields the following series of formulas:

$y = -2.35549\ln(x - 0.44878) + 6.46387, R^2 = 0.9968,$ Significance $= 0.01$

$y = -2.54165\ln(x - 0.41233) + 6.89397, R^2 = 0.99713,$ Significance $= 0.006$

$y = -2.05804\ln(x - 0.4713) + 5.65405, R^2 = 0.9974,$ Significance $= 0.03$

$y = -1.57654\ln(x - 0.48371) + 4.469, R^2 = 0.99904,$ Significance $= 0.02$

$y = -1.0918\ln(x - 0.45786) + 3.06409, R^2 = 0.99963,$ Significance $= 0.04$

$y = -0.31018\ln(x - 0.45721) + 1.79481, R^2 = 0.99523,$ Significance $= 0.02$

Summarizing the above six formulas, the approximate relationship between water film thickness H and road surface slope i is $\mathrm{H} \propto \mathrm{i}^{-1.65562}$.

From the six sets of data in Figure 3, it can be concluded that under certain conditions of rainfall intensity, drainage length, and road surface construction depth, the thickness of the water film decreases as the road surface slope increases. This inverse relationship is mainly because when the road surface slope increases, the tendency of water to flow downwards under the influence of gravity strengthens, thereby increasing the drainage speed of runoff on the slope, allowing rainwater on the road surface to be quickly drained, thereby reducing the water film's dispersion capability. When the cross-slope is less than 3%, the trend of decrease in water film thickness is relatively fast, for example, for the first set, the water film thickness at a cross-slope of 0.5% is 13.451mm to 4.188mm at a cross-slope of 3.0%; for the third set, the water film thickness at a cross-slope of 0.5% is 12.956mm to 3.676mm at a cross-slope of 3.0%. When the cross-slope is greater than 3%, the trend of decrease in water film thickness becomes slightly slower, basically decreasing in a linear fashion, such as for the first set, the water film thickness at a cross-slope of 3.0% is 4.188mm to 3.368mm at a cross-slope of 4.5%; for the third set, the water film thickness at a cross-slope of 3.0% is 3.676mm to 2.971mm at a cross-slope of 4.5%. In practical engineering projects, when the road width and longitudinal slope are fixed, the cross-slope can be appropriately increased within the allowable range to reduce the thickness of the water film, thus avoiding the harm caused by the water film effect on driving safety. Therefore, road surface slope is also an important influencing factor on water film thickness and can be a measure to improve the water film effect, that is, appropriately increasing the cross-slope of the connection line surface.

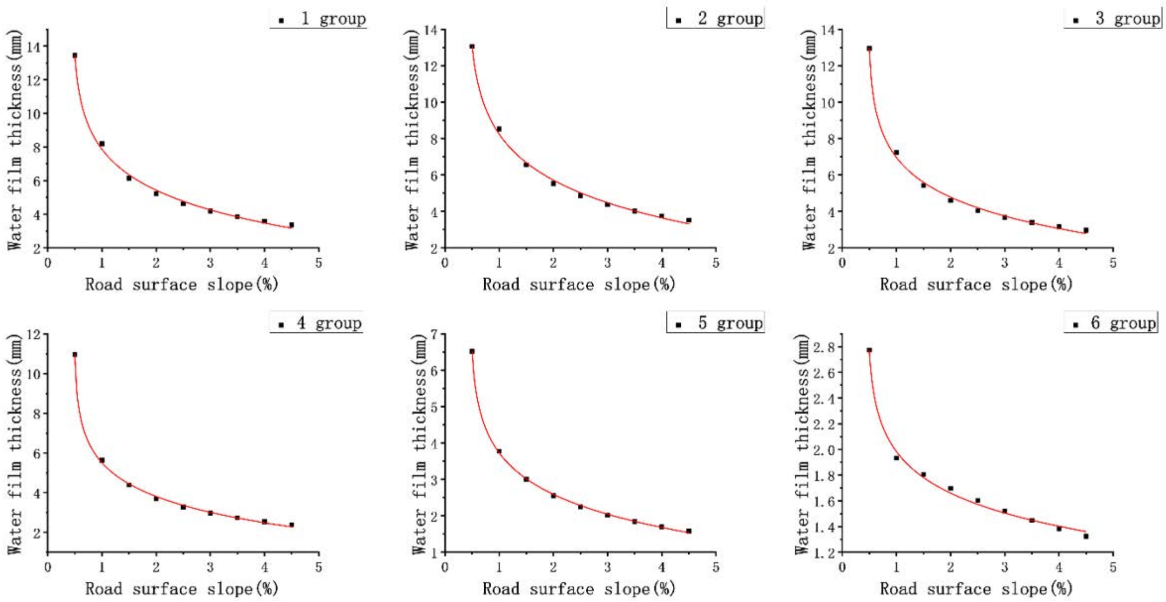


Figure 3. Relationship between road surface slope and water film thickness

4.3 Relationship Between Rainfall Intensity and Water Film Thickness

Rainfall intensity is an important factor affecting the thickness of the water film, so the magnitude of the rainfall intensity is not to be overlooked. According to the standards [19–21], the recurrence period for urban stormwater drainage is 3 years; for highways, the designed rainfall recurrence period for surface and shoulder drainage is 5 years, for the slopes within the road boundary is 15 years, and for the subgrade surface drainage facilities is 15 years. Therefore, to study the relationship between water film thickness and rainfall intensity on connecting roads, the rainfall recurrence periods chosen are 1, 2, 3, 5, 10, and 20 years, and their corresponding storm intensity formulas are based on the new-generation storm intensity formulas for Changchun city of China derived by Liu et al. [22]. The specific formulas are shown in Table 2.

In Table 2, q represents storm intensity, $L/(s \cdot hm^2)$; t is the duration of rainfall, min; P is the recurrence period, years; A_1, C, b, n are parameters corresponding to different recurrence periods. Based on the above formulas for different rainfall recurrence periods, the storm intensities I for each recurrence period were calculated to be: 1-year 2.345mm/min; 2-year 2.778mm/min; 3-year 3.033mm/min; 5-year 3.347mm/min; 10-year 3.824mm/min; 20-year 4.271mm/min.

The study of the relationship between water film thickness and rainfall intensity follows the same approach as the previous two sections. The controlled variable method is used. First, the same type of water flow line is chosen, and other influencing factors are set to fixed values, namely drainage length L at 31.5m; road surface slope i at 1.5%; flow interval at 5m; road surface construction depth T at 0.7mm. Then, by changing the rainfall intensity values in the simulation model, the results of the water film thickness are obtained, and finally, the relationship between rainfall intensity and water film thickness is analyzed.

From the fitting results shown in Figure 4, it is evident that the relationship between rainfall intensity and water film thickness differs from the nonlinear relationships between drainage length, road surface cross-slope, and water film thickness discussed in the previous two sections. While drainage length and road surface cross-slope are nonlinearly related to water film thickness, rainfall intensity and water film thickness exhibit a linear relationship, as demonstrated by the following formulas:

$y = 1.38433x + 2.40698, R^2 = 0.99856, \text{ Significance } = 0.00003$

$y = 1.30454x + 2.22743, R^2 = 0.99862, \text{ Significance } = 0.00007$

$y = 0.93299x + 1.39372, R^2 = 0.9986, \text{ Significance } = 0.01$

$y = 0.59976x + 0.648, R^2 = 0.99861, \text{ Significance } = 0.04$

$y = 0.51355x + 0.45191, R^2 = 0.9986, \text{ Significance } = 0.004$

$y = 0.51235x + 0.45084, R^2 = 0.99861, \text{ Significance } = 0.004$

Table 2. Lane width information

General Formula for Storm Intensity	Recurrence Period/Year	A_1	C	b	n	Specific Formula for Storm Intensity
$q = \frac{167A_1 \cdot (1+\text{CLgP})}{(t+b)^n}$	1	14.5	-	9.2	0.822	$q = \frac{2422}{(\text{t}+9.2)^{0.822}}$
	2	14.9	0.44	9.4	0.806	$\text{q} = \frac{2488*(1+0.44\,\text{LgP})}{(\text{t}+9.4)^{0.806}}$
	3	14.9	0.64	9.8	0.815	$\text{q} = \frac{2488*(1+0.64\,\text{LgP})}{(\text{t}+9.8)^{0.815}}$
	5	14.9	0.65	10	0.812	$\text{q} = \frac{2488*(1+0.65\,\text{LgP})}{(\text{t}+10)^{0.812}}$
	10	14.7	0.68	10	0.811	$\text{q} = \frac{2455*(1+0.68\,\text{LgP})}{(\text{t}+10)^{0.811}}$
	20	14.4	0.67	10	0.801	$\text{q} = \frac{2405*(1+0.67\,\text{LgP})}{(\text{t}+10)^{0.801}}$

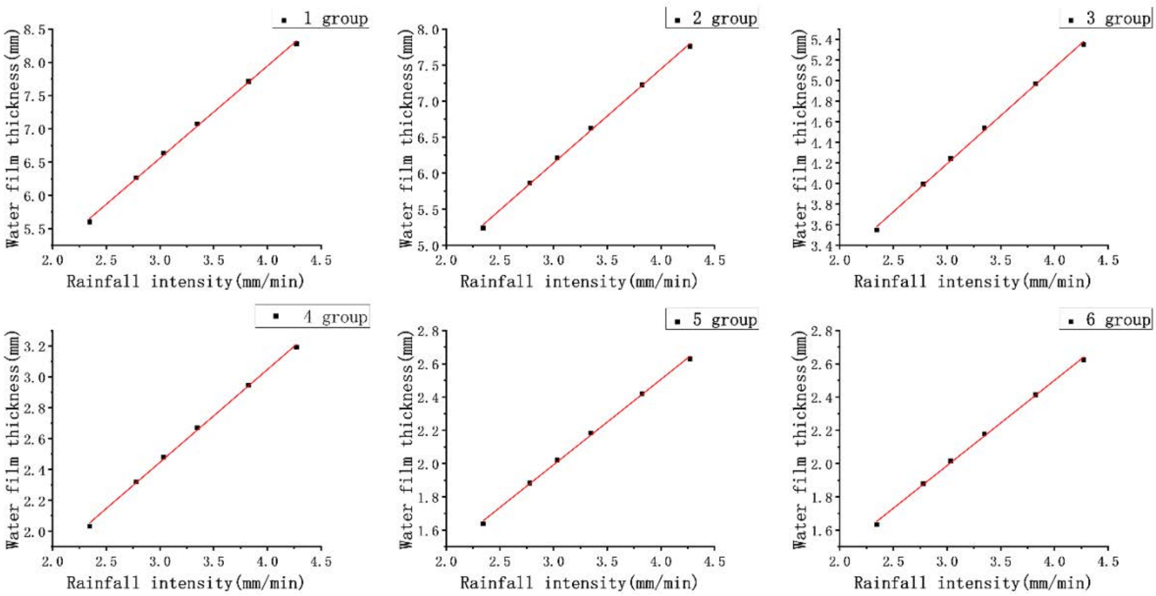


Figure 4. Relationship between rainfall intensity and water film thickness

Summarizing the above six formulas, the approximate relationship between water film thickness H and road surface slope i is H=0.87I+1.26.

Based on the six relationship curves in Figure 4, it can be concluded that under certain conditions of drainage length, road surface slope, and road surface construction depth, the water film thickness is linearly correlated with rainfall intensity, increasing as the rainfall intensity increases. This phenomenon is due to the fact that an increase in rainfall intensity means more rainwater per unit time, leading to an increase in water accumulation on the road surface. Road drainage systems have a certain capacity limit and cannot quickly drain large amounts of water. When the amount of water exceeds the road surface construction depth, a water film forms on the road surface. The greater the intensity of the rain, the more water accumulates, thereby increasing the thickness of the water film. Additionally, increased rainfall intensity can accelerate the water flow speed on the road surface. Higher water flow speeds can act as a scouring force, washing away accumulated impurities, sediment, and other materials from the road surface, further increasing the thickness of the water film. In areas with high rainfall intensity, such as in regions with a 10-year or 20-year rainfall recurrence period, the hazards posed by the water film thickness are greater. This is an important reason why traffic accidents are more likely to occur during heavy rain or stormy weather compared to lighter rain. From the six sets of curves showing the relationship between rainfall intensity and water film thickness, it can be seen that the increase in water film thickness corresponding to the rainfall intensity from a 2-year recurrence period of 2.778mm/min to 3-year at 3.033mm/min, and from 3-year at 3.033mm/min to 5-year at 3.347mm/min, is smaller than that for other rainfall recurrence periods. Therefore, rainfall intensity is an important influencing factor on water film thickness, and in areas with high rainfall intensity, measures should be taken to address the water film effect phenomenon to avoid the associated traffic hazards.

4.4 Relationship Between Road Surface Construction Depth and Water Film Thickness

Construction depth refers to the depth of open voids on the road surface within a specified area, also known as macrotexture depth. Depending on the location of the test area and the model used for calculation, it is commonly abbreviated as TD, SMTD, MPD, etc., and is measured in millimeters [23]. Road surface construction depth TD specifically refers to the average depth of the uneven open voids on a certain area of the road surface, which is an important indicator of road roughness. It is commonly used to assess the drainage performance, skid resistance, and macro roughness of the road surface. Road surface construction depth is also a factor affecting water film thickness, and many scholars have considered its impact when calculating water film thickness, incorporating it into their formulas.

Based on previous scholars' research [24–26] on road surface construction depth, this study focuses on the relationship between the construction depth of connecting road surfaces and water film thickness. The following six values of road surface construction depth are used for the study: 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm, and 3.0mm.

To study the relationship between water film thickness and road surface construction depth, the approach is consistent with the previous three sections, using the controlled variable method. First, the same type of water flow line is chosen and other influencing factors are set to fixed values, namely drainage length L at 31.5m; road surface slope i at 1.5%; flow interval at 5m; and rainfall intensity I at 3.033mm/min. Then, by changing the road surface construction depth values in the simulation model, the results of the water film thickness are obtained, and finally, the relationship between road surface construction depth and water film thickness is analyzed.

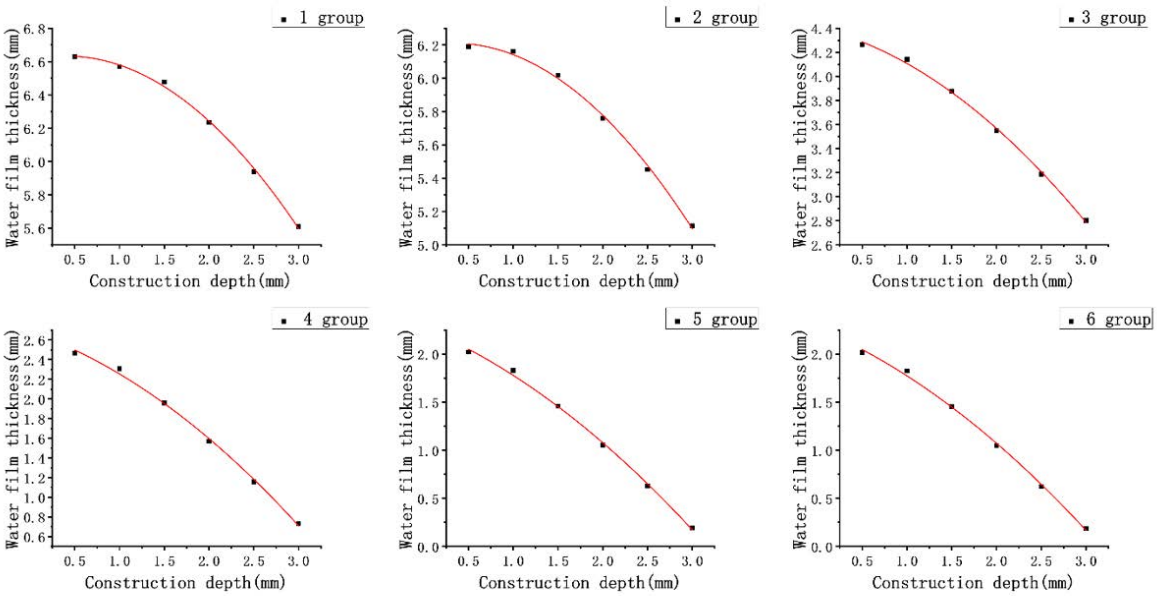


Figure 5. Relationship between construction depth and water film thickness

From the fitting results shown in Figure 5, it is evident that construction depth and water film thickness have a nonlinear relationship, which can be described by the following formulas:

$y = 6.6071 + 0.12676x - 0.15436x^2, R^2 = 0.99814,$ Significance $= 0.000006$

$y = 6.1915 + 0.10804x - 0.15764x^2, R^2 = 0.99766,$ Significance $= 0.00002$

$y = 4.4053 - 0.17692x - 0.12093x^2, R^2 = 0.99827,$ Significance $= 0.008$

$y = 2.6834 - 0.31623x - 0.11371x^2, R^2 = 0.99746,$ Significance $= 0.03$
$y = 2.2735 - 0.39218x - 0.10264x^2, R^2 = 0.998,$ Significance $= 0.04$
$y = 2.2694 - 0.39366x - 0.10229x^2, R^2 = 0.99796,$ Significance $= 0.04$

Summarizing the above six formulas, the approximate relationship between water film thickness H and construction depth T is $\mathrm{H} = 4.07 - 0.17\ \mathrm{T} - 0.13\ \mathrm{T}^2$.

From the relationship curve between construction depth and water film thickness in Figure 5, it can be seen that under certain conditions of drainage length, rainfall intensity, and road surface slope, the water film thickness decreases with the increase in construction depth. This phenomenon occurs because when the road surface construction depth is shallow, water more easily permeates the lower part of the road surface, forming a thicker water film. As the construction depth increases, the permeability of the lower part of the road surface weakens, resulting in less time for water to remain on the road surface, thereby increasing the friction between the car tires and the road surface, improving the tires' grip, and consequently reducing the formation of a water film on the road surface. From the figure, it can be observed that when the construction depth is less than 1.5mm, the trend of decrease in water film thickness is relatively slow, roughly following a curved downward trajectory; whereas when it is greater than 1.5mm, the water film thickness essentially decreases linearly, with a faster downward trend. Thus, construction depth is also an important factor affecting water film thickness, and it is possible to reduce water film thickness by appropriately increasing the construction depth within the specified range of values. The overall larger values of water film thickness calculated in the above simulation may be due to the focus on studying the relationship between construction depth and water film thickness changes, while keeping other influencing factors like rainfall intensity and cross-slope consistent with previous sections. Additionally, no drainage measures were taken during the simulation process, including the installation of pipelines or permeable road surface materials. Therefore, the formation of the water film is based on the natural trajectory of the water flow towards the sides of the road without considering external factors, and this does not affect the relationship between construction depth and water film thickness changes.

4.5 Impact of Different Water Film Thicknesses on Water Flow Distribution Around Patterned Tires

Different drainage lengths, road surface slopes, rainfall intensities, and road surface construction depths lead to varying thicknesses of the water film, which in turn affect the distribution of water flow around tires. Therefore, the study explores the distribution of water flow around patterned tires at different water film thicknesses using simulation models and finite element analysis software.

Before analyzing the distribution of water flow around patterned tires at different water film thicknesses, it is necessary to investigate the types of vehicles on the connection lines between highways and urban roads, focusing primarily on the connection lines near the urban end. The traffic data for this study was obtained through video recording with mobile devices and analyzed through video playback. Field traffic surveys were conducted based on the direct plane connection of Shenyang Qingnian Avenue and Danfu Expressway, and the interchange connection of Shenyang Lingyuan Street and the Ring Expressway. Table 3 and Table 4 present the traffic volumes in both the inbound and outbound directions for one hour at these two locations. On the Qingnian Avenue connection line, the total number of cars accounts for 96.18% of all types of vehicles; on the Lingyuan Street connection line, the total number of cars accounts for 90.31% of all vehicle types. Therefore, on the connection lines near the urban end, regardless of the type of connection, the vehicle type is predominantly cars.

Table 3. Traffic volume statistics of Qingnian Avenue connection line

Location	Direction	Turning	Vehicle Type	Number of Vehicles
Qingnian Avenue Connection Line	Urban Main Road → Highway	Straight	Car	2180
	Urban Main Road → Highway	Straight	Truck	64
	Urban Main Road → Highway	Straight	Large Passenger Vehicle	22
	Highway → Urban Main Road	Straight	Car	2048
	Highway → Urban Main Road	Straight	Truck	58
	Highway → Urban Main Road	Straight	Large Passenger Vehicle	24

Table 4. Traffic volume statistics of Lingyuan Street connection line

Location	Direction	Turning	Vehicle Type	Number of Vehicles
Lingyuan Street Connection Line	Highway → Urban Main Road	Left	Car	768
	Highway → Urban Main Road	Left	Truck	24
	Highway → Urban Main Road	Left	Large Passenger Vehicle	0
	Highway → Urban Main Road	Right	Car	220
	Highway → Urban Main Road	Right	Truck	26
	Highway → Urban Main Road	Right	Large Passenger Vehicle	0
	Urban Main Road → Highway (East Side)	Straight	Car	724
	Urban Main Road → Highway (East Side)	Straight	Truck	46
	Urban Main Road → Highway (East Side)	Straight	Large Passenger Vehicle	0
	Urban Main Road → Highway (East Side)	Straight	Moped	46
	Urban Main Road → Highway (East Side)	Straight	Bicycle	20
	Urban Main Road → Highway (East Side)	Left	Car	112
	Urban Main Road → Highway (East Side)	Left	Truck	10
	Urban Main Road → Highway (East Side)	Left	Large Passenger Vehicle	2
	Urban Main Road → Highway (West Side)	Straight	Car	706
	Urban Main Road → Highway (West Side)	Straight	Truck	72
	Urban Main Road → Highway (West Side)	Straight	Large Passenger Vehicle	2
	Urban Main Road → Highway (West Side)	Straight	Moped	32
	Urban Main Road → Highway (West Side)	Straight	Bicycle	12
	Urban Main Road → Highway (West Side)	Right	Car	712
	Urban Main Road → Highway (West Side)	Right	Truck	56
	Urban Main Road → Highway (West Side)	Right	Large Passenger Vehicle	0

Tires can be classified into bias tires and radial tires based on their structural characteristics. Radial tires are widely used due to their good durability and cushioning performance [27, 28]. From the previous traffic survey, it is known that the connection lines near the urban end are mainly used by passenger cars. Therefore, this study uses the size of the German Continental 205/55R16 91V radial tire for passenger cars as the reference for research object dimensions.

As shown in Figure 6, a 3D model of a patterned tire hydroplaning is established using the Revit family's standard model, which mainly includes the passenger car tire, water film, air, and road. The completed model is then imported into the finite element analysis software Fluent.

This simulation experiment focuses on water film thicknesses of 4mm, 6mm, 8mm, and 10mm. Considering the speed limits when cars enter the highway ramp and move towards the connecting road, this study simulates car speeds of v = 30km/h on different road surface water film thicknesses. Due to the presence of various errors, the simulation results can differ from actual results by 5%-10%. Therefore, based on previous research findings [29, 30], the fluid calculation domain on the connecting road is set to 800mm×600mm×50mm. The car tire model is positioned at the center of the entire calculation range. Figure 7 shows the three-dimensional finite element model of the patterned tire hydroplaning. During model mesh division, a tetrahedral mixed mesh is used, and the area around the tire is locally densified. Table 5 presents the fluid calculation domain mesh division for four different water film thicknesses of patterned tires.

Establishing appropriate boundary conditions is a prerequisite for all simulation and numerical calculations. Only with reasonable boundary conditions can true flow field conditions be simulated, leading to accurate computational results. The setup of boundary conditions for this study is shown in Figure 8. The model's front end features both air and water flow velocity inlets, with matching velocities based on the relative speed between the tire and fluid; the model's left and right sides are symmetrical and absolutely smooth and stationary; the top of the model is a wall surface, set to a symmetrical surface like the sides to facilitate computation. The interface between the tire and air/water is a stationary wall; the model's bottom is a moving wall, with the speed and direction matching that of air and water; the model's rear is set as a pressure outlet for the two-phase flow of air and water.

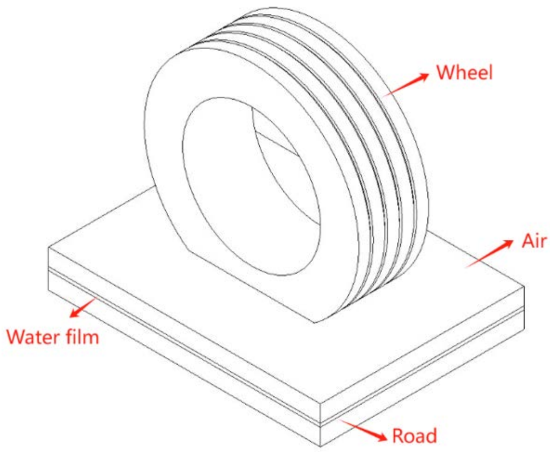


Figure 6. 3D model of patterned tire hydroplaning

Table 5. Traffic volume statistics of Qingnian Avenue connection line

Tire Type	Water Film Thickness (mm)	Number of Mesh Cells
Patterned Tire	4	794631
	6	817282
	8	874964
	10	894511

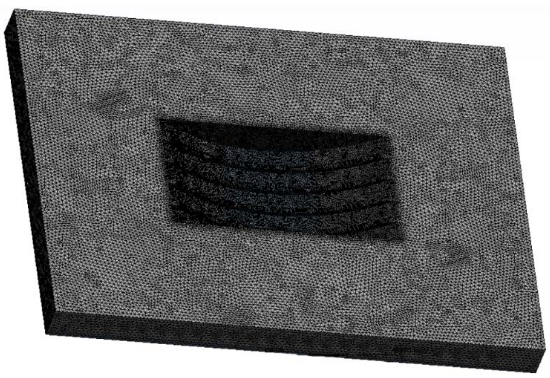


Figure 7. Mesh cell counts for patterned tires with four different water film thicknesses

The study model uses the k-epsilon RNG turbulence model to account for the turbulent motion of air and water and employs the VOF model to capture the interface between the two phases. The parameters for water and air are as listed in Table 6.

Table 6. Model material parameters

Fluid Type	Density (kg/m^3)	Dynamic Viscosity(Ns/m^3)
Air	1.204	$1.82 * 10^{-5}$
Water Flow	1000	$1.0 * 10^{-3}$

Figure 9 presents the simulation results of water flow distribution around a car's patterned tires under different water film thicknesses. In the figures, the red area represents water, blue represents air, and green represents the interface between air and water. The flow direction of water and air is along the positive x-axis, with the car tire moving in the negative x-axis direction.

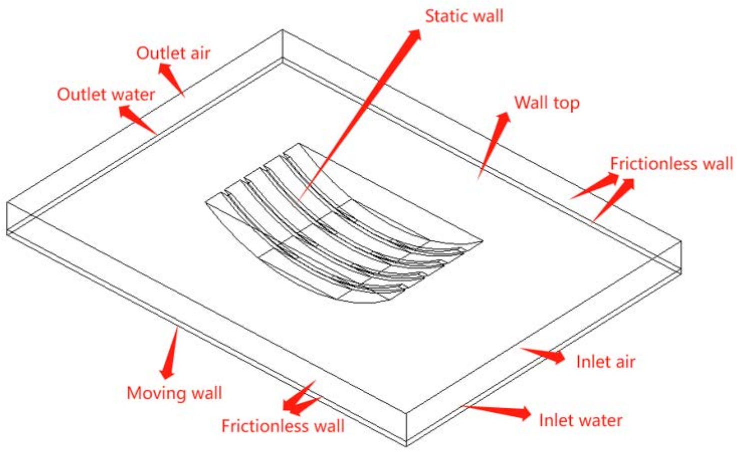
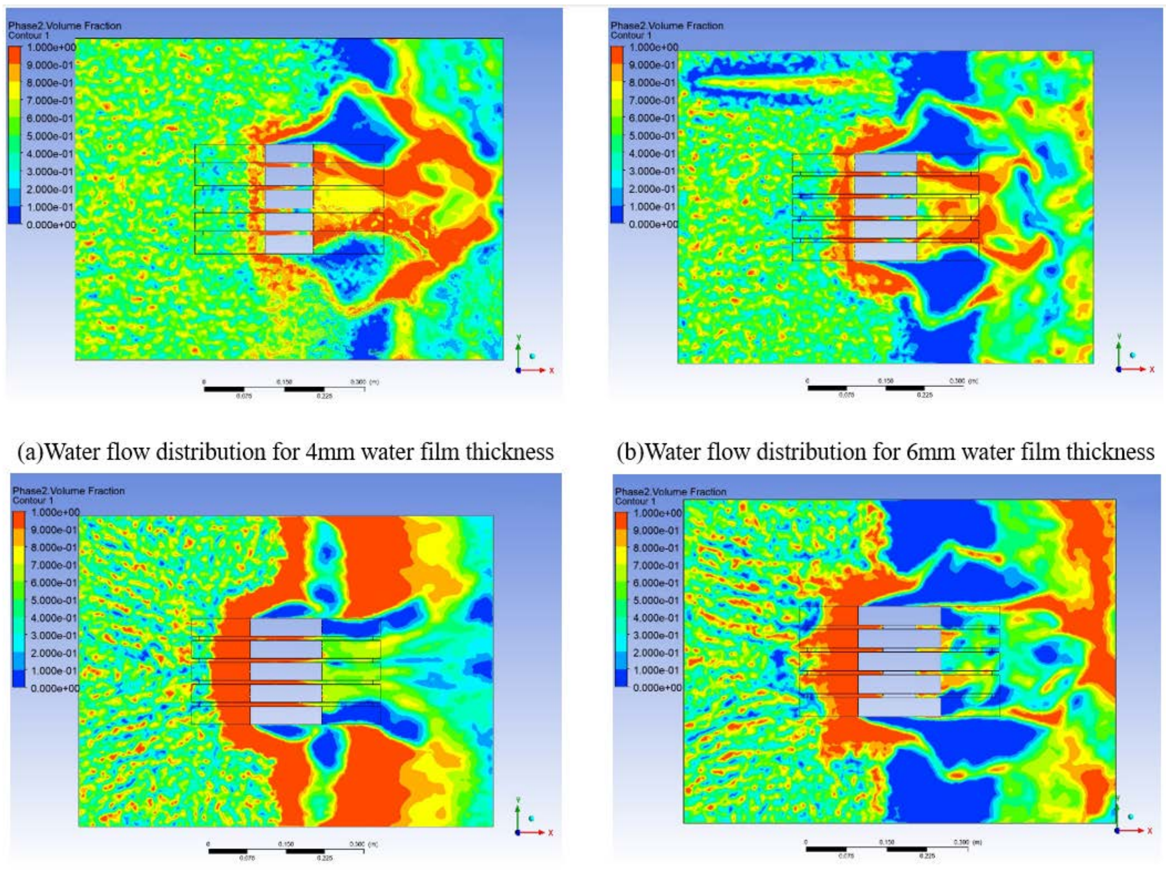


Figure 8. Boundary condition settings



(a)Water flow distribution for 4mm water film thickness

(b)Water flow distribution for 6mm water film thickness

(c)Water flow distribution for 8mm water film thickness

(d)Water flow distribution for 10mm water film thickness

Figure 9. Water flow distribution around patterned tires at different water film thicknesses

From Figure 9, it is observed that when a car tire travels at 30km/h on a road with a certain thickness of water film, water flow bifurcates at the front of the tire and flows backward from both sides of the tire (see subgraph (a) of Figure 9). The area occupied by the water film in front of the tire varies with different water film thicknesses. With a thinner water film, the area occupied by the water film in front of the tire is relatively small (see subgraphs (a) and (b) of Figure 9). As the water film thickness increases, this area gradually expands, and the tire begins to be lifted by the water film (see subgraphs (c) and (d) of Figure 9). At a speed of 30km/h on a road with a water film, water is squeezed into the tread grooves of the patterned tire from the arc-shaped wedge area in front of the tire and expelled from the grooves. This also results in water splashing at the front edge of the tire. As the water film thickness increases to a certain level, the water film in front of the tire is broken into chunks, while the water film at the rear forms a continuous layer. At this point, due to the excessive thickness of the water film, a layer of water is trapped between the tire and the road surface, reducing the friction coefficient and ultimately leading to the so-called "hydroplaning" phenomenon (see subgraph (d) of Figure 9).

As can be seen, the greater the water film thickness on the connection line surface, the greater the potential hazard to vehicles. Therefore, for areas with excessive water film thickness, measures should be taken to counteract the water film effect, such as appropriately reducing the drainage length on the connection line and increasing the road surface slope, to avoid traffic accidents.

5 Conclusions and Prospects

The connection lines between highways and urban roads must consider the differing standards of both, to avoid issues such as unclear functionality, abrupt changes in cross-sectional design, and inadequate drainage methods.

The thickness of the water film increases with the increase in drainage length and rainfall intensity, while it decreases with the increase in road surface slope and road surface construction depth. Regarding drainage length, the greatest change in water film thickness occurs within the 0-20m range. In terms of road surface slope, the water film thickness decreases more rapidly when the cross-slope is less than 3%, and the decreasing trend slows down, becoming almost linear when the cross-slope exceeds 3%. In areas with high rainfall intensity, the likelihood of water film effect occurrence increases, although the increase in water film thickness due to rainfall intensity in 2-year to 3-year and 3-year to 5-year recurrence periods is relatively small. Regarding road surface construction depth, 1.5mm acts as a watershed; below 1.5mm, the decrease in water film thickness is gradual and follows a curve, while above 1.5mm, it decreases more rapidly in a linear fashion. A preliminary approximation of the relationship between water film thickness and other parameters can be represented as: $\mathrm{H} \propto \mathrm{L}^{4.02655}\mathrm{i}^{-1.65562}(0.87\mathrm{I}+1.26)\left(4.07-0.17\ \mathrm{T}-0.13\ \mathrm{T}^2\right)$. In practical engineering, increasing the road surface slope, construction depth, or reducing the drainage length can help avoid the water film effect, providing theoretical support and methodological guidance for the design of connection lines.

Different water film thicknesses lead to different distributions of water flow around car tires. With a thinner water film, the area occupied by the water film in front of the tire is relatively small. As the water film thickness increases, this area gradually expands, lifting the tire progressively until hydroplaning occurs at a certain height.

During this research, while exploring the approximate relationship between the four influencing factors and water film thickness, its representativeness will need to be further discussed in a variety of scenarios. Currently, the analysis of water flow distribution has only considered one type of patterned tire for passenger cars; future research could explore smooth tires for passenger cars and tires for larger vehicles like trucks. Simultaneously, based on the influencing factors of water film thickness, an evaluation method and system could be established to further refine the research on the water film effect on connection lines.

Funding

This work is funded by Science and Technology Research project of Jilin Provincial Education Department (Study on minimization Method of Urban Road Construction Environment Based on BIM Technology) (Grant number: JJKH20230349KJ) and Higher education scientific research project of Jilin Association for Higher Education (Research on the influence of Virtual Reality Technology in the Reform of Road and Bridge Engineering Teaching and Independent Learning) (Grant number: GH19214).

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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