Variation Characteristics and Forecasting Model of Pavement Water Film Thickness During the Flood Season on the Eastern Qinghai Section of the Beijing-Tibet Expressway: Postprint

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Abstract

Using hourly meteorological observation data from traffic automatic monitoring stations along the Qinghai Province section of the Beijing-Tibet Expressway during the flood seasons (May–September) of 2018–2020, this study investigates the variation characteristics of road surface water film thickness and constructs a forecasting model for water film thickness based on meteorological factors. The results show that: (1) At the Gaomiaoqiao and Hanzhuangcun stations along the Beijing-Tibet Expressway, the hourly road surface water film thickness is mainly distributed between 0.0–0.2 mm, with frequencies of 66.0% and 63.0%, respectively. The frequency of water film thickness exceeding 0.5 mm is relatively low (10.0%) at both stations, which both belong to areas with strong variability. (2) Using the relative threshold method for statistical analysis, it is found that the proportions of water film thickness within 0.1 mm at the two stations are 33.8% and 36.3%, respectively; the proportions between 0.1–0.6 mm are 59.2% and 56.0%, respectively; and the proportions exceeding 0.7 mm, at which hydroplaning is likely to occur and cause dangers such as vehicle instability and loss of control, are 7.0% and 7.6%, respectively. (3) The diurnal and monthly variation characteristics of road surface water film thickness are significant. The monthly variations in water film thickness at both Gaomiaoqiao and Hanzhuangcun stations exhibit a weak bimodal pattern, though the monthly variation trends are not completely consistent between the two stations. The diurnal peak at Gaomiaoqiao station occurs at 02:00–06:00, with a trough at 14:00–16:00, while at Hanzhuangcun station, the diurnal peak occurs at 06:00 and the trough at 16:00. (4) With increasing precipitation intensity, the average water film thickness increases rapidly following a power function relationship. When precipitation intensity is between 0.00–1.75 $\mathrm{mm \cdot h^{-1}}$, the increasing trend in average water film thickness is significant; when precipitation intensity exceeds 1.76 mm · h^{-1}, the changes in average water film thickness show both increases and decreases. (5) The water film thickness models constructed using multiple regression statistical methods based on meteorological factors and under different precipitation intensities demonstrate good practical value and can be promoted for application in operational work. (6) The calculated values from the water film thickness model constructed under different precipitation intensities are significantly higher than those from the Ji Tianjian model and the Luo Jing model. The variation trend of the model in this study is relatively consistent with that of the Luo Jing model, showing a clear increasing trend in water film thickness with increasing rainfall intensity, whereas the calculated values from the Ji Tianjian model show a slow increasing trend with rainfall intensity. The research findings can be applied to rainy-day speed management and road traffic safety management in plateau environments, providing a basis for auxiliary decision-making for highway designers or operation managers.

Full Text

Variation Characteristics of Pavement Water Film Thickness in Flood Season and Construction of Forecast Model for Beijing-Tibet Expressway in Eastern Qinghai

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Abstract

Using hourly meteorological observation data from traffic automatic monitoring stations along the Beijing-Tibet Expressway in Qinghai Province during the flood season (May-September) of 2018-2020, this study investigates the variation characteristics of pavement water film thickness and constructs a forecast model relating water film thickness to meteorological factors. The results show that: (1) The hourly pavement water film thickness at Gaomiaoqiao station and Hanzhuangcun station was primarily distributed between 0.0 mm and 0.2 mm, with frequencies of 66.0% and 63.0%, respectively. Frequencies exceeding 0.5 mm were less than 10.0% at both stations, which belong to areas of strong variability. (2) Statistical analysis using the relative threshold method revealed that the proportions of water film thickness within 0.1 mm at the two stations were 33.8% and 36.3%, respectively, while proportions between 0.1 mm and 0.6 mm were 59.2% and 56.0%, respectively. When water film thickness exceeded 0.7 mm—a condition prone to hydroplaning and causing vehicle instability and loss of control—the proportions were 7.0% and 7.6%, respectively. (3) The daily and monthly variation characteristics of pavement water film thickness were significant. Both stations exhibited weak bimodal patterns in monthly variation, though the trends were not completely consistent. The daily variation peak occurred at 02:00-06:00 with a low point at 14:00-16:00 at Gaomiaoqiao station, while at Hanzhuangcun station the peak appeared at 06:00 and the low point at 16:00. (4) With increasing precipitation intensity, the average water film thickness increased rapidly following a power function relationship. When precipitation intensity was between 0.00 $\mathrm{mm \cdot h^{-1}}$ and 1.75 $\mathrm{mm \cdot h^{-1}}$, the increasing trend in average water film thickness was pronounced; when precipitation intensity exceeded 1.76 $\mathrm{mm \cdot h^{-1}}$, the water film thickness showed both increases and decreases. (5) A water film thickness forecast model based on meteorological factors and different precipitation intensities was established using multiple regression statistical methods. The model demonstrates good operational value and can be promoted for practical application. (6) Under identical conditions, the water film thickness values calculated by the model constructed in this study are significantly higher than those from the Ji Tianjian model and the Luo Jing model. The variation trend of our model is more consistent with the Luo Jing model, showing a clear increasing trend in water film thickness with rainfall intensity, whereas the Ji Tianjian model shows a slower increasing trend.

Keywords: water film thickness; precipitation; forecast model; Beijing-Tibet Expressway

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1 Introduction

When rainfall occurs on highway surfaces, water moves along the resultant slope direction under gravity, forming a water film on the road surface. As vehicles travel at high speeds, hydrodynamic pressure generated by the water film's lubricating effect reduces the contact area between tires and pavement, significantly lowering driving safety and causing traffic accidents such as vehicle skidding. The magnitude of hydrodynamic pressure is related to driving speed, water film thickness, and tire tread depth, with the contribution rates ranked from highest to lowest as: driving speed, water film thickness, and tread depth. When water film thickness reaches a certain depth, vehicles traveling above a critical speed will experience front-wheel hydroplaning. Thicker water films produce higher water spray, and due to hydrodynamic pressure effects, the tire-pavement adhesion coefficient decreases more rapidly, making hydroplaning more likely and compromising vehicle steering and braking performance, which can easily lead to traffic accidents. To reduce the risk of traffic accidents for high-speed vehicles on highways, studying the variation characteristics of pavement water film thickness and its forecast model is essential.

Since the 1960s, various water film thickness prediction models have been established both domestically and internationally. The main factors affecting pavement water film thickness include rainfall intensity, slope length, slope gradient, and surface texture depth. Research has employed artificial simulation and artificial neural networks to study pavement water film thickness, proposing specific calculation models for verification and determining that the limiting standard for pavement water film thickness can be taken as 2.5 mm.

With the rapid development of highways, traffic accidents have increased, causing substantial losses to lives and property. Adverse weather is an important trigger for highway traffic accidents, which are correlated with climatic background. Many meteorological experts have studied the status and characteristics of meteorological factors affecting traffic, established traffic meteorological early warning and forecast models and service systems, constructed traffic meteorological service index systems, and summarized evaluation methods for highway traffic precipitation. The Qinghai section of the Beijing-Tibet Expressway is a necessary route for the Silk Road Economic Belt. Within Qinghai Province, it passes through Xiangtang Bridge Provincial Boundary—Minhe—Ledu—Ping' an—Xining—Huangyuan—Gonghe—Dashui Bridge—Chaka—Dulan—Golmud City —Golmud South Exit Toll Station. The terrain along the route is complex and diverse, with poor natural conditions and numerous meteorological disasters. Due to the needs of the "Belt and Road" economic belt, 15 highway traffic meteorological stations have been established, filling the data gap for pavement water film thickness observation. However, meteorological monitoring stations along traffic routes are still sparse, and research on the variation characteristics of pavement water film thickness and its relationship with precipitation is scarce, severely lacking studies on water film thickness variation characteristics and forecast models. This paper uses data from May to September 2018–2020 from the Gaomiaoqiao and Hanzhuangcun traffic automatic monitoring stations on the Ledu section of the Beijing-Tibet Expressway to analyze the variation characteristics of pavement water film thickness and its relationship with meteorological factors, establishing a pavement water film thickness forecast model to improve the precision of highway traffic forecast services and provide refined service products for transportation safety and smoothness.

1.1 Study Area Overview

Ledu District is located in the eastern part of Qinghai Province, in the middle and lower reaches of the Huangshui River. The district has elevations between 1850–4480 m, with low precipitation and an arid climate. The annual average temperature is 7.8°C, and the annual average precipitation is 329.1 mm, with uneven temporal and spatial distribution. Precipitation from May to September accounts for 86.0% of the annual total. Gaomiaoqiao station is located at K1736+900 m on the Beijing-Tibet Expressway at an elevation of 2029 m (36°26 N, 102°16 E). Hanzhuangcun station is located at K1761+950 m on the Beijing-Tibet Expressway at an elevation of 1882 m (36°29 N, 102°32 E).

1.2 Data Sources

The highway traffic meteorological observation stations are equipped with CAWS3000 automatic weather stations, which monitor hourly precipitation, air temperature, humidity, wind speed, pavement temperature, and pavement condition in real time. The data are obtained from the Qinghai Provincial Meteorological Information Center. The main equipment configurations are shown in . Since the precipitation resolution of the traffic meteorological stations is 0.1 mm and water film thickness only occurs when precipitation happens, water film thickness data at times without precipitation were excluded from the statistical analysis.

1.3 Statistical Analysis Methods

This study uses statistical methods to analyze the variation characteristics of pavement water film thickness. Multiple linear stepwise regression is employed using software to establish regression equations between water film thickness and meteorological factors, with F-tests performed for significance. Mean bias error (MBE), root mean square error (RMSE), and correlation coefficient (r) are used to compare observed values with fitted values from the forecast equations. The calculation formulas are as follows:

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2}$$

where n is the sample size, X is the observed value, Y is the fitted value, $\bar{X}$ is the mean of observed values, $\bar{Y}$ is the mean of fitted values, σ is the standard deviation, and is the mean. The coefficient of variation (C) describes the variation degree of pavement water film thickness. $C < 0.1$ indicates weak variability, $0.1 \leq C \leq 1.0$ indicates moderate variability, and $C > 1.0$ indicates strong variability. A larger C means more pronounced temporal heterogeneity in water film thickness.

2 Results and Analysis

2.1 Variation Characteristics of Water Film Thickness

2.1.1 Frequency Distribution and Water Film Thickness Index Classification The water film thickness ranges from 0.0–1.4 mm at Gaomiaoqiao station and 0.0–1.2 mm at Hanzhuangcun station, both belonging to strong variability. Statistical analysis of hourly water film thickness at the two stations from May to September 2018–2020 shows that frequencies within 0.0-0.2 mm are 66.0% and 63.0%, respectively; frequencies within 0.2-0.4 mm are 19.4% and

19.7%, respectively; and frequencies exceeding 0.5 mm are less than 10.0%. The mean water film thickness is 0.11-0.33 mm at Gaomiaoqiao station and 0.10-0.33 mm at Hanzhuangcun station.

Extreme events refer to weather events that are statistically rare in a region. Two main methods exist for selecting extreme thresholds: absolute threshold and relative threshold. The absolute threshold method selects values greater than or equal to (or less than or equal to) a specific value. The relative threshold typically uses ranking methods, sorting the historical sequence from smallest to largest and defining the 90th (or 95th) percentile as extreme high events and the 10th (or 5th) percentile as extreme low events. Since extreme weather events have strong regional characteristics with inconsistent trends and intensities across locations, this study adopts the relative threshold method (90th percentile) for statistical analysis of water film thickness values to qualitatively evaluate the impact on driving safety.

Based on observed hourly water film thickness values at Gaomiaoqiao and Hanzhuangcun stations and actual forecast service requirements, the relative threshold method (90th percentile) is used for statistical analysis. The classification standards and corresponding impacts are shown in . The analysis reveals that during the flood season, the proportions of water film thickness within the acceptable range (0.1 mm) at the two stations are 33.8% and 36.3%, respectively. The proportions with poor water film impact (0.1-0.6 mm) are 59.2% and 56.0%, respectively. The proportions where hydroplaning is likely to occur, causing vehicle instability and loss of control (>0.7 mm), are 7.0% and 7.6%, respectively.

2.1.2 Temporal Variation Characteristics The monthly and diurnal variations of average water film thickness at Gaomiaoqiao and Hanzhuangcun stations are shown in [Figure 3: see original paper] and [Figure 4: see original paper], respectively. Both stations show weak bimodal patterns in monthly variation, though the trends are not completely consistent. At Gaomiaoqiao station, the maximum and secondary maximum appear in July and September, respectively, with the minimum in May. At Hanzhuangcun station, the maximum appears in August and the minimum in May.

The diurnal variation characteristics differ between the stations. At Gaomiaoqiao station, the peak occurs at 02:00-06:00, the secondary peak at 12:00, and the low point at 14:00-16:00. At Hanzhuangcun station, the peak occurs at 14:00-16:00, the secondary peak at 13:00, and the low point at 06:00. These diurnal variation characteristics are consistent with the findings of Ji Xiaolong et al. [17] and Liu Rongna et al. [18], who reported bimodal diurnal precipitation patterns over the Qinghai-Tibet Plateau and Huangshui River valley (overlapping with this study area) with primary peaks around 05:00 and valleys around 15:00.

2.2 Variation of Water Film Thickness Under Different Precipitation Intensities

Precipitation intensity refers to the amount of precipitation per unit time. Based on the actual hourly precipitation at Gaomiaoqiao and Hanzhuangcun stations from May to September 2018-2020, precipitation intensity is classified into different grades using two approaches. The first approach divides precipitation into light rain (0.1-0.25 $\mathrm{mm \cdot h^{-1}}$), moderate rain (0.26-1.00 $\mathrm{mm \cdot h^{-1}}$), heavy rain (1.01-4.00 $\mathrm{mm \cdot h^{-1}}$), and rainstorm and above ($ $4.01mm \cdot h^{\{-1\})at0.25mm \cdot h}${-1}$ intervals. The second approach divides precipitation at 0.10-0.25 $\mathrm{mm \cdot h^{-1}}$ intervals.

As shown in [Figure 5: see original paper], water film thickness increases rapidly following a power function relationship with increasing precipitation intensity. The power function exponents for water film thickness are 0.418 and 0.508 for the two classification methods at Gaomiaoqiao station, and 0.418 and 0.508 at Hanzhuangcun station. Based on these exponent values and correlation coefficients, the second classification method yields the maximum increase rate of water film thickness at both stations. The figure also reveals that when precipitation intensity is between 0.00-1.75 $\mathrm{mm \cdot h^{-1}}$, the increasing trend in average water film thickness is pronounced. When precipitation intensity exceeds 1.76 $\mathrm{mm \cdot h^{-1}}$, water film thickness shows both increases and decreases. The specific precipitation intensity ranges for these fluctuations differ slightly between stations: at Gaomiaoqiao station, water film thickness decreases slightly when precipitation intensity is 1.76-2.00 $\mathrm{mm \cdot h^{-1}}$, then increases rapidly until 2.60-2.75 $\mathrm{mm \cdot h^{-1}}$, after which it decreases again; at Hanzhuangcun station, water film thickness fluctuates when precipitation intensity is 1.76-3.00 $\mathrm{mm \cdot h^{-1}}$, then enters a period of rapid increase.

Given the consistent diurnal variation characteristics and relatively small sample sizes at the two stations, data from both stations were combined to establish the pavement water film thickness forecast model, with some samples reserved for verification.

2.3 Establishment and Verification of Pavement Water Film Thickness Forecast Model

2.3.1 Correlation Analysis and Forecast Model Construction Correlation analysis between water film thickness and main meteorological factors is presented in . The results show that hourly precipitation, hourly relative humidity, and previous-hour water film thickness are significantly positively correlated with water film thickness, while hourly air temperature is significantly negatively correlated—all passing the 0.01 significance test. Hourly wind speed and pavement temperature have relatively minor effects on water film thickness.

The stability and accuracy of a water film forecast model based on statistical methods depend on the selection of forecast factors. Using hourly data from May to September 2018-2020 at Gaomiaoqiao and Hanzhuangcun stations, with wind speed, air temperature, relative humidity, pavement temperature, precipitation, previous-hour water film thickness, and current water film thickness as basic modeling data (reserving some samples for later verification), multiple stepwise regression was employed to establish linear regression equations between water film thickness and meteorological factors.

The regression equations, multiple correlation coefficients, and F-statistics for overall flood season and monthly water film thickness versus meteorological factors are shown in . The regression equations all pass the 0.01 significance test. While water film thickness shows good linear relationships with hourly air temperature, relative humidity, precipitation, and previous-hour water film thickness, the multiple correlation coefficients are relatively small and cannot meet forecast requirements. To improve forecast accuracy, monthly regression equations were developed for the flood season. The monthly equations show different linear relationships between water film thickness and meteorological factors: in June, water film thickness correlates well with relative humidity and precipitation; in July, with precipitation and previous-hour water film thickness; in August, with air temperature and precipitation; and in September, with relative humidity, precipitation, and previous-hour water film thickness. The coefficients of determination range from 0.418 to 0.508, with F-statistics far exceeding critical values, indicating the regression models can serve as forecast equations.

Additionally, based on the power function relationship between precipitation intensity and water film thickness, the average hourly precipitation for each intensity interval was calculated, and regression equations between average hourly precipitation and water film thickness were established. All equations pass the 0.01 significance test, with coefficients of determination greater than 0.418, confirming that water film thickness follows a power function relationship with average hourly precipitation ([Figure 6: see original paper]).

2.3.3 Verification of Forecast Equations [Figure 7: see original paper] compares observed, fitted, and forecasted values of average water film thickness. The models constructed based on hourly meteorological factors and different precipitation intensities show consistent variation trends between observed and fitted values, with correlation coefficients passing the 0.01 significance test. The model based on hourly meteorological factors has mean bias error and root mean square error of -0.002 mm and 0.083 mm, respectively, while the model based on hourly average precipitation under different intensities has values of -0.001 mm and 0.081 mm, respectively. Therefore, the water film thickness forecast models basically meet forecast requirements.

2.4 Comparison of Water Film Thickness Regression Models

Following the methods of Ji Tianjian et al. [4] and Luo Jing et al. [5], hourly precipitation at Gaomiaoqiao and Hanzhuangcun stations from May to September 2018–2020 was classified into light rain, moderate rain, heavy rain, and rainstorm categories. Multiple stepwise regression was used to establish relationships between water film thickness and meteorological factors (hourly wind speed, air temperature, relative humidity, precipitation, and previous-hour water film thickness) under different precipitation intensities.

Ji Tianjian et al. [4] and Luo Jing et al. [5] obtained asphalt pavement water film thickness regression equations through experiments. When studying the effect of rainfall intensity on water film thickness, unified values were assigned to pavement surface texture depth (0.3 mm), drainage length (3.0 m), and slope (3%) in both models, with only rainfall intensity varied to calculate water film thickness values for comparison with our model.

As shown in [Figure 8: see original paper], under identical conditions, the water film thickness values calculated by our model under different precipitation intensities are significantly higher than those from the Ji Tianjian and Luo Jing models. In terms of variation trends, our model shows better consistency with the Luo Jing model, both exhibiting clear increasing trends in water film thickness with rainfall intensity, while the Ji Tianjian model shows a slower increasing trend.

3 Conclusions

(1) The hourly pavement water film thickness at Gaomiaoqiao and Hanzhuangcun stations on the Beijing-Tibet Expressway was mainly distributed between 0.0 mm and 0.2 mm, with frequencies of 66.0% and 63.0%, respectively. The frequency of water film thickness exceeding 0.5 mm was less than 10.0%. Both stations exhibited strong variability, with mean water film thickness of 0.11-0.33 mm and 0.10-0.33 mm, respectively.

(2) Using the relative threshold method for statistical analysis, the classification standards and impact assessment for pavement water film thickness index were established. The proportions of water film thickness within 0.1 mm at the two stations were 33.8% and 36.3%, respectively. The proportions between 0.1 mm and 0.6 mm were 59.2% and 56.0%, respectively. The proportions exceeding 0.7 mm—where hydroplaning is likely to cause vehicle instability and loss of control—were 7.0% and 7.6%, respectively.

(3) The daily and monthly variation characteristics of pavement water film thickness on the Beijing-Tibet Expressway were significant. Both stations showed weak bimodal patterns in monthly variation, though the trends were not completely consistent. At Gaomiaoqiao station, the maximum and secondary maximum appeared in July and September, respectively, with the minimum in May; at Hanzhuangcun station, the maximum appeared in August and the minimum in May. The diurnal variation showed peaks at 02:00-06:00 (secondary peak at 12:00) and low points at 14:00-16:00 at Gaomiaoqiao station, while Hanzhuangcun station showed peaks at 14:00-16:00 (secondary peak at 13:00) and low points at 06:00. The

variation in precipitation intensity was opposite to that of water film thickness, both showing strong variability.

(4) With increasing precipitation intensity, the average water film thickness increased rapidly following a power function relationship. When precipitation intensity was between $0.00\ \mathrm{mm}\cdot\mathrm{h}^{-1}$ and $1.75\ \mathrm{mm}\cdot\mathrm{h}^{-1}$, the increasing trend was pronounced; when precipitation intensity exceeded $1.76\ \mathrm{mm}\cdot\mathrm{h}^{-1}$, water film thickness showed both increases and decreases.

(5) Through correlation analysis between hourly precipitation and water film thickness, statistical methods were used to establish forecast models based on meteorological factors and different precipitation intensities. These models demonstrate good operational value and can be promoted for practical application.

(6) Under identical conditions, the water film thickness model constructed in this study under different precipitation intensities yields significantly higher values than the Ji Tianjian and Luo Jing models. Our model shows better consistency with the Luo Jing model in variation trend, both exhibiting clear increasing trends in water film thickness with rainfall intensity, while the Ji Tianjian model shows a slower increasing trend.

The research results can be applied to rainy-day speed management and pavement traffic safety management in plateau environments, providing auxiliary decision-making basis for highway designers and operation managers.

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