The Speed Limit Determination of Tunnel Entrance And Exit Section On Rainy Days

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Abstract. In order to reduce the number of traffic accidents caused by rainy days on the entrance and exit sections of tunnels, a reasonable speed limit value on the entrance and exit sections of tunnels is proposed to improve the safety of vehicles on these sections. This paper takes passenger cars as the research object, and by exploring the changes of road friction coefficient and visibility in rainy weather, the driving environment parameters under different rainfall intensity are clarified. Taking the visible distance of the driver and the critical state of vehicle sideslip as safety indexes, the speed limit value of the section outside the tunnel in rainy days is obtained, and the allowable speed of the section inside the tunnel is determined by taking the continuity of the running speed as the standard. The study shows that the speed limit value of the tunnel entrance and exit section in rainy days takes visibility as the main limit index and decreases with the increase of rainfall intensity. When the rainfall intensity is greater than 1.5mm/min, the speed limit of the tunnel section is needed.

1. Introduction

The wet road surface and reduced visibility caused by rainfall are the main reasons affecting the highway driving safety, especially the unreasonable speed in rainy days aggravates the severity of the accident. According to U.S. statistics, 47% of traffic accidents each year occur during rainfall, resulting in more than 3,400 deaths and 57,300 injuries. In rainy days, most of the accidents occurred in the tunnel entrance and exit section and other high-incidence road. Therefore, formulating a reasonable speed limit value of tunnel entrance and exit section in rainy days can effectively improve the accident rate in rainy days, which is of positive significance to the safety and traffic efficiency of expressway.

The researches of domestic and foreign scholars on driving safety in rainy days mainly focus on the influence of rainfall on the friction coefficient of pavement and speed limit measures. At present, many water film thickness prediction models are used, including the model proposed by Gallaway[1] for the US Department of Transportation and the empirical formula on water film thickness proposed by Anderson[2] in the UK. On the basis of summarizing the water film thickness formula proposed by foreign scholars, Domestic Ji [3] improved the relationship among rainfall intensity, slope structural depth, length and slope. In addition to the above regression model, the University of Pennsylvania has developed PAVDRN, a software system for predicting the surface water film thickness for the Us National Cooperative Highway Research Program. The model used in PAVDRN is a mathematical and physical model based on the road roughness coefficient (Manning coefficient) [4]. However, there are few researches on rainfall visibility carried out by scholars in this field, and most of them use meteorological monitoring stations along expressways to conduct regression analysis on the statistical data of rainfall intensity and visibility. Some scholars in meteorology can estimate the visibility under...
moderate and light rainfall intensity by fitting m-P distribution or Gamma distribution to the rainfall spectrum, but the research on the visibility under heavy rainfall intensity still lacks theoretical support. The speed limit value of expressways in rainy days has always been the focus of attention of domestic and foreign scholars. Gao[5] proposed the speed limit value based on meteorological, road environment, accident historical data and other factors by studying the speed limit measures of existing expressway. Liu [6] proposed the concept of safe allowable velocity and its determination method, and gave a model for determining the variable speed limit value comprehensively considering road alignment, line-of-sight, road state and other factors. Liu and Zhao [7-8] established speed limit standards and closing standards for expressway vehicles from the perspective of vehicle stability.

It is not difficult to find that most of the above researches are carried out on the general section of expressway, but few researches are carried out on the speed limit value in rainy days on the section with high accident incidence such as tunnel entrance and exit section. In addition, most of the existing studies focus on the safety of vehicles in a single section without considering the highway as an extended strip structure, and the continuity of speed between sections is also the key to reduce the accident rate. Therefore, on the basis of previous studies, this paper takes passenger cars as the research object, and through defining the influence degree of different rainfall intensity on driving safety, calculates the safety speed limit value of the rainy day tunnel entrance and exit section with the driver's visual distance, vehicle sideslip critical state and speed continuity as safety indicators.

2. Determining driving environment parameters on rainy days

2.1. Determine the allowable friction coefficient between tires and road surface in rainy days

1) Consideration of water skiing status

When it rains, the water enters the gap of the road surface to form a certain amount of water between the original road surface and the tire. With the increase of road surface water film thickness and the increase of vehicle speed, the tire and road surface are completely separated by water film. At this time, the friction coefficient between wheel and water film is close to zero, and the vehicle will at a very dangerous situation named complete water skiing. Foreign scholars have been conducting in-depth and extensive research on the prediction of critical water film thickness and critical water skiing speed. Studies by scholars such as Horne, Mounce and Fwa[9-11] show that the critical water skiing speed is affected by road roughness, tire pressure, ground area, pattern and other factors, and the critical speed for predicting the occurrence of water skiing phenomenon is established through data regression. Therefore, considering that the current tire and highway drainage facilities are well designed and the road surface water film thickness is generally not too thick, it is considered that controlling the driving speed below 100km/h can basically prevent the occurrence of complete water skiing phenomenon.

2) Consideration of water skiing status

In rainy days, when the water film thickness is not large on the highway, the vehicle will be partially water skiing. At this time, the friction coefficient between vehicle tires and road surface is a key parameter that affects driving safety. The study considers that the friction coefficient between vehicle tires and road surface is related to driving speed and road surface water film thickness and other factors. The technical parameters in the accepted guidelines for highway geometry design show the relationship between the allowable longitudinal friction coefficient and the design speed. Therefore, in view of safety, economic and environmental requirements, the following longitudinal friction coefficient formula can be used to determine the maximum allowable longitudinal friction coefficient.

\[
f_{l} = 0.59 - 4.85 \times 10^{-3} V_d + 1.51 \times 10^{-5} (V_d)^2
\]  

Where \(V_d\) is design speed(km/h)

2.2. Relationship between visibility and rainfall intensity

The influence of rainfall on visibility is related to rainfall intensity and rainfall distribution. Visibility is relatively stable when rainfall is evenly distributed, but sudden rainfall will cause water mist,
resulting in sudden change in driving visibility, and seriously harm driving safety. Existing studies on the impact of rainfall on visibility mainly focus on the field of meteorology, in which Carlton[11] scholars use the fitting of the Gamma distribution to the rainfall spectrum to estimate the visibility under moderate and light rainfall intensity, which has been widely recognized. However, up to now, there is still no consensus on the research on the visibility level under heavy rainfall.

Moderate and light rainfall intensity has a very limited impact on visibility, and is generally considered to have a low impact on traffic safety. Therefore, this paper mainly analyzes the visibility level under heavy rainfall weather based on the statistical data of rainfall intensity and visibility from coastal expressway meteorological monitoring stations. The regression analysis of rainfall and visibility monitoring data in heavy rainfall weather on Shanghai-Nanjing Expressway can fit the relationship between rainfall intensity $R$ and visibility $H$ as follows [12].

$$H = 294.8R^{-1.1}$$

Where $H$ is visibility in meters; $R$ is the rainfall intensity in mm/min.

According to the above formula, the visibility levels under different rainfall intensity are shown in the following table:

| rainfall intensity (mm/min) | 0.2 | 0.3 | 0.5 | 1  | 1.5 | 2  | 2.5 | 3  | 4  | 5  |
|----------------------------|-----|-----|-----|----|-----|----|-----|----|----|----|
| Visibility (m)             | 1731| 1108| 631 | 294| 188 | 137| 107 | 88 | 64 | 50 |

3. Determine the speed limit outside the tunnel on rainy days

In order to ensure the driving safety on highways, drivers need to have enough time, space and operation possibility to effectively maintain the driving stability of vehicles to avoid collisions with obstacles or accidents such as sideslip. The reasonable design of stopping sight distance and lateral friction coefficient in highway design can provide sufficient operating space for the average driver in fine weather. However, with the decrease of road friction coefficient and visibility in rainy weather, the longitudinal braking distance of vehicles increases while the lateral driving stability decreases. In order to guarantee the driving stability in rainy days, it is necessary to set the reasonable speed limit value in rainy days by taking the visibility and friction coefficient of rainy days as the safety limit index.

3.1. Distribution of longitudinal and lateral friction coefficients

When vehicle brakes in the straight sections, the friction between tire and road surface is all used to the longitudinal brake, when the car brakes in the curve section, the tire and road surface friction is divided into two parts on the basis of vector distribution method, the longitudinal friction used to complete the vehicle longitudinal braking, the lateral friction is used to maintain the stability of vehicles running in the curve. When rain occurs, the friction between tire and road surface will decreases continuously along with the increase of rainfall intensity, and when the longitudinal friction force is insufficient, the car can't brake in time to avoid collision. When the lateral friction is less than the centrifugal force, the car will slide along the direction of the centrifugal force, which causes serious damage to road safety.

International experience shows that 92% of the longitudinal friction coefficient can be used when the vehicle accelerates, decelerates, brakes or avoids the vehicle on the curve road, and the utilization ratio of the lateral friction coefficient is 40%~50%. Therefore, the maximum allowable friction coefficient can be considered as follows:

$$\psi_h = 0.45 \times 0.925 \times f_t = 0.416f_t$$

$$\psi_l = \sqrt{f_t^2 - \psi_h^2}$$
3.2. Longitudinal braking

The driving distance is composed of two parts: 1. Driver's reaction driving distance; 2. Braking Distance from start to stop. According to the Highway Route Design Specification (JTG D20-2017) [13], the stopping sight distance of vehicles can be calculated as follows:

\[ S = \frac{v}{3.6} t + \frac{v^2}{254(\psi_l + i)} \]  \hspace{1cm} (5)

Where \( \psi_l \) is the longitudinal friction coefficient; \( i \) is the road longitudinal slope; \( t \) is the driver response time. According to AASHTO research, the average reaction time of drivers is 2.5s.

Sufficient parking line-of-sight is the key to ensure the safety of vehicle driving. However, the water fog caused by rain will blur the driver's sight and shorten the visual distance. Therefore, when visibility is damaged in rainy days and cannot meet the designed stopping line-of-sight, the speed limit based on visibility as the stopping line-of-sight is as follows:

\[ V \leq -88.138(\psi_l + i) + \sqrt{7768.307(\psi_l + i)^2 + 254H(\psi_l + i)} \]  \hspace{1cm} (6)

3.3. Lateral sideslip

The longitudinal slope design of the tunnel section is not more than 3%, and the passenger car can be regarded as a rigid vehicle with uniform mass distribution. So the stress of its sideslip critical state is shown in the figure below:

![Figure 1. Vehicle stress analysis diagram](image)

According to the stress in the figure above, the stress parallel and perpendicular to the road surface can be obtained

\[ \begin{align*}
X &= F \cos \theta - G \sin \theta \\
Y &= F \sin \theta + G \cos \theta
\end{align*} \]  \hspace{1cm} (7)

Where \( F \) is the centrifugal force; \( G \) is the vehicle gravity; \( \theta \) is the road lateral inclination, as \( \theta \) is small, we can simplify \( \sin \theta \approx \tan \theta = i_0 \), \( \cos \theta = 1 \) in general.

The conditions for the passenger car not to sideslip are as follows:

\[ \begin{align*}
X &\leq Y = \psi_h \approx G \psi_h \\
V &\leq \sqrt{127R(\psi_h + i_h)}
\end{align*} \]  \hspace{1cm} (8, 9)

Where \( \psi_h \) is the lateral friction coefficient; \( R \) is the turning radius; \( i_h \) stands for superelevation.

3.4. Speed limit outside tunnel on rainy days

When the driver's visual distance and the critical state of vehicle sideslip are integrated as safety indexes, the speed limit value of the section outside the tunnel in rainy days is:

\[ V = \min \left\{ \begin{align*}
V &\leq -88.138(\psi_l + i) + \sqrt{7768.307(\psi_l + i)^2 + 254H(\psi_l + i)} \\
V &\leq \sqrt{127R(\psi_h + i_h)}
\end{align*} \]  \hspace{1cm} (10)
4. Speed limit of tunnel entrance and exit section on rainy days

In the consideration of driving safety, speed has always been regarded as a simple and intuitive factor. Drivers in unrestricted sections choose their driving speed according to the actual environmental characteristics of the section. However, due to the comprehensive influence of many factors like curve radius, line of sight distance and road conditions, the driving environment in highway may cause abrupt changes in the speed selection of drivers between two consecutive sections. This sudden change is particularly prominent in the entrance and exit section of the tunnel in rainy days. When the vehicles from the bright dry tunnel into the dark wet rainy road section need to slow down to reach the safe speed of the rainy road section. In this process, if the vehicles slow down too quickly, it will cause discomfort to drivers and passengers, or even rear-end collision and other traffic accidents, which will seriously harm driving safety. Therefore, when the maximum permissible running speed is too low due to rainfall in the section outside the tunnel, it is necessary to limit the driving speed in the tunnel according to the principle of speed continuity, so that the vehicles can slow down smoothly at the entrance and exit section of the tunnel, thus improving the driving safety at the entrance and exit section of the tunnel.

As early as the 1960s, some scholars [14] proposed that the speed of the latter section between two consecutive sections could achieve safety consistency if the speed of the latter section did not exceed 15% of the speed of the former section. Then European countries used different models to determine the reasonable speed difference. By 1995, Lamm[15] a relatively recognized velocity continuity model based on the average accident rate. He proposed when the average velocity difference $\Delta V \leq 10 \text{km/h}$, the safety level of the section is higher. When $10 \text{km/h} \leq \Delta V \leq 20 \text{km/h}$, the safety level of the section is within an acceptable range, When $V \geq 20 \text{km/h}$, the safety level of the section is poor.

According to the analysis in Chapter 3, the maximum permissible speed outside the tunnel in rainy days is shown in the following table:

| Table 2. Maximum permissible speed outside tunnel on rainy days (km/h) |
|-----------------------------|---|---|---|---|---|---|
| rainfall intensity (mm/min) | ≤1 | 1.5 | 2  | 2.5 | 3  | 4  |
| Straight sections           | 120| 90 | 80 | 65  | 60 | 50 |
| Curve sections(R=400m,i=3%) | 70 | 70 | 70 | 60  | 55 | 45 |

It is generally believed that the established speed limit value should not be higher than the above maximum permissible speed, and the variable speed limit value should be set in the tunnel when the rain is heavy, so that the difference between the inside and outside of the tunnel should not be higher than 20km/h.

5. Conclusion

In this paper, the influence of rainfall on the driving environment of expressway is studied by literature analysis, and the maximum permissible speed of rainy day outside tunnel is established based on the friction coefficient and visibility of rainy day. The following conclusions can be obtained based on above study.

1. Frequent accidents in the entrance and exit section of tunnels in rainy days are closely related to the reduction of road friction coefficient and visibility, and according to the analysis, visibility should be considered as the main influencing factor in the establishment of speed limit value in rainy days.

2. The existing speed limit model on rainy days does not consider the distribution of longitudinal and transverse friction coefficient when the vehicle is driving on the curve, and the speed limit value adopted is too large. Therefore, it is necessary to establish the safe speed limit value to ensure the stability of the vehicle in both directions.

3. The tunnel entrance and exit section has the risk of sudden change of driving environment, which is directly reflected in the driving speed. A reasonable speed limit value should be set to ensure that the difference between the inside and outside of the tunnel is less than 20km/h.
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