A New Water Leakage Classification Method for Tunnel Lining Based on Traffic Safety

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Abstract: Leakage disease would adversely affect the lining structure and operation environment, which may endanger the normal operation of tunnel projects. Existing leakage classification standards for tunnels are mainly based on the apparent view state, and the impacts of the actual operating environment are not fully taken into consideration. Based on the current classification standards, guidelines and the shortcomings of the current classification system, a new method has been put forward to classify the leakage of tunnel lining considering the influence on driving safety. In addition, Numerical software (CARSIM) is used to investigate the safety states of passenger car and freight car in different leakage level, vehicle types and driving speed conditions. Simulation results show that the maximal speed of passenger car on the road surface with a leakage-water depth of 1 mm, 5 mm and 11 mm is 110 km/h, 95 km/h and 75 km/h respectively; while that of freight car is 90 km/h, 85 km/h, and 60 km/h respectively in the same condition. The results of overtaking simulation on the two-shift line surface with 5-mm-deep leakage indicate that cars will not be unstable as the speed increases. However, when the speed of passenger car exceeds a critical value, a large error between actual trajectory and the expected dual-trajectory would appear. It would easily cause lane departure and vehicle collision. When the speed of freight car exceeds a critical value on the double-shift line, the yaw rate, side slip angle, lateral acceleration and lateral displacement velocity would go out of control. Combining with the tunnel leakage states and driving operation, this paper establishes a new classification method of tunnel leakage disease based on operation safety. It makes up for the insufficiency of tunnel leakage classification method and has guiding significance in actual tunnel projects.

1. Introduction

With rapid development of highway tunnel construction, the number of long tunnels is surging. By the end of 2016, the mileage of highway tunnels in China has reached 14039.9 km, increasing 9.7% from a year earlier. 49.3% of the tunnels are long tunnels and 23.8% are extra-long tunnels. Restricted by tunnel construction technology and technical problems in early stages, numerous tunnels have diseases. Statistics suggest that 30% of Chinese highway tunnels and 28.4% of railway tunnels suffer severe leakage disease. Meanwhile, 30% of metro tunnels in Beijing, Shanghai and Guangzhou have leakage disease. Even in Japan that enjoys more developed underground engineering techniques, more than 30% of its tunnels have leakage disease [1-3]. As a line goes that nine out of ten tunnels suffer water
leakage, leakage disease is one of the most common diseases in tunnel operation. It would impact lining structure, machine equipment, highway pavement and operating environment. What’s worse, it may undermine structure bearing capability, disturb driving order and endanger traffic safety [4-6].

Water leakage classification based on the influences on traffic safety involves not only traditional leakage classifications in civil engineering, but also traffic safety in rain condition. It is an interdisciplinary study, and there are few reports on it at present. Some academics in abroad have taken the lead to research vehicles, driving speed and driving behaviours on wet roads. Some academics at home have analysed disaster-causing mechanisms and negative influences of disaster weather such as heavy rain and fog on pavement, driver and driving condition in factors of driving speed, visibility and stopping sight distance. They have built mathematical models of grey analysis, chart analysis and regression analysis based on characteristics of driving safety such as driver, vehicle and road. They have gained vehicle driving states in rain condition and introduced management measures of vehicles on expressway in rain condition. It would promote safety operation on expressway [7-10]. However, the main research method of existing researches is qualitative analysis. Compared to open-pit environment, tunnel, as a closed linear structure, has different structure, leakage source, drainage way, sphere of action and influence degree. Therefore, it is inappropriate to use the results of existing research on traffic safety in sleety weather to judge water leakage in highway tunnels.

Combining with characteristics of water leakage disease in tunnels, this paper summarizes the impacts of leakage on driving safety. In light of shortcomings of the existing guides, leakage classification systems and index value takings, the paper proposes water leakage classification based on the influences on traffic safety. It uses automobile numerical simulation to research safe driving states in different conditions of tunnel leakage, vehicle types and driving speeds. It puts forward a classification of tunnel leakage disease from the perspective of operating safety.

2. CARSIM Simulation Model
Leakage classification method considering driving safety should base on a large amount of data. From the perspective of research safety and economy, this paper combines automotive expertise and conducts numerical simulation.

2.1. Calculation software
CARSIM, a well-known standard software in automobile industry, has been used by numerous international automobile manufactures and parts suppliers. The simulation systems based on CARSIM includes vehicle model, road model and driver model. From the perspective of tunnel operation safety, the paper simulates and analyses yaw rate, lateral acceleration, side slip angle and emergency braking distance when vehicles are braking and steering in different driving speeds and different leakage conditions. Through the simulation, the paper finds out the maximum safe driving speed in leakage tunnels and introduces a water leakage classification based on the influences on traffic safety.

2.2. Vehicle model
CARSIM presents parametric definition of vehicle model through its seven subsystems: car body, tire, steering system, suspension, braking system, transmission system and aerodynamics. This paper simulates and analyses the parameters of representative passenger car and freight car.

2.3. Road model
Pavement leakage in tunnels impacts the adhesion coefficient of road. The thickness of water film is 1 mm, 5 mm and 11 mm when vehicles are running in different speed. In the simulation of braking condition, we adopt uniform pavement and split pavement with different degrees of leakage to simulate vehicles running on roads with local or overall leakage. In the simulation of overtaking condition, we adopt two-shift line pavement with different adhesion coefficient to simulate the running track of vehicles changing lines and overtaking in tunnels.
2.4. Driver model

Open-loop model and closed-loop model are the two control modes of driver model. In closed-loop model, the gap between target track and simulation result is used to judge driving skills and road alignment condition. In the research of safe driving speed in leakage tunnels, vehicle physical index and mechanical response curve are the two yardsticks. In practical process, we should comprehensively consider drivers, cars and driving conditions. Because drivers have subjective initiative to change driving speed, we choose closed-loop model in the simulation.

3. CARSIM Simulation Parameters

3.1. Critical Hydroplaning Velocity

Water leakage on road surface results in water film. When vehicles are running on the water film shouldering pressure of cars, hydrodynamic pressure appears, and adhesion coefficient declines. Driving safety is impacted. Researchers consider the thickness of water film that can be measured easily, tunnel leakage degrees and road drainage ability as vital parameters of influences of leakage on tunnel operation.

In 1968, Home and Leland in NASA Langley Research Centre made some experiments and first got the formula of critical hydroplaning velocity. Based on the Home-Leland formula, Dunlap and other researchers [11] figured out the relationship among critical hydroplaning velocity, thickness of water film and depth of tire tread pattern:

\[ v_p = 6.25\sqrt{P} + 12\frac{t}{h} + 0.006\exp\left(-3\left(h - \left(3 + \frac{t}{b}\right)\right)\right) \]

Where: \( P \) is tire pressure, kPa; \( T \) is the depth of tire tread pattern, mm; \( h \) is thickness of water film, mm; \( b \) is width of tire, mm

3.2. Adhesion Coefficient

Overtaking, braking and steering are the most common operation modes of vehicles running in tunnels. In tunnels with leakage disease, water film caused by impeded drainage decreases adhesion coefficient. Braking and sideslip distance increase. Vehicles tend to roll or move sideways when they are traveling in high speed. At this time, emotional, delayed or inappropriate reaction would make vehicles out of control, and cause traffic accidents. Braking and steering are the most frequent operations in driving. Therefore, they are taken as objects of simulation of vehicles driving on wet road.

Wu Qi [11] from Southeast University converted the hydro-dynamic pressure in tunnel leakage condition to the adhesion coefficient in the same condition. He figured out the quantitative relationships among driving speed, thickness of water film and depth of tire tread pattern:

\[ \mu' = 1.0052 - 0.0051v - 0.0206h + 0.0022t \]

Where: \( \mu' \) is adhesion coefficient of road; \( v \) is driving speed, km/h; \( h \) is thickness of water film, mm; \( t \) is depth of tire tread pattern, mm.
4. Testing Designs

4.1. Types of vehicles
In operating highway tunnel, large bus (A1), tractor (A2), urban bus (A3), medium bus (B1), large freight car (B2), compact car (C1) and compact automatic transmission car (C2) are the major vehicles. In order to decrease the numbers of calculation models, we choose passenger car and freight car as the subjects of the simulation.

4.2. Thickness of water film
According to relative regulations in China, the maximum abrasion depth of tire tread pattern is 1.6mm. When tire pressure reaches 250 kPa, and tire-contact width (b) reaches 185mm, the limiting thickness of water film is \( h_p = 1.021 \text{mm} = 1 \text{mm} \). According to different thickness of water film, we define different pavement conditions as:

1. Dry pavement (h =0mm)
2. Wet pavement (0<h≤1mm)
3. Wet pavement (h>1mm)

In the simulating calculation, the thickness of water film is chosen to be 0mm, 1mm, 5mm and 11mm to analyse the influences of different leakage degrees on driving safety. They respectively represent dry pavement, wet pavement, pavement covered by a layer of water and pavement with serious ponding.

4.3. Driving speed
According to relative regulations of highway tunnel operation, we adopt 60km/h as the minimum driving speed and 120 km/h, the maximum speed. In the simulation, the speed increases 10 km/h incrementally from 60 km/h to 120 km/h.

5. Results and Discussion

5.1. An Analysis on the Results of Braking Condition Simulation
When the gap between braking distance on wet pavement and that on dry pavement is less than 5m, the speed is considered as a safe speed. However, when the gap is more than 5m, the speed is a dangerous speed.

After 52 simulations, the braking distances of passenger car driving in different speeds are shown in Figure 3. The figure shows that when water film thickness is 1mm and driving speed is lower than 110 km/h, the difference between braking distance on dry pavement and that on wet pavement is less than 5 m. When water film thickness is 5 mm and driving speed is less than 95 km/h, the difference of braking distance is less than 5 m. When water film thickness is 11 mm and driving speed is less than 75 km/h, the difference is less than 5 mm. Therefore, the maximum driving speed on pavement with 1-mm-deep, 5-mm-deep and 11-mm-deep leakage is respectively 110 km/h, 95 km/h and 75 km/h.

After 52 simulations, the braking distances of freight car running in different speeds are shown in Figure 4, and the maximum safe speeds in different water film conditions are presented in Figure 5.
From the figures, we conclude that the maximum driving speeds on pavement with 1-mm-deep, 5-mm-deep and 11-mm-deep leakage are respectively 90 km/h, 85 km/h and 60 km/h.

Fig. 3 Braking distances of passenger car running in different speeds

Fig. 4 Braking distances of freight car running in different speeds

Fig. 5 The maximum driving speeds in different water film conditions
5.2. An Analysis on the Results of Braking Stability Simulation of Vehicles Running on Split Road with Local Leakage

In order to ensure driving safety, the yaw rate of vehicles is limited to 8.6°/s and the side slip angle is no more than 5.7° during braking process. In the simulation, vehicles run on split road with 1-mm-deep local leakage. After calculations, the braking distance, lateral displacement, maximal yaw rate and maximal side slip angle of vehicles driving in different speeds are shown in Figure 6.

From the figure, we find that when passenger car is driving in the speed of 110 km/h, the yaw rate and side slip angle are in the safety threshold. However, when the speed reaches 120 km/h, both of them outnumber the maximal values. When freight car is running in the speed of 100 km/h, the yaw rate and side slip angle are kept in the safety threshold and the car is stable. When the speed climbs to 110 km/h, the values of yaw rate and side slip angle are more than the maximal values and lateral displacement appears so that the car cannot move straightly. When the lateral displacement, yaw rate and side slip angle surge, the car lose its stability and tend to suffer accidents.

5.3. An Analysis on the Results of Overtaking Condition Simulation

In overtaking process, the maximal safe overtaking speed is judged by the lateral displacement difference between the real driving trail and target trail, the change of yaw rate and the change of side slip angle.

Figure 7. shows the driving trails of passenger car running on pavement with 5-mm-deep leakage in different speeds. Because the centroid of passenger car is in low position, the car would be stable on double-shift line pavement. However, when the speed climbs up to a certain value, the gap between the real track and expected track would be large, and the car would lose control to go over lane line or crash into other cars. Compared to passenger car, freight car has a higher centroid position. Therefore,
when its speed reaches a certain value, the yaw rate, side slip angle, lateral acceleration and lateral displacement speed would lose control, and the car would run outside lane line or collide with other vehicles. Traffic accidents would happen in that condition.

![Fig.7 The driving trails of vehicles running in different speeds](image)

In order to succeed to change lanes, the difference between the real lateral displacement and the expected one should be less than 10% (0.35m). Figure 9 shows the lateral displacement difference of passenger car driving in different speeds. When the car is running on dry pavement, the maximal difference is 0.21 m which stays in the safety threshold of 0.35 m. Nevertheless, when the car is driving on double-shift road with 5-mm-deep leakage in the speed of 100 km/h, the difference increases to 0.46 m which outnumber the safety value. Therefore, the maximum safety speed of the car on that road is 100 km/h. In the speed of 90 km/h, freight car runs stably while it loses stability when the speed reaches 100 km/h. Therefore, the maximum overtaking speed of freight car on that road is 90 km/h.
5.4. Classification of Leakage Based on The Influence on Tunnel Operation

In light of the analyses of safe driving speeds of vehicles running on pavement with different depths of water film, Table 1 ~ Table 4 illustrate the classification of leakage based on its influences on tunnel operation. In practical use of the classification, water film depth can be measured easily. If the value of the depth is between the values in the table, we choose the larger one.

Table 1. Classification of leakage influences

| Driving speed (km/h) | Dry pavement | 1-mm-deep water film | 5-mm-deep water film | 9-mm-deep water film |
|----------------------|--------------|----------------------|----------------------|----------------------|
| 60                   | A            | A                    | B                    | B                    |
| 80                   | A            | B                    | B                    | C                    |
| 100                  | B            | B                    | C                    | D                    |
| 120                  | B            | C                    | D                    | D                    |

Note: the degree of influences of leakage on freight car is one-level higher than that on passenger car. A level: no influence; B level: few influences; C level: some influences and driving speed should be controlled to ensure driving safety; D level: great influences and driving speed should be slashed down.

Table 2. Classification of leakage level

| Site       | Level of leakage |          |          |          |
|------------|------------------|----------|----------|----------|
|            | ejection         | Flow     | drip     | wet      |
| Arch       | 4                | 3        | 2        | 1        |
| Side Wall  | 3                | 2        | 2        | 1        |

Table 3. Leakage classification based on its influences on operation

| Influence | Level | A | B | C | D |
|-----------|-------|---|---|---|---|
| 1         | I     | II | III | IV |
| 2         | II    | III | IV | IV |
| 3         | III   | IV | IV | V  |
| 4         | IV    | IV | V  | V  |

Table 4. Leakage Strategy based on its influences on operation

| Degree | Strategy                                      |
|--------|-----------------------------------------------|
| I      | The risk can be accepted                      |
| II     | The risk can be accepted                      |
| III    | The risk can be accepted but therapies to the risk and emergency plans shall be made |
| IV     | The risk cannot be accepted, traffic should be limited and measures shall be taken to lower down |
6. Conclusion
Based on analyses of the influences of leakage on tunnel operation safety, the paper proposes a leakage classification based on operation safety. Through simulation calculation, the paper analyses critical parameters quantitatively and draws the following conclusions:

(1) From the perspective of operation safety, it analyzes the negative influences of water leakage and proposes the idea of leakage classification based on operation safety.

(2) It puts forward evaluation indexes, calculation methods and simulation schemes.

(3) It figures out safe driving states in conditions of different driving speeds, leakage degrees and vehicle types through numerical simulations. It also proposes quantitative classification criteria of leakage.

The leakage classification based on tunnel operation requires the support of numerous data. Although the numerical simulation applied in the paper has some limitations, further experiments and testaments would be adopted to modify and refine the research in further investigations.

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