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Study on four-section lighting demand of highway tunnel based on allowable risk

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Abstract: In order to solve the contradiction between tunnel lighting safety and energy saving, this paper puts forward the concept of allowable risk degree, determines the lighting demand based on different risk lighting safety time intervals, and puts forward the calculation model of different traffic flow patterns based on mathematical statistics and vehicle arrival compliance law. The relationship between the traffic volume and the risk degree is obtained by the regression analysis of the characteristic values of different traffic flow patterns. The results are compared with the norm, and it is found that when the allowable risk is 5%, the characteristic traffic quantity value in free flow stage is larger than the norm value. After the free flow stage, the traffic volume value in this paper should first reach the maximum brightness, and then present a two-stage pattern, that is, the brightness decreases with the traffic volume and then remains unchanged after reaching the minimum value, which is different from the standard.

1. Introduction

Tunnel lighting is one of the key points of road traffic. Reasonable tunnel lighting should not only ensure traffic safety, but also solve the problem of energy saving and consumption reduction. Existing studies are: (1) the relationship between light source and lighting needs: Sha Xin [1] proposed the selection of LED light source, PWM-based LED stepless dimming mode, the use of neural network fuzzy control model automatic real-time control as a tunnel lighting energy-saving and consumption reduction strategy,Xu Meng[2] according to the different colors of the light source of the visual function of the test to get a special color of the red light band can alleviate the driver in the tunnel hypnosis phenomenon; (2) The relationship between vision and lighting requirements: Liang Bo[3] considers the variability of the different regions of the human retina's discriminatory ability, and obtains the influence of central backlighting lighting parameters on the STV value of different visual ranges of the law, Du Feng [4] analyzes the existing k-value determination of the process of the problem, using visual efficiency experiments to obtain the driver in the tunnel outside the tunnel cave brightness is constantly changing and the entrance section of the tunnel under the conditions of color temperature and brightness of different reaction times, and then get the discount factor of the change law of the relationship between the formulas.Dong Changsong et al. [5]took the pupil diameter change rate as an index to analyze the buffering effect of awning on the adaptation process of light and shade in the connecting sections of tunnel groups, and verified that awning has a good lighting buffering effect.Li Ping et al.[6] combined with lighting system upgrading, side wall lighting coating and intelligent lighting control technology, carried out lighting quality upgrading and upgrading of the current situation of the two tunnels, and used multidimensional evaluation indicators to analyze the transformation effect. The results show that the safety, comfort and energy saving of the tunnel lighting after the transformation have been significantly improved.

Existing research results on lighting demand have little to do with the relationship between traffic flow patterns, traffic behavior and lighting demand. And did not consider the different values of brightness outside the cave, different lighting brightness inside the cave, different traffic risk and energy consumption. The larger the value of brightness outside the cave, the larger the brightness inside the cave, and the smaller the difference with the environment outside the cave. Based on this, this paper proposes the concept of permissible risk degree, according to the law of vehicle arrival obedience, to meet a certain risk degree when the required minimum hourly distance as a parameter, to determine the critical traffic volume of different traffic streams, the traffic pattern is divided into four segments, to determine the lighting demand.

2. Basic Concepts

2.1. Concept of permissible degree of risk

Tunnel lighting involves risks to both safety and energy conservation, so the permissible risk can be defined as follows:

Tolerable risk refers to the maximum risk of safety and energy saving that can be tolerated by tunnel users and managers under certain economic conditions, and the confidence level can be used to express the degree of risk. For example, if L_{20} takes the 75th maximum brightness, this means that 74 days out of 365 days in a year the tunnel lighting will not be able to meet the brightness outside the cave, i.e. the risk level is:

$$R_T = 74/365=0.2 \tag{1}$$

2.2. Basic assumptions

For the purpose of analysis, the following assumptions are made in this paper for comparison with the Rules for Road Tunnel Design (JTG/T D70/2-01-2014)[7]:

The lighting paragraph is divided into the same.

1) The same maximum brightness required for the same speed.

2) Same minimum brightness required for the same speed.

3) The brightness required for lighting in the same paragraph is linearly related to the size of traffic volume.

2.3. Traffic flow patterns

Road traffic flow pattern is divided into free flow, interference flow and tracking flow[8]. When the traffic flow is in free flow, the traffic volume is small and there is no need to change lanes; when the traffic flow is in interference flow, the driver's traffic behavior is interfered with and there is a need to change lanes; when the traffic flow is in tracking flow, the vehicle can only follow the vehicle in front of it due to the large traffic volume and cannot change lanes. Whether it can change lanes depends on the recognizable distance provided. In this paper, we address the lighting needs, so the interference flow is subdivided into general interference flow and severe interference flow. When the traffic flow is in the interference flow, the maximum interference requires the largest recognizable distance, and requires the largest illumination brightness.

3. Mathematical Models

When the traffic flow is in the free flow state, the braking distance needed for the static state is the largest, and the braking distance needed for the motion state is the smallest, so the safety distance should be to satisfy the principle of not colliding with the static obstacle; Similarly, when the traffic flow is in the interference flow state, the workshop distance needed for the motion state is smaller than the workshop distance needed for the static obstacle. Therefore, the minimum workshop time distance of the two is calculated with static obstacles.

Denote the set of minimum workshop time distance required by vehicles byΔt, i.e., the

$$\Delta \mathrm{t} = (\Delta t_1, \Delta t_2) \tag{2}$$

Where: $\Delta t_1$is the free exercise traffic state, static obstacles; $\Delta t_2$is the changing lane traveling traffic state, static obstacles.

3.1. Minimum Shop Time Distance for Free Flow

Denote the speed of the vehicle by v. At this point, the braking distance required to ensure that the vehicle does not collide with an obstacle is

$$S_{static} = \frac{vt}{3.6} + \frac{kv^2}{254(\phi \pm i)} + l_0 \tag{3}$$

$$\Delta t = \frac{S_{static}}{v} \tag{4}$$

Where: Δt is the reaction time, take 1.2s; ϕ is the friction coefficient of the road surface; i is the longitudinal slope of the road, take the + sign for the upper slope, take the - sign for the lower slope.

Thereby, Δt_1 can be calculated to obtain Table 1:

Table 1: Free flow minimum identifiable workshop time interval.

speed(km/h)	speed difference
	0
120	5.632
100	4.959
80	4.305
60	3.686
40	3.157

3.2. Minimum inter-vehicle time distance for interference flows

As shown in Figure 1, Vehicle 2 does not know that there is a car in the left lane that wants to brake, and just after it changes to the left lane, the car on the left has stopped (which can also be viewed as a static obstacle). At this time, it should be ensured that vehicle 2 does not collide with the vehicle. And vehicle 2 can brake, because vehicle 2 brakes, so it should also ensure that vehicle 3 does not collide with vehicle2. Therefore, theminimum identification distance needed consists of 2 parts, the safety spacing between vehicle 2 and vehicle and the safety spacing between vehicle 3 and vehicle 2, the minimum safety spacing when the front vehicle is a static obstacle, and the minimum safety spacing when the rear vehicle is a dynamic obstacle, which is calculated as follows:

$$S_T = \frac{vt(2+\rho)}{3.6} + \frac{k[v(1+\rho)]^2}{[254(\phi \pm i)]} + 2l_0 \tag{5}$$

Where: t is the reaction time; k is the safety coefficient; ϕis the road friction coefficient; i is the longitudinal slope of the road, take the + sign for uphill, take the - sign for downhill; h is the safety distance; v is the ratio of the speed of the rear vehicle to the speed of the front vehicle minus1.

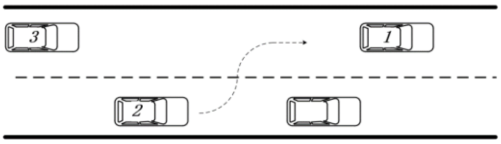

Figure 1: Schematic diagram of safe overtaking.

Δt_2 can be calculated to obtain Table 2.

Table 2: Time interval of interference flow workshop

speed (km/h)	speed difference(%)						
	0	5	10	15	20	25	30
120	7.012	7.150	7.295	7.446	7.602	7.763	7.928
100	6.375	6.475	6.581	6.694	6.812	6.935	7.062
80	5.775	5.834	5.900	5.973	6.052	6.135	6.224
60	5.246	5.261	5.284	5.314	5.351	5.393	5.441
40	4.897	4.860	4.832	4.813	4.801	4.796	4.796

4. Lighting requirements

Comparison with the specification, different traffic flow patterns under the lighting requirements as shown in Figure 2, divided into three patterns of four paragraphs, the traffic volume and the required lighting luminance is a linear relationship, and the general interference and serious interference critical point of the required luminance is the largest, the point corresponds to the traffic volume of b, the free flow of the critical maximum traffic volume of a, point c is the capacity of the passage.

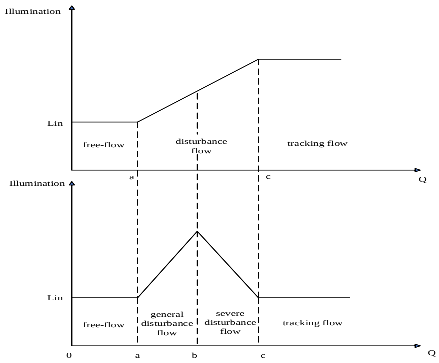

Figure 2: Mapping between brightness and traffic volume.

According to the law of vehicle arrival obedience, the calculation of permissible risk degree of different traffic flow patterns (in which the free flow adopts Poisson distribution, and the interference flow adopts binomial distribution), combined with the obtained safety time distance under different traffic flow patterns, can be calculated with different permissible traffic risk degree, the traffic volume characteristics of different traffic flow patterns, a, b. Taking the speed difference of 0 as an example, the results of the calculations are as follows:

4.1. Eigenvalues a

The results of the calculations are shown in Table 3 (Δt_1 is taken from Table 1).

Table 3: A value

tolerance risk	speed(km/h)				
(%)	40	60	80	100	120
5	400	340	300	260	230
10	600	520	440	380	320
15	780	660	560	500	440
20	900	800	680	600	520

Using the values in Table 3 as the regression analysis points, the regression equations for the allowable risk and traffic volume at different speeds can be obtained, as shown in Fig 3, with a speed of 80 km/h. The regression equations are as follows:

$$Q=25.2R_T+180\ (R^2=0.9985) \tag{6}$$

From Figure 3 and Eq. (6), it can be seen that at the same speed, the value of an increases with the increase of the degree of permissible risk; at a certain degree of permissible risk, the value of a decreases with the increase of speed.

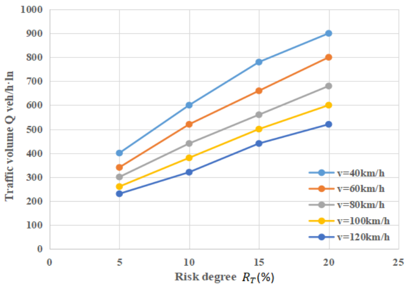

Figure 3: Variation range of a value with risk degree.

4.2. Eigenvalue b

The results of the calculations are shown in Table 4 (Δt takes the value of the column in Table 2 where the velocity difference is 0).

Table 4: b value

tolerance risk(%)	speed(km/h)				
	40	60	80	100	120
5	1980	1950	1870	1690	1550
10	1950	1870	1690	1530	1410
15	1850	1730	1570	1410	1290
20	1710	1610	1410	1310	1210

Using the calculated values in Table 4 as the regression analysis points, the regression equations for the allowable risk and traffic volume at different speeds can be obtained, as shown in Fig. 4, with a speed of 80 km/h. The regression equations are as follows:

$$Q = -30R_T + 2010 \quad (R^2 = 0.9947) \tag{7}$$

It can be seen from Figure 4 and Eq. (7) that for the same speed, the value of b decreases with the increase of the degree of permissible risk; at a certain degree of permissible risk, the value of b decreases with the increase of speed.

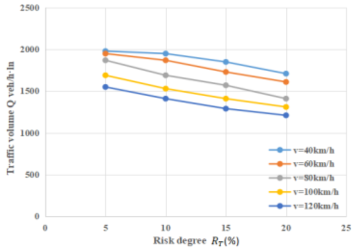

Figure 4: Variation range of B value with risk degree.

4.3. Eigenvalues c

From the “Highway Route Design Code” (JTG D20-2017) [9], the value of c (in terms of highway capacity) can be known, and the results are shown in Table 5:

Table 5: c value

speed km/h	120	100	80
mobility	1650	1600	1500

5. Conclusions and Discussions

In the free-flow phase, this paper and the specification for point a, the lighting requirements are the same, and with a speed of 80km/h, for example, in the permissible risk degree of 5%, this paper a value is smaller than the specification a value; in the permissible risk degree is greater than 5%, this paper a value is greater than the specification a value.

After the free-flow phase, the traffic volume corresponding to the point with the largest required brightness in this paper is point b, while the point with the largest required brightness in the specification is point c.

After reaching the maximum luminance, the relationship graph between lighting demand and traffic state in this paper presents a two-stage pattern, i.e., the luminance decreases with the increase of traffic volume until it reaches the minimum value and remains unchanged when it is in the tracking flow; while it remains unchanged after reaching the maximum luminance in the specification.

This paper proposes the concept of permissible risk degree and the safe time-distance model, which provides an effective way to solve the contradiction between tunnel lighting safety and energy saving.

References

[1] Sha Xing. Research on energy saving technology of LED Light Source in Tunnel lighting of Huangyan Expressway [J]. Highway engineering, 2018, 43 (06).

[2] Xu Meng, Pan Xiaodong, Chen Feng, Ma Xiaoxiang. Experimental study on the effect of color light visual adjustment on driving hypnosis in long tunnel [J]. China journal of highway and transport, 2020, 33(11):235-244.

[3] Liang Bo, Chen Kai, He Shiyong, Huang Youlin, Zhang Yi. Journal of chongqing jiaotong university (natural science edition), 2019, 38(07):40-47.

[4] Du Feng, Weng Ji, Hu Yingkui, Cai Xianyun. Journal of Central South University, 2018, 25(09):2040-2048. (in Chinese).

[5] Dong Changsong, Zhao Chaozhi, He Lianchao et al. Study on buffer effect of awning lighting in connection section of Tiantaishan Highway tunnel group based on driving test [J/OL]. Highway, 2023(07):43-49[2023-07-24].

[6] Li Ping, Shi Lingna, Wen Sen et al. Analysis and improvement of Highway Tunnel Lighting Quality based on low-

carbon concept in Chongqing [J]. Highway Transportation Technology, 2023, 39(03):145-150+158.
[7]Jiang Shuping.Highway tunnel lighting Design Rules: JTG/T D70/2-01-2014[M]. Beijing: People's Communications Press, 2014.
[8] Han Zhi. Road tunnel Energy Saving Technology [M]. Beijing: People's Communications Press, 2010.
[9] Wang Shuangjie. Code for Highway Route Design: JTG D20-2017 [M]. Beijing: People's Communications Press, 2017.