The Correlation Research on Reflection Characteristics of Road Tunnel’s Internal Surface & Lighting Quality

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Abstract. The internal wall and road surface of tunnel form the background of roadblock or vehicle together, and have a significant influence on the safety and comfort of tunnel lighting. In this paper, the optical simulation program is adopted to analyze the correlation between the reflectivity of tunnel wall and such illumination indexes as luminance and illuminance of road surface inside a tunnel, as well as the visibility of small target etc. It shows from the study that: (1) The reflectivity of wall on the luminance gain level of road surface is closely related to the luminous intensity distribution of lamps. (2) Under the circumstance that the luminous intensity distribution of lamps is consistent, the linear relations basically exist among the reflectivity of wall, the illuminance and luminance of road surface and the luminance of wall, while the maximum growth slopes are 11.29, 0.45 and 11.50 respectively. (3) The field of vision of driver can be significantly improved by a higher reflectivity of wall. (4) Compared with the three illumination modes, the visibility of small target under the pro-beam lighting is highest (the minimum visibility is 10, and the highest visibility can reach 11.6), while the visibility of small target under the counter-beam lighting is the second-highest and the visibility of small target under the symmetric lighting is most non-obvious.

1. Introduction

According to the exposure condition of natural light environment inside a tunnel, the tunnel is longitudinally divided into five sections, which separately are access section, entrance section, transition section, middle section and exit section [1-2]. From the view of traffic safety, the entrance section of tunnel is the most important part of illumination section, and also the part studied the most both at home and abroad at present. However, for the illumination at the longitudinal length of whole tunnel, the lighting demand in the middle section of tunnel is the main part, and has an important influence on the driving vision [3] of long time. According to the statistics, the probability of traffic accident in a tunnel is not higher than that on the common road section outside the tunnel [4]. But, once a traffic accident happens inside the tunnel, the driver will not have enough space to respond to the emergency and the consequence will be more serious than an accident on the common road section due to the narrow space inside the tunnel. From this view, improvement of the lighting quality of...
longer middle section inside a tunnel [5-6] will contribute to the reduction of accident rate and enhancement of the traffic safety inside a tunnel.

In terms of researches on the effect of the reflection characteristics of internal surface of tunnel on the lighting quality in the field of tunnel lighting, the corresponding researches on the middle section illumination of tunnel have been made overseas, and there is a set of perfect standard [7-10]. The domestic researchers have made some relevant researches [11-13] by applying the reflection properties of materials to tunnels. In this research, the different luminous intensity distribution conditions of lamps were set, and the correlation between the reflectivity of tunnel wall and the illumination indexes of luminance and illuminance of road surface inside a tunnel, as well as the visibility of small target etc was analyzed under the conditions. The correlation contributes to the reasonable adjustment of the distribution form of luminous intensity and the reflectivity of tunnel’s inner wall, ensures that the road surface and tunnel wall will have certain luminance levels, and provides corresponding references for the lighting design of road tunnel, so that a driver on the middle section of tunnel can be aware of any roadblock and the running conditions of other vehicles in a darker luminous environment.

2. Reflection Characteristics of Wall

When a ray of light casts on the surface of object, some light is reflected, while some light are transmitted and the rest is absorbed. The reflectivity of object surface is expressed by $R$, the transmissivity by $T$ and the absorptivity by $A$. The definitions of these parameters are all based on the parameter of luminous flux [14-15]. The reflectivity calculation formula of object surface is below:

$$R_{\phi} = \frac{\Phi_{\phi}}{\Phi_{\text{total}}} \quad (1)$$

In the formula, $\Phi_{\phi}$ is the luminous flux reflected from the surface of object, and $\Phi_{\text{total}}$ is the total luminous flux of incident light.

For an ideally-reflecting surface, the relation between its luminance $L$ and illuminance $E$ is:

$$L = \frac{E}{\pi} \quad (2)$$

However in fact, some light energies are always absorbed by the surface of object and transformed into the heat energies. Therefore, the reflection coefficient of object surface is always less than 1. Such surface is called a similar ideally-reflecting surface. Its actual reflectivity can be expressed by $\rho$. For this reason, the relation between luminance and illuminance of similar ideally-reflecting surface can be written as:

$$L = \frac{\rho}{\pi} \cdot E \quad (3)$$

The wall surface of tunnel is normally made of concrete. It can be regarded as an ideal diffuse reflecting surface, and a certain reflection coefficient can be assigned in the numerical calculation.

3. Model

3.1. Calculation Model

The one-way three-lane tunnel section is adopted for the calculation model. The clearance height is 8m, while the overall width of roadway is 13m and the width of traffic lane is 3.75m. It is shown as Figure 1. The decorative sheets are laid or other material with a higher reflectivity is sprayed on the above wall within the range of 3m from the road surface.
The illumination lamps and lanterns are furnished on both sides of tunnel, longitudinally staggered at a spacing of 10m, horizontally positioned over the centrelines of traffic lanes on both sides at a spacing of 7.5m, and installed at a height of 6.0m. The plane layout of lamps and lanterns is shown as Figure 2.

3.2. Reflectivity of Material
In engineering practice, the reflectivity of material surface is generally not more than 0.8. In the calculation model, the reflectivity of the wall within the range of 3m from the road surface ranges from 0.2 to 0.8, the step length is 0.1 and the reflectivity of lining surface for the rest part is 0.3. The type of road surface is R3 (the road surface mainly with diffuse reflection and a little specular reflection); the size of average luminance coefficient $Q_0$ is 0.07 and the reflectivity of road surface is 0.22.

3.3. Luminous Intensity Distribution of Lamps
Two forms of luminous intensity distribution are adopted in the calculation model. The first is a symmetric lighting form. It is ordered as “Luminous Intensity Distribution Type 1”, and its distribution curve flux of corresponding lamps and lanterns is shown as Figure 3. The second is an asymmetric lighting form, and ordered as “Luminous Intensity Distribution Type 2”. The asymmetric lighting includes the pro-beam lighting and the counter-beam lighting (the types of light distributions adopted in the pro-beam lighting and counter-beam lightings are fully identical, and only the ray-casting directions are different.), and the distribution curve flux of corresponding lamps and lanterns is shown as Figure 4. The whole-lamp luminous flux of lamps is 6000lm, and the overall maintenance factor is 0.8.
4. Simulating Calculation & Analysis of Reflectivity on Luminance & Illuminance

The two luminous intensity distribution conditions of symmetry and asymmetry were set in the research, and the reflectivity between 0.2~0.8 was selected for the reflectivity simulation section of tunnel wall. By setting the parameters of already built model, the average illumination of tunnel’s road surface and average luminance of road surface & wall were respectively studied and calculated. The output results of calculation were separately shown as Table 1, Table 2 and Table 3. The output results of Table 1 were analyzed, and the fitted curve of relation between the reflectivity of wall and the average illumination of road surface was established and as shown in Figure 5. For the asymmetric luminous intensity distribution type 2, the average illuminance difference of road surface will not be over 0.1lx when the luminous intensity distributions of counter-beam lighting and pro-beam lighting are set under the same conditions, namely that the counter-beam lighting and pro-beam lighting of luminous intensity distribution type 2 will almost have the same changing relationships of road surfaces’ illuminances. So only the curves of two luminous intensity distribution types are fitted. It is analyzed from Figure 5 that the linear correlation basically exists for the relation between the reflectivity of wall and the average illumination of road surface under the condition of same luminous intensity distribution type. Moreover, the growing slope between the luminous intensity distribution type 1 and the changing curve of wall’s reflectivity is 7.12, and the growing slope between the luminous intensity distribution type 2 and the changing curve of wall’s reflectivity is 11.29. It can be seen that there is an obvious difference between the average illuminations of road surface under the two types of luminous intensity distributions. The average illumination of road surface with the wall reflectivity of 0.2 in the luminous intensity distribution type 1 is 6.38lx higher than that with the wall’s reflectivity of 0.8 in the luminous intensity distribution type 2. Compared with the luminous intensity distribution type 2, the average illumination of road surface with the wall’s reflectivity of 0.8 in the luminous intensity distribution type 1 is higher by 10.65lx. Compared with the luminous intensity distribution type 1, although the increasing acceleration for the average illumination of road surface in the luminous intensity distribution type 2 is faster with the growth of wall’s reflectivity, the average illumination gain of luminous intensity distribution type 2 will be larger under the condition of acceptable reflectivity (0.2~0.5) in the actual engineering practices.
Table 1. Reflectivity of Wall & Average Illumination of Road Surface

| Reflectivity | Luminous Intensity Distribution Type 1 (cd/m²) | Luminous Intensity Distribution Type 2 (cd/m²) |
|--------------|-----------------------------------------------|-----------------------------------------------|
|              | Counter-beam lighting                         | Pro-beam lighting                              |
| 0.2          | 89.80                                         | 76.64                                         |
| 0.3          | 90.47                                         | 77.73                                         |
| 0.4          | 91.14                                         | 78.79                                         |
| 0.5          | 91.86                                         | 79.92                                         |
| 0.6          | 92.56                                         | 81.04                                         |
| 0.7          | 93.32                                         | 82.24                                         |
| 0.8          | 94.07                                         | 83.42                                         |

Figure 5. The curve of relationship between the reflectivity of wall and the average illumination of road surface

Through the research on correlation between the reflectivity of wall and the average luminance of road surface, the output results are shown in Table 2, and the fitted curve of relationship is shown in Figure 6. It can be obtained from the analysis that the linear correlation basically exists for the relation between the reflectivity of wall and the average illumination of road surface under the two luminous intensity distributions too. Moreover, the growing slope of fitted curve between the reflectivity of wall and the average illumination of road surface under the luminous intensity distribution type 1 is 0.29, while the growing slope of fitted curve for the counter-beam lighting under the luminous intensity distribution type 2 is 0.45, and the growing slope of fitted curve for the pro-beam lighting under the luminous intensity distribution type 2 is 0.45. Compared with type 2, the average luminance differences of road surface under the luminous intensity distribution type 1 are 0.09cd/m² and 0cd/m² when the reflectivities of wall in the counter-beam lighting are 0.2 and 0.8 respectively. It shows that the average luminances of road surface in the luminous intensity distribution types 1 and 2 laid by the counter-beam lighting under the same reflectivity of wall are approximately the same. Compared with the pro-beam lighting, the average luminance difference of road surface in the pro-beam lighting of luminous intensity distribution type 2 will be basically stable between 2.41cd/m²~2.43cd/m² when the reflectivity of wall is within the range of 0.2~0.8. It shows that a linear growth approximately appears for the relation between the average illumination of road surface and the reflectivity of wall under the
back and pro-beam lighting. However, it is much better for the luminance gain of counter-beam lighting on the road surface.

Table 2. Reflectivity of Wall & Average Luminance of Road Surface

| Reflectivity | Luminous Intensity Distribution Type 1 (cd/m²) | Luminous Intensity Distribution Type 2 (cd/m²) |
|--------------|-----------------------------------------------|-----------------------------------------------|
|              | Counter-beam lighting | Pro-beam lighting | Counter-beam lighting | Pro-beam lighting |
| 0.2          | 5.16 | 5.07 | 2.65 |
| 0.3          | 5.20 | 5.11 | 2.70 |
| 0.4          | 5.22 | 5.16 | 2.73 |
| 0.5          | 5.25 | 5.20 | 2.78 |
| 0.6          | 5.28 | 5.24 | 2.82 |
| 0.7          | 5.30 | 5.29 | 2.88 |
| 0.8          | 5.34 | 5.34 | 2.92 |

Figure 6. The relationship curve between the reflectivity of wall and the average luminance of road surface

Through the correlation research on the reflectivity and average luminance of wall, the output results are shown in Table 3, and the fitted curve of relationship is shown in Figure 7. It is the same to the relationship between the reflectivity of wall and the illuminance of road surface. For the asymmetric luminous intensity distribution type 2, the average luminance difference of wall is around 0.01cd/m² when the luminous intensity distributions of counter-beam and pro-beam lighting are set under the same condition, namely that the counter-beam lighting and pro-beam lighting of luminous intensity distribution type 2 almost have the same changing relationship of wall’s luminance. So only the curves of two luminous intensity distribution types are fitted. It is seen from the analysis of the output results and fitting figures that there is a positive correlation between the reflectivity and luminance of wall under the two luminous intensity distribution types, and the positive correlation is basically linear. Moreover, the growing slope of fitted curve between the reflectivity and average luminance of wall under the luminous intensity distribution type 1 is 10.16, while the approximately growing slope of fitted curve under the luminous intensity distribution type 2 is 11.50. When the reflectivity of wall is within the range of 0.2–0.8, the maximum and minimum luminance differences of wall’s average luminance between the luminous intensity distribution types 1 and 2 are 1.15cd/m² and 0.24cd/m² respectively. Thus, the difference in the wall’s average luminance between the two luminous intensity distribution types is not quite big. The following is worth mentioning here. It can
be seen from the figure that there is a sluggish increasing phenomenon for the average luminance value of wall corresponded by the reflectivity of wall within the range of 0.3–0.4 under the luminous intensity distribution type 2, while the reflectivity of wall will be rapidly increased and returned to the stable growth rate after the reflectivity of wall is 0.4. Therefore, for the practical engineering applications, the gain slope of wall luminance under the luminous intensity distribution type 1 will be stable at 10.16 with the reflectivity increase of wall.

Table 3. Reflectivity & Average Luminance of Wall

| Reflectivity | Luminous Intensity Distribution Type 1 (cd/m²) | Luminous Intensity Distribution Type 2 (cd/m²) |
|--------------|-----------------------------------------------|-----------------------------------------------|
|              | Counter-beam lighting                        | Pro-beam lighting                              |
| 0.2          | 1.67                                          | 1.94                                          |
| 0.3          | 2.66                                          | 2.96                                          |
| 0.4          | 3.62                                          | 3.06                                          |
| 0.5          | 4.58                                          | 5.13                                          |
| 0.6          | 5.63                                          | 6.27                                          |
| 0.7          | 6.70                                          | 7.41                                          |
| 0.8          | 7.79                                          | 8.64                                          |

Figure 7. The relationship curve between the reflectivity and average luminance of wall

5. Visibility of Reflectivity on Target Object

In order to make a driver be aware of any roadblock and the running conditions of other vehicles in a darker luminous environment of tunnel, the research on correlation between the reflectivity of wall and the visibility of small target is further made. The experimental conditions remain unchanged, while the output results are seen in Table 4, and the fitted curve of relationship is shown in Figure 8. It can be seen from the output results and fitted curve that there is almost a linear correlation between the reflectivity of wall and the visibility of small target under the two luminous intensity distribution too. The growing slope of relational fitted curve between the reflectivity of wall and the visibility of small target under the luminous intensity distribution type 1 is 0.68, while the growing slope of fitted curve in the counter-beam lighting of luminous intensity distribution type 2 is -4.21, and the growing slope of fitted curve in the pro-beam lighting is 2.64. Therefore, there is a positive correlation between the reflectivity of wall and the visibility of small target under the luminous intensity distribution type 1. However, there is a negative correlation between the reflectivity of wall and the visibility of small target in the counter-beam lighting of luminous intensity distribution type 2, and there is a positive correlation between them in the pro-beam lighting of luminous intensity distribution type 2. Under the
luminous intensity distribution type 1, the visibility of small target is only increased by 0.4 during the process when the reflectivity of wall is changed from 0.2 to 0.8. Thus, the gain result of visibility of small target is not obvious under the luminous intensity distribution type 1. It is higher than that of counter-beam lighting or luminous intensity distribution type 1 for the visibility of small target with the wall reflectivity within 0.2 to 0.8 in the pro-beam lighting of luminous intensity distribution type 2. Compared with the counter-beam lighting, the maximum and minimum visibility differences of small target in the pro-beam lighting are 6.9 and 2.8 separately. Compared with the luminous intensity distribution type 1, the maximum and minimum visibility differences of small target in the pro-beam lighting are 9.8 and 7.8 separately. Although the visibility gain of small target in the pro-beam lighting of luminous intensity distribution type 2 is only 1.6 during the process when the reflectivity of wall is increased from 0.2 to 0.8, the integrally improved effect on the visibility of small target inside a tunnel is the best when compared with that of luminous intensity distribution type 1 or counter-beam lighting.

Table 4. Reflectivity of Wall & Visibility of Small Target

| Reflectivity | Luminous Intensity Distribution Type 1 (cd/m²) | Luminous Intensity Distribution Type 2 (cd/m²) |
|-------------|-----------------------------------------------|-----------------------------------------------|
|             | Counter-beam lighting                         | Pro-beam lighting                             |
| 0.2         | 1.8                                           | 7.2                                           | 10.0                          |
| 0.3         | 1.8                                           | 6.8                                           | 10.3                          |
| 0.4         | 1.9                                           | 6.4                                           | 10.5                          |
| 0.5         | 2.0                                           | 5.9                                           | 10.8                          |
| 0.6         | 2.0                                           | 5.5                                           | 11.1                          |
| 0.7         | 2.1                                           | 5.1                                           | 11.3                          |
| 0.8         | 2.2                                           | 4.7                                           | 11.6                          |

Figure 8. The relationship curve between the reflectivity of wall and the visibility of small target

6. Conclusions

- The research shows that under the same reflectivity of wall, there are the obvious differentiations among the luminances and illuminances of road surface, luminance of wall, and visibilities of small target, which are obtained by the experimental calculation on the different luminous intensity distributions.
- Under the same type of luminous intensity distribution, the reflectivity of wall basically is linearly correlated with each index of illumination. Moreover, the reflectivity of wall is positively correlated with the average illuminance & luminance of road surface and average luminance of wall. The maximum growing slopes respectively are 11.29, 0.45 and 11.50.
• Under the condition when the reflectivity of wall are same, the form of Luminous Intensity Distribution Type 1 (symmetric luminous intensity distribution) has the best gain effects on the illuminance & luminance of road surface. The maximum and minimum average illuminances of road surface separately are 94.07 lx and 89.80 lx. The maximum and minimum average luminances of road surface separately are 5.34cd/m² and 5.16cd/m². The gain of Luminous Intensity Distribution Type 1 on the luminance of wall will be more stable with the increase of wall reflectivity, and the growing slope is approached to 10.16.

• The visibility of small target under the front-lighting illumination is the highest (The minimum value is 10, and the highest value can reach 11.6). The visibility of small target under the back-lighting illumination is secondly highest, and the visibility of small target under the symmetric lighting is most non-obvious.

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