Simulation experiments on counter beam lighting in highway tunnel

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Received 2 June 2010; received in revised form 26 July 2010

Abstract: Counter beam lighting was introduced as well as transverse symmetrical lighting and longitudinal symmetrical lighting. Simulation experiments were carried out by using DIALux lighting software for the above three lighting methods. The results show that counter beam lighting is more reasonable to be adopted in the tunnel entrance zone because its threshold increment of disability glare is greater. Counter beam lighting can improve the background luminance of the obstacles and lighting efficiency compared with transverse symmetrical lighting and longitudinal symmetrical lighting. Therefore, tunnel lighting energy-saving can be achieved by reducing the road luminance demands and luminaries power. Longitudinal symmetrical lighting is conducive to the large luminaries spacing in the tunnel internal zone; so power consumption can be reduced by decreasing the number of luminaries used. Tunnel walls are unsuitable to pave with smooth or bright material. Installation height of the luminaries has less effect on counter beam lighting.

Keywords: counter beam lighting; simulation experiments; disability glare; lighting efficiency

CLC number: U452, TP391 Document code: A

1 Introduction

Tunnels have the advantages of shorting highway mileage, promoting transport efficiency, using underground space and protecting ecological environment. With the rapid development of the road construction, especially in the highway construction, road tunnel scheme was widely adopted and tunnel project increased steadily. Until 2007, the total number of road tunnels is 4 673 in China. The total length of road tunnels was about 2 555.5 km. According to Ministry of Transport of the People's Republic of China, more than 40 000 km of road tunnels will be built in the future in China [1-2].

Research of tunnel lighting technologies in abroad started earlier and the tunnel lighting technologies are relatively maturer after years of exploration and practice. In the early 60’s of 20th century, the tunnel (named ‘Mont Blanc’ [3]) between Italian and French was able to adjust light by the variation of traffic volume. From the 80’s of the 20th century, many countries in the world promulgated standards of tunnel ventilation and lighting. Currently, the widely accepted standard was CIE No.30.2 1998 [4] formulated by CIE (Commission International d’Eclairage) in 1982. Then the standard was revised twice. In the meantime, corresponding design standards about tunnel lighting were issued in various countries [5-7].

Before 2000, the design of the tunnel lighting system mainly followed “Code for Design of Road Tunnel” (JTJ026090) [8] in China, but it was far from complete. With the rapid development of highway tunnel, “Specifications for Design of Ventilation and Lighting of Highway Tunnel” (JTJ026.101999) [9] was promulgated in January, 2000, based on existing
experiences and advanced technology of foreign countries. It gave elaborate explanation on the composition of tunnel lighting system, the length and luminance of the tunnel section, the overall uniformity and the longitudinal uniformity of the road surface, the distribution of the luminaries, illumination and luminance calculating and so on.

Tunnel lighting system sends necessary visual information to drivers to avoid the potential traffic accident arising from lack of visual information. Consequently, driving safety can be enhanced and driving comfort can be improved. Unlike road lighting, lighting is also needed in tunnel during the day and the lighting problems in daytime are more complex than at night [10]. According to the current standard of tunnel lighting, a long tunnel can be divided into five sections: access zone, entrance zone, transition zone, interior zone and exit zone. Lighting demands for different zones are different. The tunnel access zone is to eliminate the black hole phenomenon; the tunnel transition zone between the tunnel entrance zone and the tunnel interior zone is to avoid strong luminance change and makes luminance level decrease gradually.

Tunnel lighting is also the greatest energy consumption unit in tunnels. In the eleventh five-year plan of national development and reform commission in China, it is clearly stipulated that lighting energy-saving is an important strategic measure to support the sustainable development of national energy [11]. Therefore, establishing a high-efficiency, economic, comfortable and environment-friendly lighting system is the direction of tunnel builders’ continuously pursuit. In this paper, we carried out simulation experiments using DIALux lighting software for counter beam lighting, transverse symmetrical lighting and longitudinal symmetrical lighting, discussed the applied characteristics and energy-saving effects of counter beam lighting, and studied influences of installation inclination angle of the luminaries, wall reflection coefficients and pavement paving materials for counter beam lighting.

2 Counter beam lighting

Tunnel lighting methods must adequately take into account tunnel’s characteristics and driving demands. Current lighting methods mostly adopt symmetrical lighting which includes transverse symmetrical lighting and longitudinal symmetrical lighting. Another lighting method is counter beam lighting widely used in abroad which should be adopted in China, particularly in energy-saving respect [12-14]. Light intensity distribution curve of counter beam lighting presents non-symmetrical distribution along the road axis, and light beam focus against the direction of vehicle driving to improve the background luminance of the obstacles on the road surface and easy identification. However, for symmetrical lighting, the obverse side of the objects usually is lightened, thus the background luminance of the obstacles is reduced, and the safety of drivers driving is affected.

In generally, the larger the difference between the obstacles and the background luminance is, the higher the visibility. If lighting system forms very high luminance on the road surface and the vertical illuminance (a plane at a height of 0.1 m above the road surface and against the direction of the vehicle driving) is low, the difference between the obstacles and the background luminance can be larger [15-17]. The contrast results of three lighting methods were shown in Table 1.

3 Contrast experiments

3.1 Experimental conditions

Simulation experiments were carried out in the model of the tunnel internal zone established by using DIALux lighting software. Suppose that the length of tunnel is 1 000 m, the height of tunnel is 7.0 m, the width of motorway is 8.5 m, two-way traffic with double lane is designed, vehicle speed is 60 km/h, traffic volume is greater than 1 300 vehicles per hour, asphalt pavement is adopted, wall reflection coefficient is 0.75, and the experiment length of the tunnel internal zone is 70 m. In accordance with “Specifications for Design of Ventilation and Lighting of Highway Tunnel” (JTJ 026.101999), the average luminance of the road surface is 2.5 cd/m² which can be converted into illuminance as 27.5lx, the overall uniformity (\( \frac{L_{\min}}{L_{\text{av}}} \), where \( L_{\min} \) is the minimum luminance of road surface, and \( L_{\text{av}} \) is the average luminance of road surface) of luminance is no less than 0.4, and the longitudinal uniformity (\( \frac{L_{\min}}{L_{\max}} \), where \( L_{\min} \) is the minimum luminance of road surface centerline, and \( L_{\max} \) is the maximum luminance of road surface centerline) of luminance is no less than 0.6-0.7.
Table 1  Contrast of three lighting methods

<table>
<thead>
<tr>
<th>Feature</th>
<th>Transverse symmetrical lighting</th>
<th>Longitudinal symmetrical lighting</th>
<th>Counter beam lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>light incident along the direction of tunnel cross section; symmetrical light distribution</td>
<td>light incident along the direction of tunnel vertical section; symmetrical light distribution</td>
<td>light incident along the direction of tunnel vertical section; non-symmetrical light distribution</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Simulation contents

Tunnel LED luminaries produced by Thorn Lighting Co., Ltd, Tianjing, China, were adopted as experimental luminaries. The luminary type is GT78LED64W. Its adjustable angle is from $-15^\circ$ to $65^\circ$, and maintenance factor is 0.65. The luminaries were installed in the center of the tunnel, and installation height of the luminaries was 6.5 m. Simulation experiments were carried out by using DIAlux lighting software for counter beam lighting, transverse symmetrical lighting and longitudinal symmetrical lighting. Under different luminaries spacing, illuminance values of the road surface were collected, and the applied characteristics and energy savings effects of counter beam lighting were discussed.

3.3 Simulation methods

Illuminance values per point on the road surface are influenced by adjacent luminaries. Because we only simulated one section of the tunnel internal zone to carry out experiments, the illuminance adjacent to this section may be different. To avoid illuminance error caused by the situation, we divided calculating area in the center position of the selected tunnel internal zone and distributed measurement points. The calculating area is 50.0 m long and 8.5 m wide. The distribution of measurement points is $21 \times 7 = 147$ (Fig. 1). Illuminance values of measurement points were collected, and the average illuminance of the road surface, the overall uniformity and longitudinal uniformity were calculated.

3.4 Simulation results

When the luminaries spacing is 10 m, 11 m, 12 m, 13 m, 14 m and 15 m, respectively, illuminance values of the measurement points of three lighting methods were collected. The corresponding average illuminance of the road surface $E_{m}$, the overall uniformity $U_{0}$, the longitudinal uniformity $U_{L}$, and the threshold increment of disability glare $T_{l}$ were calculated. Table 2 shows the simulation results. Comparison of the average illuminance of three lighting methods are shown in Fig. 2, and increment percentages of relative illuminance are shown in Fig. 3.

3.5 Results analysis

Date of Table 2 and Fig. 2 show that counter beam lighting has a higher lighting efficiency. The average illuminance of counter beam lighting is higher than longitudinal symmetrical lighting, the average illuminance of longitudinal symmetrical lighting is higher than transverse symmetrical lighting. Therefore, if counter beam lighting is adopted in tunnels, the...
tunnel energy-saving can be achieved by reducing the luminance demands of the road surface and luminaries power. Compared with transverse symmetrical lighting and longitudinal symmetrical lighting, counter beam lighting can save energy about 55% and 26%, respectively (Fig. 3). Meanwhile, counter beam lighting is more suitable to strengthen lighting of the tunnel entrance zone because threshold increment of disability glare of counter beam lighting is much larger than the other two lighting methods. In addition, when the luminaries spacing of longitudinal symmetrical lighting is greater than 15 m, it can be seen from Table 2 that longitudinal symmetrical lighting still meets the lighting demands. Transverse symmetrical lighting and counter beam lighting do not meet the tunnel lighting demands when the luminaries spacing of longitudinal symmetrical lighting is greater than 11 m. The tunnel internal zone is a long lighting section. If the larger luminaries spacing is realized, in a great extent the number of the luminaries will decrease and reduce the electric energy consumption. Longitudinal symmetrical lighting just could meet the demands of the larger luminaries spacing.

![Fig. 2 Comparison of average illuminance of three lighting methods illuminances](image)

### Table 2. Simulation experimental results

<table>
<thead>
<tr>
<th>Lighting method</th>
<th>luminaries spacing/m</th>
<th>Road surface quality</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$E_{av}$/lx</td>
<td>$U_0$</td>
<td>$U_L$</td>
<td>$TI$ %</td>
</tr>
<tr>
<td>Transverse symmetrical</td>
<td>10</td>
<td>36</td>
<td>0.79</td>
<td>0.84</td>
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<tr>
<td></td>
<td>11</td>
<td>33</td>
<td>0.71</td>
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<tr>
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<td>12</td>
<td>30</td>
<td>0.65</td>
<td>0.68</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>28</td>
<td>0.58</td>
<td>0.62</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>26</td>
<td>0.52</td>
<td>0.56</td>
<td>2.79</td>
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<tr>
<td></td>
<td>15</td>
<td>25</td>
<td>0.48</td>
<td>0.53</td>
<td>3.19</td>
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<tr>
<td>Longitudinal symmetrical</td>
<td>10</td>
<td>50</td>
<td>0.82</td>
<td>0.87</td>
<td>6.43</td>
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<td></td>
<td>11</td>
<td>45</td>
<td>0.78</td>
<td>0.83</td>
<td>6.27</td>
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<tr>
<td></td>
<td>12</td>
<td>42</td>
<td>0.75</td>
<td>0.78</td>
<td>7.79</td>
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<tr>
<td></td>
<td>13</td>
<td>39</td>
<td>0.69</td>
<td>0.76</td>
<td>7.34</td>
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<tr>
<td></td>
<td>14</td>
<td>35</td>
<td>0.68</td>
<td>0.74</td>
<td>6.26</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>33</td>
<td>0.65</td>
<td>0.73</td>
<td>8.81</td>
</tr>
<tr>
<td>Counter beam lighting</td>
<td>10</td>
<td>68</td>
<td>0.72</td>
<td>0.81</td>
<td>15.61</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>62</td>
<td>0.63</td>
<td>0.73</td>
<td>15.94</td>
</tr>
<tr>
<td></td>
<td>12</td>
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<td>0.59</td>
<td>0.67</td>
<td>17.88</td>
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<tr>
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<td>0.56</td>
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<td>17.46</td>
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<td>49</td>
<td>0.48</td>
<td>0.58</td>
<td>16.50</td>
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<tr>
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<td>15</td>
<td>46</td>
<td>0.43</td>
<td>0.54</td>
<td>18.86</td>
</tr>
</tbody>
</table>

Notes: $E_{av}$: Corresponding average illuminance of the road surface; $U_0$: Overall uniformity; $U_L$: Longitudinal uniformity; and $TI$: Threshold increment of disability glare
Effect of some factors on counter beam lighting

4.1 Effect of luminaries inclination angle

The effect of installation inclination angle of the luminaries on counter beam lighting is shown in Fig. 4. The simulation parameters are as follows: the luminaries are installed in the center of the tunnel, type of the luminaries is GT78LED144W, installation height of the luminaries is 6.5 m, and the luminaries spacing is 1 m. Supposing that the road luminance is $L_e$, and the vertical illuminance is $E_v$. A specific value of $L_e/E_v$ is used. In general, $L_e/E_v \leq 0.2$ for symmetrical lighting and $L_e/E_v \geq 0.6$ for counter beam lighting. $L_e/E_v$ values are calculated when installation inclination angle of the luminaries ($\alpha$) is $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$, and $50^\circ$, respectively.

Fig. 4 shows that the installation inclination angle has profound effect on counter beam lighting. Only when $\alpha$ is greater than about $20^\circ$, $L_e/E_v$ values are higher than 0.6, which meets the demands of counter beam lighting. When $\alpha$ is greater than $40^\circ$, $L_e/E_v$ values quickly increase with the changes of installation inclination angle. Therefore, reasonable adjustment of installation inclination angle of the luminaries is very important.

4.2 Effect of wall reflection coefficient

The effect of wall reflection coefficient on counter beam lighting is shown in Fig. 5. The simulation parameters are as follows: the luminaries are installed in the center of the tunnel, type of the luminaries is GT78LED144W, installation height of the luminaries is 6.5 m, the luminaries spacing is 1 m, and installation inclination angle of the luminaries is $20^\circ$. $L_e/E_v$ values are calculated for the wall reflection coefficient ($\rho$) of 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7, respectively.

Fig. 5 shows that $L_e/E_v$ values decrease approximately linearly as $\rho$ increases. When $\rho$ is less than 0.6, the lighting system is no longer the counter beam lighting. Therefore, the tunnel wall is unsuitable to pave with smooth or bright materials in order to avoid excessive wall reflection coefficient.

4.3 Effect of installation height

The effect of installation height on counter beam lighting is shown in Fig. 6. The luminaries are installed in the center of the tunnel, type of the luminaries is GT78LED144W, installation height of the luminaries
is 6.5 m, the luminaries spacing is 1 m, and installation inclination angle is 20°. $L/E_v$ values are calculated for the installation height ($H$) of 4.0 m, 4.5 m, 5.0 m, 5.5 m, 6.0 m, and 6.5 m, respectively.

Fig. 6  Effect of luminary installation height of on counter beam lighting

Fig. 6 shows that $L/E_v$ values just change in a very small range as $H$ increases, but the lighting is still counter beam lighting. A common feature can be concluded by the data of Figs. 5, 6 and 7 that $L/E_v$ values of concrete pavement are smaller than those of asphalt pavement.

5 Conclusions

The primary function of tunnel lighting is to ensure drivers’ safety and comfort. In this paper, we studied counter beam lighting and factors influencing it. Counter beam lighting can improve the background luminance of the obstacles and lighting efficiency. Therefore, the road luminance demands and luminaries power can be reduced while counter beam lighting is adopted in the tunnel entrance zone. Tunnel lighting energy-saving can be achieved if the luminaries spacing is large by using longitudinal symmetrical lighting. The influences of counter beam lighting are different under the conditions of different tunnel lighting. $L/E_v$ values change notably when installation inclination angle of the luminaries reaches a certain value, which is favorable to counter beam lighting. Excessive wall reflection coefficient in the tunnel entrance zone is not conducive to counter beam lighting, so tunnel walls are not suitable to pave smooth and bright materials. Installation height of the luminaries has little effect on counter beam lighting. The asphalt pavement is better for counter beam lighting than the concrete pavement.

References


Edited by XUE Jing-yuan