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Original

The Evaluation of the Lighting at the Entrance of Very Long Tunnels

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Abstract

Background: One of the major topics related to the very long tunnels is dark hole effect. This is a common phenomenon caused by the sunlight reflected from the surroundings of the tunnel to the eyes of drivers and the lack of sufficient light at the tunnels' entrance, which decreases the contrast of barriers inside the tunnel and also makes it difficult to see potential obstacles at the entrance. The result is an increased risk of traffic accidents in these tunnels. Therefore, the aim of this research is to subjectively assessment the safe rate of lighting in one of the very long tunnels located in the province of Ilam. **Methods**: To subject evaluation the safe rate of lighting at the tunnel entrances, two parameters of the average luminance of tunnel entrance and equivalent luminance are required. In this study, Luminancemeter device model S3 was used to measure the average luminance of tunnel entrance. Then, to calculate the equivalent luminance, a YASHICA108 camera with a 35 mm lens was photographed at a distance between the tunnel entrance and a safe stopping point, and then the Holliday polar diagram was used to calculate equivalent luminance (accordance with the standard CIE88-2004). **Results**: In this study, the average luminance at tunnel's entrance was equal to $17\frac{cd}{m^2}$, the luminance was equal to 127.5 $\frac{cd}{m^2}$. Using the ADRENAL equation, the quality of lightening at the tunnel entrance was less than 1. **Conclusion**: Comparison of the results obtained from the healthy and safety rate of lighting levels at the tunnel's entrance with the De Boer mental scale indicated that a dark hole effect occurs at the entrance of the tunnel under investigation and the light sources installed at the entrance of this tunnel did not have the sufficient ability to inhibit the dark hole effect.

Keywords: Dark Hole Phenomenon; Luminance; Road Tunnels; De Boer Mental Scale; Safe rate of lighting

Introduction

With the development of road transport and in order to reduce traffic load, reduce travel time and save energy consumption, the need to build road tunnels increased;[1] however, very long road tunnels cause stress, fear, anxiety, and accidents among drivers and passengers.[2, 3] One of the roads' main problems is the tunnels' safety; because the severity of accidents, injuries, and casualties in tunnels are higher than open roads.[4] For example, in the Shanxi Yanhu Tunnel in China, a car accident killed 40

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people, injured 12, and ultimately resulted in a direct financial loss of $ 12 million; two other people were killed, and 70 others were injured in another traffic accident at the Hatchi Tunmatsu Tunnel in Japan.[5] Drivers need accurate visual information while driving in tunnels so that they can easily observe the existing obstacles and movements of other vehicles and make the necessary decision in the fastest time;[6] therefore, the visual system plays an important role in driving, and its disorder causes negative effects on drivers' performance.[6] In road tunnels, proper design and lighting systems are effective parameters in improving the visual system.[7] Therefore, lighting system standards such as IESNA PR-22-05 and Cie88 2004 have been provided to improve safety and reduce traffic accidents in tunnels.[8]

One of the major topics related to the very long tunnels is dark hole effect. This effects occurs especially in summer days and as a result of the sunlight Reflection of the environment around the tunnel to the eyes of drivers. Moreover, the insufficient lighting at the tunnels' entrance reduces the contrast of barriers inside the tunnel, and seeing these obstacles at the entrance to the tunnels faces a problem.[9, 10] A study by Amundsen revealed that a significant proportion of traffic accidents happen in tunnels 50 meters before to entering the tunnel, as the rate of accidents in this area proven to be muitiple greater than in the middle of the tunnel.[11] Also, a study by Leedsom, which examined the effect of tunnel entrances on drivers' compliance with the lighting inside the tunnel, showed that 150 meters before to tunnel entrance, drivers focused their attention inside the tunnel and ignored almost all the signs around the tunnel.[12] Because of lighting challenges at the entrances of tunnels and also to reduce possible accidents in these tunnels, CIE in 2004 developed a new standard CIE-88-2004 in this standard, the amount of lighting required to avoidance the drk hole effect determined the tunnels at the entrance, as studies have shown that by applying these standards at the entrance to the tunnels, the rate of traffic accidents can be effectively reduced.[8]

According to the CIE standard, Adrien et al. provided a way to evaluate tunnel entrances' luminance mentally. In this reaserch, drivers were placed in a simulated environment near the tunnel entrance, which with changes in luminance tunnel entrance, luminance environment around the tunnel, and also the change in barrier contrast at the tunnel entrance, participants Due to the changes in these parameters, it was requested to evaluate the quality of lighting to enter safely into the tunnel through the De Boer mental scale.[13] According to this description and considering that study has not been done in Iran related to the safety lighting levels at the tunnels' entry, so the aim of this research is to assessment the safety levels of lighting at the entrance of one of the very long tunnels in Ilam city.

Methods

Azadi Tunnel is located on Hamil Road in Ilam (one of the cities in the southwest of Iran). The length of this tunnel is 1200 meters, and its width is 10.6 meters. According to the luminance of the around the tunnel and luminance of the tunnel entrance, the safety rate of lighting at the tunnels' entrance was estimate according to Equation 1. The method proposed herein allows the determination of both the entrance luminance and the equivalent veiling luminance that influences the eye adaptation. It is weighted for given target visibility or subjective rating and provides more accurate lighting of tunnel entrances that Adrian presented in 2013.[13] Then, to survey the quality of lighting at the tunnel entry, the result of Equation 1 was compared with the De Boer mental scale shown in Table 1.[13]

$$SRN = 6\left(log\frac{L_{th}}{L_{seq}}\right) + 4.1 \qquad \text{Eq. 1}$$

L_{th} = mean luminance at the entry tunnels

L_{seq} = equivalent luminance

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According to Equation 1, the initial step in assessing the safety rate of luminance at the tunnel entrance is ذ the tunnel entrance's mean luminance. As shown in Figure 1, the luminance meter was mounted on a pedestal in the center of the road line and at the height of the drivers' eyes and at an angle of 1 degree below the line of sight, luminance was measured in the center of the grid. Then, according to the CIE standard guidelines, and the longitudinal distance of 4 to 5 meters from each other and the transverse distance of $\frac{1}{6}$ of the width of the road line with the measuring points, the luminance was measured in other points.[14, 15] In this study, to measure the luminance of the tunnel entrance, the height between the road surface and Iranian drivers' eyes was required. According to a study by Nissan and Lahmi and measurements from the height of eye driver's personal vehicles to ground in ordinary cars in the country was 131 cm.[16] The luminance meter was then mounted on a pedestal in the center of the road and at a height between the ground and drivers' eyes, which was difficult and sometimes impossible to install the luminance meter at an angle of 1 degree below the line of sight. Thus, facilitating measurement according to the height between the road surface to drivers' eyes and using the relationships between the sides of the triangle, the distance between the central measuring points at the tunnel entry to the drivers was ascertained 75 meters. Therefore, based on the CIE standard recommendation to prevention natural light interference in the tunnel entrance lighting, the measurements were taken after sunset.[7] Figure 2, the marked points at the tunnel entrance were measured. Figure 1 shows the measured points at the tunnel entrance.

The next step involves determining the luminance of the environment, known as the equivalent luminance. In determining the equivalent luminance, the first step is to determine the safe stopping distance. safe stopping distance is equal to the summation of the distance between the obstacle processing in the brain and the motor reaction to braking so that this distance prevents the vehicle from colliding with possible obstacles on the road.[16] Safe stopping distance is one of the important parameters in lighting design in tunnels, Which is dependent on various factors such as road slope (ascending or descending) (± S), the maximum speed of passing vehicles (U), reaction time of the drivers (t0), gravitational acceleration (g) and the friction coefficient between the tire and the road (f). To determine it, use Equation 2

Eq.2 $SD = U \times t_0 + \frac{U^2}{2 \times g \times (f \pm s)}$

S= road slope (upward or downward) (%)

U= passing vehicle speed limit (m/s)

t_0= reaction time of the drivers (s)

g= gravitational acceleration (g, m/s2)

The friction coefficient between the tire and the road (f, dimensionless)= f

Figure 2 was also using to determine the friction coefficient between the road and the tire, which also based on the vehicle speed and ground condition (dry, wet).

Table 1. De Boer mental scale for evaluating the quality of lighting at the entrance of road tunnels

Lighting quality at the tunnel entrance	De Boer mental scale
Creating a dark hole effect at the tunnel entrances	1<
Insufficient lighting for safe entrance to the tunnel	3
The lighting at tunnel entry is relatively sufficient	5
The lighting at t tunnel entry is sufficient	7
The lighting at the tunnel entry is very suitable	9

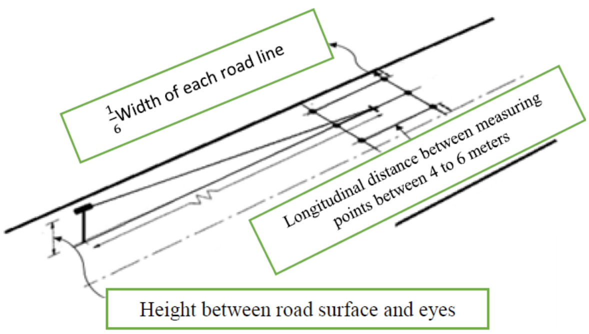

Figure 1. How to measure luminance at the entrance of road tunnels[14, 15]

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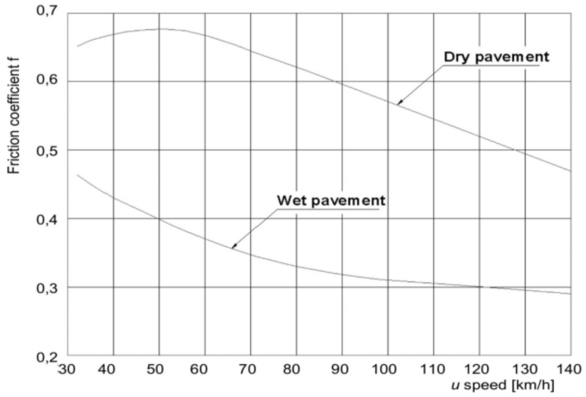

Figure 2. Determining the friction coefficient between the road and the tire

Figure 3. YASHICA108 camera with 35 mm lens

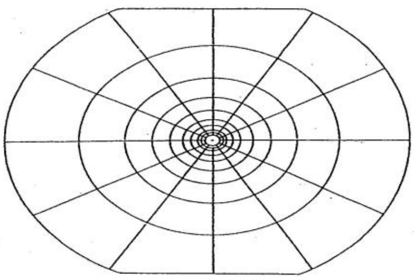

Figure 4. Holliday polar diagram

Table2. Determine the luminance of each part of the rings of the Holiday polar graph

Driving path (in the Northern Hemisphere)	The luminance of the sky ($\frac{kcd}{m^2}$)	Road luminance ($\frac{kcd}{m^2}$)	The luminance of the environment around the tunnel($\frac{kcd}{m^2}$)		
			Grassland	Building	Rock
North	8	3	2	8	3
East- West	12	4	2	6	2
South	16	5	2	4	1

Table 3. The angles of rings of the Holliday polar diagram

rings	central	1	2	3	4	5	6	7	8	9
degree	2	3	4	5.8	8	11.6	16.6	24	36	56.8

After determining the safe stop distance, to determine the equivalent luminance, as shown in Figure 3, a YASHICA108 camera with a 35 mm lens was used, which according to the recommendation CIE88-2004, can cover about 56 degrees in the horizontal and 38 degrees in the vertical direction[3]. After taking a photo of the tunnel entrance, drawing a Holliday polar diagram (Figure 4) on the photo (Figure 5) and according to the position of the driving path and the type of coverage around the tunnel in each part of the polar diagram rings drawn on the tunnel entrance photo, the luminance of each section was determined according to Table 2. It is noteworthy that at first, we considered a ring and determined the percentage of the environment such as rock, and grassland in each ring, then, according to each section's percentage, we multiply then in the luminance given in Table 2. This stage repeat for all rings.

It is noteworthy that the Holliday polar diagram include 9 rings, rings being separated into 12 sections; the angles of rings are shown in Table 3.

After determining the luminance of each part of the rings, the luminance of the whole ring is calculated ($\sum L_{ije}$) and then, according to Equation 3, the equivalent luminance is determined.

$$L_{seq} = (5.1 \times 10^{-4}) \times \sum L_{ije} \qquad \text{Eq.3}$$

Results

Initially, according to Figure 1, after measuring the luminance at all points, the mean luminance at the the tunnel's entry was computed equal to 17 $\frac{cd}{m^2}$. In the next step, to estimate the equivalent luminance as previously stated, a safe stopping distance must first be determined, which is dependent on the maximum vehicle speed, road slope, reaction time, and friction coefficient between the road and the tire. The International Lighting Committee recommends that drivers' average reaction time be taken into account according to studies conducted in the country. A

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research conducted by Ali Mohammadi and colleagues using a driving simulator showed that drivers' average reaction time is 0.69 seconds.[14] Also, in determining the friction coefficient between the road and the tire, they suggested that in places where the mean annual rainfall is more than 75 hours per year, the road surface should be considered wet when designing lighting in road tunnels.[17] Therefore, based on the 10-year information of the 40780 meteorological stations of Ilam province, the average rainfall was 73.8 days. As a result, to determine the friction coefficient between the road and the tire, the road conditions were considered wet, which according to Figure 2, using the speed of vehicles and the wet road surface, the friction coefficient between the road and the tire was determined. Then, according to the variables in Table 4 and Equation 1, the safe stopping distance at the tunnel entrance was calculated to be 64 meters.

Table 4. Necessary variables in determining safe stop distance

Driving path	Maximum permitted vehicle speed (meters per second)	Road slope	Reaction time (seconds)	Friction coefficient between road and tire
South line of tunnel entrance	18	-0.03	0.69	0.35

Therefore, as shown in Figure 5, a safe stopping distance was taken from the entry of the tunnel , and then a photo was taken of the tunnel entrance at the height of 131 cm above the ground. Then, by drawing a Holliday polar diagram on the relevant photo and by using the networking of each slice of the rings, the percentage of environmental factors (rock, grassland, road, etc.) in each part of the ring was determined. And then, according to Table 1, the luminance in each part of the rings was determined, as shown in Table 5. It should be noted that, as shown in Table 5, in some parts of the outer ring of the Holiday diagram, the luminance is not calculated, which the CIE standard states that in these parts, the dashboard and roof of cars prevent the luminance from reaching the eyes of drivers.

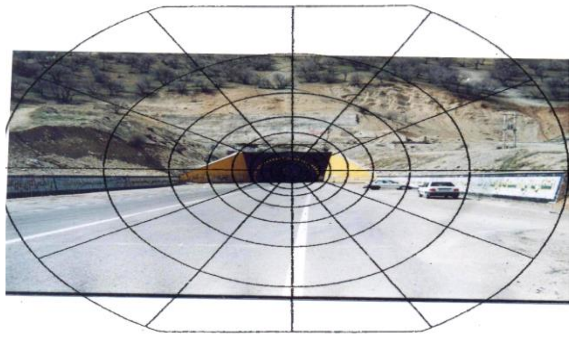

Figure 5. Determining the equivalent luminance at the tunnel entrance based on the Holliday polar graph

Table 5. The amount of luminance in each part of the rings of the Holiday polar diagram

Sections	rings								
	1	2	3	4	5	6	7	8	9
1	1	2	3	5.0	5.0	5.0	5.0	5.0	Not calculated
2	5	5	5	5.0	5.0	5.0	5.0	5.0	5.0
3	0	5	5	2.9	4.5	4.5	4.3	4.7	4.7
4	0	0	0	0.2	3.8	2.8	1.0	1.0	1.0
5	0	0	0	0.0	0.95	1.0	1.0	1.0	1.8
6	0	0	0	0.05	1.0	1.0	1.0	1.5	Not calculated
7	0	0	0	0.1	1.0	1.0	1.0	1.6	Not calculated
8	0	0	0	0.0	0.55	1.0	1.0	1.1	2.0
9	0	0	0	0.0	3.6	3.4	1.15	1.0	1.02
10	0	0	0	2.5	4.5	4.6	4.8	4.8	4.8
11	0	0	0	5.0	5.0	5.0	5.0	5.0	5.0
12	0	2.5	5	5.0	5.0	5.0	5.0	5.0	Not calculated
The luminance of each ring	5	5	5	25.75	39.6	29.9	35.25	36.7	25.32
The luminance of the whole rings	$\sum L_{ije=250.02} \frac{kcd}{m^2}$								

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Table 5 explain that after determining the luminance in all the rings of the Holliday polar diagram, using Equation 3, the luminance equivalent to 127.5 $\frac{cd}{m^2}$ was determined. Therefore, according to the equivalent luminance and luminance of the tunnel entrance and using Equation 1, the safe level of lighting at the entry of the tunnel was ascertained to be -1.1(Less than 1), which can be compared with the De Boer mental scale shown in Table 1. Also, it may be concluded that a dark hole effect is created at the entrance of this tunnel.

Discussion

Road tunnels play an critical role in the transportation . In Iran, due to mountainous areas and some large cities due to heavy traffic, tunnels are drilled. Lighting in road tunnels should be provided to such an extent that it creates visual adjustment of the eye when entering the tunnel[18, 19] reduce the contrast of obstacles inside the tunnel as drivers approach the tunnel due to the radiance of the environment around the tunnel. It also makes it difficult to see the obstacles inside the tunnel, which results in the creation of the dark hole phenomenon. researchers have suggested that this phenomenon causes drivers to hesitate to make appropriate decisions when approaching the tunnel.[20, 21] Therefore, the result is an increase in the severity of injuries caused by traffic accidents in these tunnels.[22, 23] This study indicated that a dark hole effect occurs at the entrance of the studied tunnel. This problem has the potential to greatly raise the probably of traffic accidents at the entrances of these tunnels. To reduce this phenomenon, by reducing the luminance equivalent to the environment around the tunnel and increasing the luminance at the entry of the tunnel entrance, the probability of traffic accidents can be prevented, and driving safety can be achieved. researchs have suggested ways to less the occurrence of the dark hole effect, such as the study of ONAYGİL, which tried to reduce the effect of dark hole, reduce the luminance of the environment around the tunnel in the eyes of drivers, and by planting trees and painting the surfaces around the tunnel with dark colors, that were significantly reducing glare in the eyes of drivers and then reduced the luminance required at the entrance to the tunnels.[20]

Studies show that because asymmetric lights scatter the illumination of the light source in the opposite direction of the vehicle, it increases the luminance of the road surface and reduces the luminance of the obstacle, which results in increased visibility of obstacles at the entrance to the tunnels. However, In the studied tunnel, symmetrical lights have been used that illuminate the road surface and the obstacle equally, which results in reducing the contrast between the obstacle and the road surface and thus increasing the dark hole phenomenon and thus the risk of traffic accidents in this tunnel. It should be noted that among the advantages of asymmetric lights at the tunnels' entrance, its disadvantages such as dazzling and flicker effect should be mentioned that if the necessary care is not taken in installing these lights, it will cause problems in creating annoying dazzling.[22] Porous asphalt (ZOBA) was used at the entrance of the studied tunnel. Various studies have shown that the level of road coverage at the entrance of road tunnels is important as background lighting for road barriers. A study conducted by Martinez showed that Porous type asphalt (ZOBA) reduces the contrast in asymmetric lights, so it is recommended not to use this type of asphalt at the entrances of these tunnels.[22]

In recent years, In addition to the discussing safety at the entrance of road tunnels, other concerns have been raised, including high energy consumption at the entrance of this tunnel, which led researchers to reduce energy consumption in addition to improving safety.[18, 19, 22] Therefore, in recent years, laboratory studies have been conducted in connection with the installation of translucent layers outside the entrances of road tunnels. In addition to the improving safety at the entrances of these tunnels, it reduces energy consumption, increases equipment maintenance, and reduces damage. It has also reduced environmental damage.[24] For this reason, a study conducted by Garcia in one of the tunnels in Spain showed that the required luminance at the entrances of the tunnel understudy was equal to 560 and 402$\frac{cd}{m^2}$, respectively, which after installing a semi-transparent layer Near the tunnel entrance and luminance measurements at the tunnel entrance found that in one of the tunnel paths during the day, there was no need for artificial lighting at the beginning of the tunnel and in the other tunnel entrance after installing a semi-transparent layer 76% reduction in energy consumption at the tunnel entrance. Found. Besides, translucent layers made drivers' eyes better and faster adapt to the darkness inside the tunnel.[25]

Conclusion

In this study, the safe rate of light at the tunnels' entrance was determined, which by comparing with the De Boer mental scale showed that the light generated from artificial sources at the entrance of these tunnels did not have the necessary ability to prevent the dark hole effect. Adaptation of drivers' eyes at the tunnel entrance increases the risk of road accidents at the tunnel entrance. Therefore, in this study, it is suggested that by presenting methods such as planting trees, painting the surfaces around the tunnel with colors with low reflection coefficients, installing asymmetric lights, and also using new methods such as translucent surfaces near the entrance of this tunnel Prevented the effects of dark holes at the entrance of these tunnels.

Conflict of interests

Authors declare no conflicts of interests.

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