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# Parameters Affecting the Determination of the Tunnel Threshold-Zone Luminance

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**Abstract**

In order to determine the level of the tunnel threshold-zone luminance, as series of visual experiments were conducted using a tunnel entrance simulator. For the experiments 110 observers were used. The results showed that the assumed parameters for the definition of the critical object and environmental conditions strongly affect the recommended luminance levels.

**Key Words:** Threshold-zone luminance, Visual ability, Duration time, Perception probability, Safe stopping distance.

## Tünel Eşik Bölgesi Parıltısının Belirlenmesinde Etkili Olan Parametreler

**Özet**

Bu çalışmada, tünel eşik bölgesi parıltı seviyesinin belirlenmesi için, bir tünel girişi simulatörü kullanılarak bir seri görüş deneyleri gerçekleştirilmiştir. Deneylerde 110 gözlemci kullanılmıştır. Deney sonuçları, kritik cisim tanımı ve çevre koşulları için kabul edilen parametrelerin önerilen parıltı seviyeleri üzerinde çok etkili olduğunu göstermektedir.

**Anahtar Sözcükler:** Eşik bölgesi parıltısı, Görüş yeteneği, Gözlem süresi, Algılama olasılığı, Emniyetle durabilme mesafesi.

## Introduction

The increased volume of traffic has made the construction of suitable tunnels necessary. However, they are expensive. A long tunnel, when it is not lit, especially on bright sunny days, appears as a black hole for the approaching driver. In order for the driver not to lose his visual ability, and carefully taking the dark adaptation of the eye into account, it is necessary to have intensive lighting in the threshold (first) zone of the tunnel. If the lighting in the tunnel is at the same level as daylight, this may be a solution to this problem. When the costs of the establishment and operation required to achieve such lighting are taken into account, daylight level will not be economically appropriate. If only the budget reduction is considered and a low luminance level is provided, that will disturb and hinder the visual ability of drivers, and traffic conditions will become very dangerous. The engineer has to find the economically sufficient and optimum solution that provides the most effective lighting of the threshold zone at the minimal luminance level.

Generally, the threshold zone luminance level is given as a ratio between the threshold zone luminance and the access zone luminance. There are major differences among the ratios that are given in national and international recommendations. For example, in Publication CIE 26 (1973) about tunnel lighting, based on Schreuders research, the ratio is given as 1/10. Furthermore, the Japanese recommendations, based on Narisada and Yoshikawa's studies (1974 and 1975), recommend the ratio to be 1/42 with the speed factor of 100 km/h, or the ratio 1/117 with the speed factor of 40 km/h. The reasons for these differences are the assumptions about the environmental conditions and the lighting arrangements employed in the tunnels. To find the optimum solution for road tunnels, two technical reports have been published in recent years by CIE:
Pub. CIE 61 (1984) "A survey of fundamentals for determining the luminance in the threshold zone" and Pub. CIE 88 (1990) "Guide for the lighting of road tunnels and underpasses". Two Technical Committees of Division 4 of CIE are continuing their studies on tunnel lighting: TC 4-24 "Calculation and measurement of tunnel lighting quality criteria" and TC 4-35 Tunnel lighting(CIE 88-2, 1999).

In order to determine the level of the threshold-zone luminance and the effects of the assumed parameters, a series of visual experiments were conducted using a tunnel entrance simulator in the Lighting Technology Laboratory of Istanbul Technical University. The objective of this study was to clarify the discrepancies between the experimental results of various published materials.

## 1. Experiments and Measurements

### 1.1. Aim of Experiments

The aim of the experiments was to determine the influence of assumed parameters of the critical object and environmental conditions on the necessary background luminance, in order to prevent a black hole appearing for the approaching driver and to provide sufficient visual ability in the tunnel. Necessary background luminances are determined by observing a critical object, which has a known contrast, on a known adaptation luminance and at a certain angular size for a very short duration of time.

### 1.2. Choice of Limits of Parameters to be Varied

Road safety demands that obstacles which constitute a danger are seen and recognized soon enough to carry out the maneuver required, without endangering the driver's own vehicle, the obstacle or the rest of the traffic. The maneuver in question can be, for example, stopping in front of a large obstacle or changing direction to avoid a small obstacle. The critical size of this obstacle corresponds roughly to the size that could harm the body structures of normal cars. An object 20 cm $\times$ 20 cm is of minimal danger on the road for a normal sized vehicle. On the other hand, if a larger object is employed for the determination, the luminance value will not be very economically advantageous because of the necessity to build up a longer threshold zone.

If experiments and applications of tunnel lighting during the past 30 years are carefully examined, it can be said that an object 20 cm $\times$ 20 cm with a contrasting luminance against its background of 20 - 30%, observed 100 meters ahead, presented for a short duration of 0.1 second or 0.2 seconds with 75% probability of perception, realistically represents the visual ability of a driver who is approaching a tunnel under tangible traffic conditions (Onaygil, 1990).

It is frequently necessary to see and recognize objects or parts of objects of smaller dimensions or with low contrasts. However, in practice objects should be seen at various distances, and most obstacles are larger than the critical object and partly of greater contrasts. It is therefore necessary to investigate not only the critical object but other objects of different parameters as well.

In these experiments contrast values of 26%, 53% and 81% were achieved. The adaptation luminance values, which can occur during daytime in front of the tunnel gate, were taken. These levels range from 1000 cd/m$^2$ up to and including 7500 cd/m$^2$.

It is prerequisite for tests that the state of adaptation is not altered during presentation of an object. The shutter has to be opened for as short a time as possible. Most experiments are carried out for t=0.1 s and also with 0.2 and 0.3 seconds duration. Measurements have to be independent of the dimension of the size of the shutter opening. Because of this, a value of $\alpha_2 = 3°$ is used to maintain a stable state of visual adaptation during observations.

The critical object can be seen from 100 meters under an angle of 7$'$. When the speed limit is 80 km/h, 100 meters is an adequate distance considered safe for reaction and stopping. While driving at 55 km/h, 50 meters is considered a safe stopping distance (DIN 67524, 1972 and SEV 8915, 1983). The critical object can be seen from 50 m under an angle of 14′. For considering different angular sizes of the critical object that correspond to different safe stopping distances, 7′, 14′ and 28′ view angles are used.

Furthermore, to determine the influence of the observation probability, experimental results are evaluated based on 50%, 75% and 90% probability.

### 1.3. Measuring Arrangements

In these experiments, the observer (G) is placed 4 meters in front of a 1.4 m × 1.4 m white square screen (E)(see Fig. 1). With this arrangement an observation is made from a distance of 100 m at 2×10° angle. Up to about 2×5° outside the center, the luminance is uniform within the measuring accuracy. An opening closed by a shutter is made in the center of this screen. The opening subtends an angle of $\alpha_2$ (see Fig. 2). The shutter is only open for a short time t; in this way a surface with luminance $L_2$ is displayed and at the same time an object (O) is observed at an angle $\alpha_3$ with luminance $L_3$.

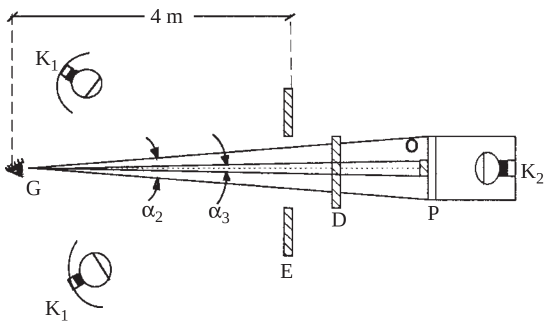


**Figure 1.** Diagram of Experimental Setup

Internally mirrored 220V/150W incandescent lamps ($K_1$) are used for lighting the screen (Fig. 1). The shutter consists of a large disc (D), driven by a synchronous motor. A small gap in the disc shows the opening for fixed durations t=0.1s, 0.2 and 0.3 seconds. The angle $\alpha_2$ also has a fixed value of 3°.

The simultaneous display of a background with luminance $L_2$ and an object with luminance $L_3$ is achieved by placing in front of lamp $K_2$ a vacuum-evaporated glass plate (P). A 220V/150W dimmable lamp with an opal bulb is used for $K_2$. Three glass plates having in their centers different sized squares are used for characterizing the following angular sizes of the object (O): 7′, 14′ and 28′. Transmissions and thus luminance ratios between $L_2$ and $L_3$ are fixed to 26%, 53% and 81%.

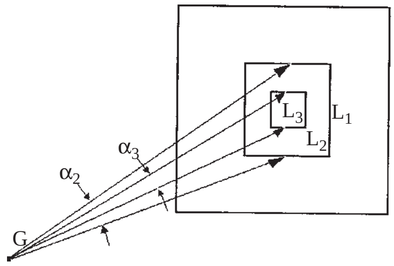


**Figure 2.** Diagram of Luminances and View Angles

The luminance $L_2$ can be adjusted between 1.0 cd/m$^2$ and 1200 cd/m$^2$ by regulating the voltage of the lamp $K_2$. Since the value of $L_2$ has to be changed very often in each series of the experiment we use 24 fixed steps of $L_2$ logarithmically divided over two decades. This is done to save time and to avoid errors of adjustment.

### 1.4. Measuring Procedure

Prior to the beginning of the experiment, the observer looks continually at the uniformly lighted screen for at least two minutes. After the adaptation time to a certain luminance $L_1$, an object with contrast C and 7′ angular size is shown several times for 0.1 second. $L_2$ is changed in a random sequence unknown to the observer. A number of successive values of $L_2$ are shown. These values are situated around the observation threshold that is estimated on the basis of a short test directly preceding the actual experiment. Each of these $L_2$ values, at least 5 in number, is shown five times. After each presentation of the object, the observer has to state whether he is certain that he has seen the object or not.

The reaction that the observer has to give consists of a choice of two possibilities: "positive reactions" in which he states that he is certain that he has seen the object, and "negative reactions" in all other cases. This type of appraisal is called phenomenal report.

For each observer a group of at least 25 observations for one value of $L_1$ and one value of C are plotted in a diagram as shown in Figure 3. The abscissa gives the consecutive steps for $L_2$ and is therefore a scale for log $L_2$. The ordinate states the number of positive reactions with the relative $L_2$ values and can be considered as giving the observation probability.

The best fit to points on the diagram is a straight line, which is shown in Figure 3.

| Name: A.K. | Datum: 30.3.96 |
|---|---|
| Age: 45 | $L_1$=5000 cd/$m^2$ |
| Volt. pos. 50% | 9.0 |
| Volt. pos. 75% | 10.5 |
| Volt. pos. 90% | 11.45 |

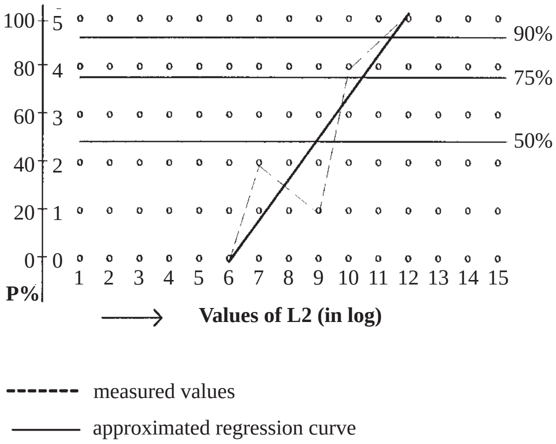


**Figure 3.** Example of Recording Data

The straight line cuts lines of 50%, 75% and 90% observation probability at certain points. $L_2$ values belonging to these points can be found by interpolation. This procedure is achieved for each observer and for each adaptation luminance level and contrast of the critical object. The experiment belongs to the type known as "constant stimuli" (Schreuder, 1964).

In the second stage, experiments are repeated for 0.2 and 0.3 seconds duration. After the adaptation to the level of 5000 cd/m$^2$, an object with contrast C and $7'$ angular size is shown several times for examining the influence of different duration times.

To investigate the influence of variations in angular size of the critical object, another group of experiments is carried out. Measurements are made for $14'$ and $28'$ angular sizes of the critical object with 26% contrast for an adaptation level of 5000 cd/m$^2$ for a duration of 0.1 s.

All observations are plotted in a similar manner in the same type of diagram shown in Figure 3.

### 1.5. Results

Experiments are conducted using 110 observers with normal sight required to obtain a driving license. Their ages are between 20 and 65, representing possible drivers. Ten observers are female.

In order to match the background luminance data found at the simulator with a certain probability, with those for the threshold luminance required under tangible conditions, all the results of the experiments were multiplied by a factor of 4. Adrian (1982) defined this factor by comparing his laboratory test results with those of Rober and Howard's experiments which were conducted under real road conditions in 1938.

**Table 1.** Relationship between the adaptation luminance $L_1$ and the required background luminance $L_2$

| $L_1$ (cd/m$^2$) | C(%) | | |
|---|---|---|---|
| | 26 | 53 | 81 |
| | $L_2$(cd/$m^2$) | | |
| 1000 | 46.0 | 25.2 | 24.9 |
| 1500 | 50.4 | 30.4 | 27.2 |
| 3000 | 144.9 | 47.1 | 29.6 |
| 5000 | 205.3 | 58.0 | 32.4 |
| 7500 | 296.4 | 63.6 | 34.0 |

(p=75%; $\alpha_2 = 3°; \alpha_3=7'$; t=0.1 s)

**Table 2.** Relationship between the probability p and the required background luminance $L_2$

| p (%) | $L_1$ (cd/m$^2$) | | | | |
|---|---|---|---|---|---|
| | 1000 | 1500 | 3000 | 5000 | 7500 |
| | $L_2$ (cd/m$^2$) | | | | |
| 50 | 39.4 | 43.5 | 118.0 | 159.3 | 181.0 |
| 75 | 46.0 | 50.4 | 144.9 | 205.3 | 296.4 |
| 90 | 51.7 | 55.1 | 159.3 | 226.3 | 333.5 |

(c=26%; $\alpha_2 = 3°; \alpha_3=7'$; t=0.1 s)

Table 1 represents average values of the required background luminance found from the first group of experiments. In that group adaptation luminance levels and contrast of the critical object are taken as the parameters. Results are also evaluated based on 50% and 90% probability. The average values are given in Table 2.

The average values of the results from the second and third group of experiments are shown in Tables 3 and 4 respectively.

**Table 3.** Relationship between the duration t and the required background luminance $L_2$

| t | C (%) | | | C (%) | | |
|---|---|---|---|---|---|---|
| | 26 | 53 | 81 | 26 | 53 | 81 |
| (s) | | $\log L_2$ | (cd/m$^2$) | | $L_2$ | (cd/m$^2$) |
| 0.1 | 2.31 | 1.76 | 1.51 | 205.3 | 58.0 | 32.4 |
| 0.2 | 2.12 | 1.55 | 1.42 | 131.9 | 35.5 | 26.3 |
| 0.3 | 1.94 | 1.49 | 1.33 | 88.1 | 30.6 | 21.3 |

($L_1$=5000 cd/m$^2$; p=75%; $\alpha_2 = 3°; \alpha_3 = 7'$)

**Table 4.** Relationship between the angular size of the object $\alpha_3$ and the required background luminance $L_2$

| $\alpha_3(')$ | | | Luminance ratio | |
|---|---|---|---|---|
| 7 | 14 | 28 | $L_{2(14')}/L_{2(7')}$ | $L_{2(28')}/L_{2(7')}$ |
| | $L_2$ | (cd/m$^2$) | | |
| 204.0 | 44.0 | 33.2 | 0.216 | 0.613 |

$(L_1 = 5000cd/m^2; C = 26\%; p = 75\%; \alpha_2 = 3°; t = 0.1s)$

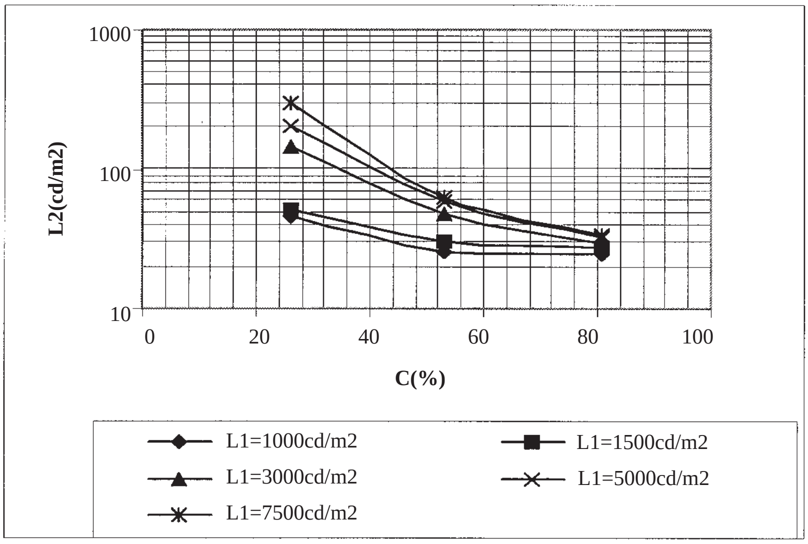


**Figure 4.** Relationship Between the Contrast of the Critical Object and the Required Background Luminance for Various Adaptation Luminance Levels

## 2. Discussion of Results

A driver can perceive an object ahead only when the luminance contrast existing between the object and its background is greater than the luminance contrast threshold of the drivers eyes. Therefore, the contrast of the critical object is the most important parameter for visual ability in a tunnel. Figure 4 is derived from the results of the first group of experiments, taking the adaptation luminance as a parameter. It shows that the required background luminance decreases steeply for a small increase of the contrast value of the critical object.

Ratios between the adaptation luminance and the required background luminance to provide the sufficient visual ability in the tunnel are given in Table 5 depending on the contrast and observation probability of the critical object. If Table 5 is examined, it is seen that there is a good agreement between adaptation luminance levels in $L_1/L_2$ ratio values for the contrast of 26% but this is not true for contrast values of 53% and 81%. For the 26% contrast for all adaptation luminances, a single average ratio can be estimated.

**Table 5.** The ratios between the adaptation luminance $L_1$ and the required background luminance $L_2$

| $L_1$ (cd/m$^2$) | C (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 26 | | | 53 | | | 81 | | |
| | p (%) | | | p (%) | | | p (%) | | |
| | 50 | 75 | 90 | 50 | 75 | 90 | 50 | 75 | 90 |
| | $L_1/L_2$ | | | | | | | | |
| 1000 | 25.4 | 21.7 | 19.4 | 46.3 | 39.7 | 34.7 | 46.6 | 40.3 | 38.3 |
| 1500 | 34.5 | 29.8 | 27.2 | 56.8 | 49.3 | 45.2 | 65.5 | 55.1 | 50.7 |
| 3000 | 25.4 | 20.7 | 18.8 | 74.4 | 63.8 | 59.5 | 111.6 | 101.4 | 95.7 |
| 5000 | 31.4 | 24.4 | 22.1 | 99.9 | 86.2 | 80.6 | 174.5 | 154.3 | 146.8 |
| 7500 | 31.0 | 25.3 | 22.5 | 138.0 | 117.9 | 107.8 | 257.3 | 220.6 | 206.0 |

$(\alpha_2 = 3°; \alpha_3 = 7'; t=0.1$ s$)$

Ratio values change depending on observation probabilities. If there are $L_1/L_2$ values for only one probability, let's say 75%, it is possible to interchange between other probabilities by multiplying by certain factors. For example, to adapt the $L_1/L_2$ values for 50% probability to $L_1/L_2$ values for 75% probability, a multiplying factor of 1.2 is necessary. On the other hand, to adapt $L_1/L_2$ values for 75% probability to $L_1/L_2$ values for 90%, values must be multiplied by a factor of 1.1.

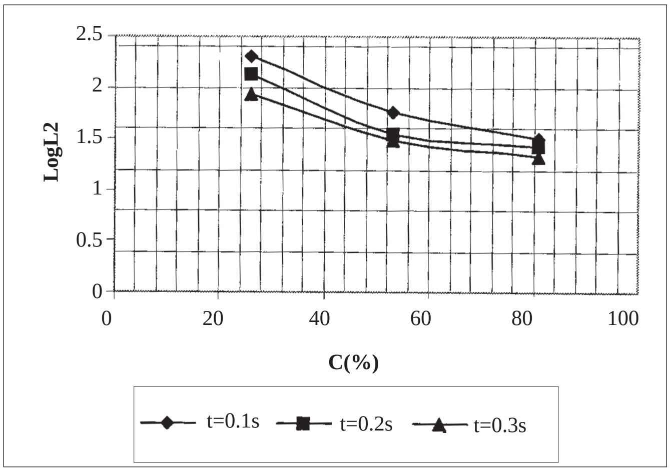


**Figure 5.** Relationship Between the Contrast of the Critical Object and the Required Background Luminance in Log for Various Duration Times

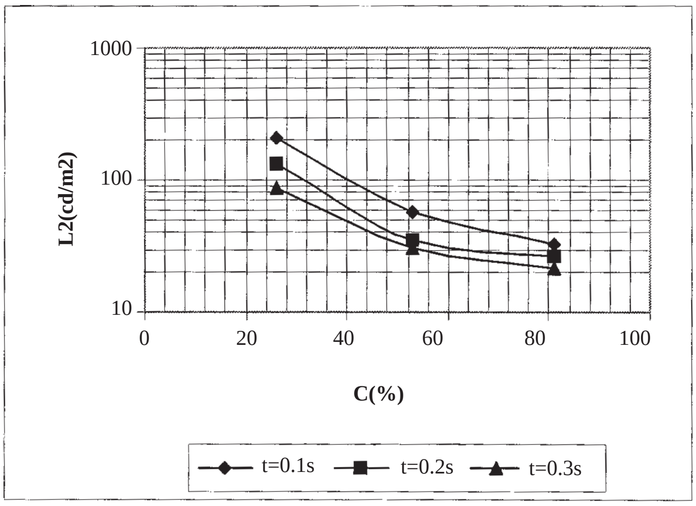


**Figure 6.** Relationship Between the Contrast of the Required Background Luminance for Various Duration Times

Figures 5 and 6 are drawn from the average values in Table 3. These figures show that there is a good agreement between curves for a certain duration time. Low background luminance levels are sufficient for the perception of the object with a certain contrast as duration time increases. A difference of approximately 0.15 in logarithms between $\log L_2$ values for a certain contrast is determined depending on the duration time from experimental results. When this difference is taken as a base, it can be said that to adapt values for t=0.1 s to t=0.2 s, multiplying by a factor of 0.7 and to adapt values for t=0.1 s to t=0.3 s, multiplying by a factor of 0.5 is necessary.

As can be seen from Table 4 the required luminance to percept the 14′ angular size of the object, is only 21.6% of the luminance level that is required for the 7′ view angle on an adaptation level of 5000 cd/m$^2$. The angular size of the critical object has a strong effects on the required background luminance. The angular size of the critical object has a changes with the speed. Therefore determining the speed limit before beginning with the lighting of the tunnel is very important.

## 3. Conclusion

Research about road and tunnel lighting applications carried out until now has defined the critical object with some assumptions under moving view conditions as given below:

"The object of 20 cm × 20 cm size with a contrasting luminance against its background of 20-30%, observed 100 meters ahead, presented for a short duration time of 0.1 second with 75% probability of perception, realistically represents the visual ability of a driver who is approaching a tunnel under tangible traffic conditions".

When this definition is taken as a base, from the results of our experiments, it can be concluded that the ratio between the threshold zone luminance and the access zone luminance is approximately 1/25, and this is sufficient to provide the necessary visual ability for the driver approaching the tunnel entrance at 80 km/h. This value of $L_1/L_2$ obtained from experimental results is in good agreement with the value of the new CIE recommendations (1990 and 1999).

It is clear that the assumed parameters for the definition of the critical object and environmental conditions strongly affect the recommended luminance values. Because of this, in all recommendations and applications, to select the assumed parameters suitably and carefully is very important.

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