DESIGN METHOD FOR THE LIGHTING OF TUNNELS BASED ON THE ASSESSMENT OF THE VEILING LUMINANCE

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ABSTRACT

In usual low-land situations, the adaptation of the visual system of drivers/observers follows without an appreciable adaptation lag the changes in the luminance of the immediate surround.
This luminance may be assessed by adding the intrinsic luminance of the actual objects which are observed and the veiling luminance caused by scatter of light in the media in between.

This system is applied in several new and renovated tunnels in the Netherlands. The high values of the luminance in the threshold zone are arrived at by applying louvres that are not sun-tight, and by artificial light. New design principles of the louvres are introduced.

1. INTRODUCTION

Tunnels for road traffic have been built for a long time. In the beginning, efforts were concentrated on the lighting of the tunnel interior. When speeds and intensities of motor traffic increased this trend was reversed: the major emphasis was placed on the lighting of the tunnel entrance; One might call these two steps the first and the second generation of traffic tunnel lighting respectively. The considerations of the second generation stood as a cornerstone for the recommendations for tunnel lighting of the CIE and for the many ensuing national codes and standards. Many problems have been solved in the following years by the efforts of the practical engineers engaged in the design and operation of new tunnels. It was proven that quite acceptable tunnel lighting installations could be designed. So a practical way of lighting did present itself, the "third" generation, that, however, did lack a theoretical support. It is the aim of this paper to present a number of considerations on which such a theoretical structure for the third generation lighting could be based. These considerations have been applied to a number of new and renovated tunnels in the Netherlands. Recent study did suggest that an important aspect of driving is to keep course. It seems that in the past an undue emphasis was placed on avoiding obstacles so at the moment the theoretical fundament for the third generation lighting is beginning to take shape, a fourth generation lighting is beginning to evolve!

2. THE BASIC FORMULA

The major visibility problem in tunnels is the daytime entrance. The approaching driver requires, however, to see into the tunnel even before he has reached the portal. A certain level of lighting is required in the tunnel entrance. This is conveniently indicated with L_2.
According to the traditional viewpoints the requirements will be expressed in the visibility of specific objects.
The contrast of the specific object is expressed as

$$C = \frac{L_2 - L_3}{L_2}$$

where C is the contrast as would be measured at the location of the object (intrinsic contrast); L_2 and L_3 are the luminance of the background and the object itself.

From a distance the contrast of the object seems to be different. Neural effects and stray light add to the luminances; to all luminances a "disturbance" L_d must be added that can be expressed in luminance terms (Schreuder, 1981). The contrast seems to be reduced.

$$C' = \frac{(L_2 + L_d) - (L_3 + L_d)}{L_3 + L_d} = \frac{L_2 - L_3}{L_3 + L_d} < C \; ; \text{ so } C' = \frac{L_2}{L_2 + L_d} C.$$

It is not possible to measure C' directly. However, $C' = f\,C''$; where C'' is the threshold value of the contrast as is found in laboratory investigations, f is a "field factor".

$$\text{So } fC'' = \frac{L_2}{L_2 + L_d} C.$$

$$(L_2 + L_d)\, fC'' = L_2 C$$

$$L_2 = \frac{L_d fC''}{C - fC''} \qquad (1)$$

In this way L_2 can be assessed if L_d, f and C'' are known and if a value of C is chosen.

This expression (1) is the basic formula for tunnel entrance lighting. The different factors have been established (Schreuder, 1985). We will give a summary here.

The threshold of the contrast sensitivity is given by Adrian & Eberbach (1969).

The logarithm of the threshold luminance difference ΔL is proportional to the logarithm of the adaptation luminance L_A. For 100% probability of perception, free view and an object of 7' (corresponding with 20 cm at 100 m) the expression follows:

$$\log \Delta L = 0.75 \log L_A - 1.$$

For $L_A = 1000$ the resulting threshold $C'' = 0.0133$.

L_d consists of two major components: the first is related to the fact that the adaptation of the visual system is not instantaneous. Schreuder (1981) indicates that this deficiency may be expressed in luminance terms: L_{adef} (of adaptation deficiency).
The second component is the straylight. Apart from the very widely known eye scatter (L_e) we have to acknowledge in the practice of tunnel lighting two more sources: the atmosphere (L_{at}) and the vehicle windscreen (L_w) (Vos, 1983, 1984; Padmos, 1984; Padmos & Alferdinck, 1983, 1983a).
In a first approximation, $L_d = L_{adef} + L_e + L_{at} + L_w$.
For intermediate values of the adaptation luminance ($10 < L_A < 1000$ cd/m^2) the adaptation deficiency may be disregarded.

The light scatter in the eye is the major contributing factors to glare. Vos (1984) summarized all the available material, and concluded that the ocular straylight can be assessed by a relatively simple equation:

$$L_e = a\, E_e \left(\frac{1}{\theta^2} + \frac{1}{\theta^3} \right) \qquad (2)$$

where E_e is the illuminance at the eye (lux) and θ the angle between glare source and line of sight (degrees). For young adults a equals about 10, for 70 year old persons a equals about 20. This equation may be used for $0{,}1 < \theta < 100$ and for point sources and for areas (where an appropriate summation must be applied).

The atmospheric straylight may contribute considerably to the total straylight. Padmos & Alferdinck (1983) concluded to the following relationship:

$$L_{at(d)} = \frac{3.8\, d}{V_m} L_{o(150)} \qquad (3)$$

where $L_{at(d)}$ is the atmospheric straylight (cd/m^2) at a distance d (m) from the tunnel entrance; V_m is the meteorological visibility (m) and $L_{o(150)}$ the average luminance measured within a cone with an apex of 2×10^o around the line of sight (straight ahead) at a location 150 m in front of the tunnel.
L_o is a quantity that is often used in tunnel lighting considerations; see e.g. CIE (1984). However, Schröter (1985) pointed out recently that this quantity can not be applied when the sun is near the line of sight.

Padmos (op. cit) proposes to use only one value of V_m. His own data suggest, however, a simple relationship $\log p = \log V_m - 2.3$ where p is the cumulative probability to have visibility equal or larger than V_m (p in %; V in m; $700 < V_m < 10,000$).

As one might expect, the contribution of the scatter from the windscreen is very complicated and shows a very large variation. Broadly speaking, there are four distinct components:

- scatter due to water droplets (haze, rain)
- scatter due to dirt (both inside and outside)
- scatter due to damage to the windscreen (scratches)
- scatter due the reflection of the vehicle interior in the glass.

The final results are "nominal" values for the straylight components of diffuse light and the central part of the field of view due to scatter in the windscreen (damage and dirt) $L_{w,1}$ and the components from other sources $L_{w,2}$. It is shown that $L_{w,1}$ depends upon the distance, and $L_{w,2}$ not. Padmos (op. cit) gives the following nominal relationships:

$$L_{w,1\ (150)} = 0.07\ L_{o(150)}$$

$$L_{w,2} = 0.05\ L_{o(150)}$$

where $L_{w,1(150)}$ is assessed for the "standard" distance of 150 m. Combined this yields for distance d (m):

$$L_{w\ (d)} = (0.093 + 0.00018\ d)\ L_{o(150)}. \qquad (4)$$

The factor connecting C' and C" can be assessed by making measurements of the threshold of detection in real tunnel situations and in the laboratory. It can be approximated by using the original experiments of Schreuder (1964). Using the Vos formula, L_e can be calculated for the situation as used in the experimental set-up: $L_e = 0.07\ L_1$, where L_1 is the luminance of the (uniform) surrounding field of view.

This yields $f = \dfrac{L_2}{L_2 + L_e} \quad \dfrac{C}{C''}$

Schreuder (1964, p. 74) gives the relationships between L_1, L_2, C and p (the probability of detection).

This yields for f:

$f_{0.1;0.5} = 2.9$ and $f_{0.1;0.75} = 3.27$ (5)

where $f_{0.1;0.75}$ stands for the factor for C = 0.1 and the probability of detection of 0.75.

3. THE SPREAD IN THE BASIC FORMULA

The basic formula can be written as follows

$$L_2 = \frac{(p_{adef} + a' + \frac{3.8d}{V_m} + 0.093 + 0.00018\ d)}{1.5\ (C - fC'')}\ L_2' .\ fC'' \qquad (1b)$$

in which $p_{adef} = L_{adef}/L_1'$. We will discuss the influence of variations of the individual parameter terms.

A. Assume $p_{adef} = 0.2$ in stead of 0.

The result is that $L_2 = 0.114\ L_1'$ in stead of $L_2 = 0.078\ L_1'$.

B. Assume the observers are aged : $a' = 0.142$ in stead of 0.074.

The result is $L_2 = 0.091\ L_1'$

C. Assume V_m is 10,000 m or 1000 m in stead of 2500 m.

The result is $L_2 = 0.046\ L_1'$ or $0.139\ L_1'$ respectively.

D. Assume f = 2.9 in stead of 3.27. The result is $L_2 = 0.067 L_1'$.

E. Assume $L_o = \frac{1}{1.3} L_1'$ in stead of $\frac{1}{1.5} L_1'$.

The result is $L_2 = 0.090\ L_1'$.

F. Assume we select a contrast C of 0.3 or 0.5 in stead of 0.2.

The result is $L_2 = 0.048\ L_1'$ or $0.027\ L_1'$.

G. Assume we select a different distance d: we take 50, 75, 100 and 200 m in stead of 150 m. The result is $L_2 = 0.046\ L_1'$; $0.054\ L_1'$; $0.061\ L_1'$; and $0.096\ L_1'$ respectively.

H. We will not consider another degree of light scratter in the wind-screen; if one would do so, the influence on L_2 might be even larger.

It is not allowed to just add these different discrepancies. The results are summarized in Table 1. (See also Schreuder, 1985).

It does not seem to be useful to be very precise in the calculation or the measurement of the different parameters. Furthermore, it seems that the rule-of-thumb as used in the CIE-Recommendations ($L_2/L_1 = 0,1$) falls well within the area that is covered by the more elaborate assessment as given here (CIE, 1973).

4. EXPERIMENTS ON TUNNEL LIGHTING ASPECTS

During the last decennia a large number of experiments has been made as regards tunnel lighting. A comprehensive review of these investigations is given by Schreuder (1981). In the following we will deal with a number of recent investigations that are directly related to the system of tunnel lighting design that is used in the Netherlands. Many of these investigations were executed by the Locks and Weirs Division of Rijkswaterstaat (the Dutch Ministry of Transport).

The assessment of the veiling luminance

The veiling luminance as a result of the scatter in the eye is a very important component of the visual disturbance. In order to calculate the veiling luminance Rijkswaterstaat designed a computer programme. This programme consists of two parts. The first part enables to construct a perspective view from a road scene - e.g. a tunnel entrance - on the basis of the actual drawings of the tunnel. The second part is the actual calculation of the veiling luminance. This part of the programme is based on the Vos formula and uses the fact that, as it deals with "physical" straylight, the Vos formula may be summated or integrated.
The programme is used as follows: first a perspective view of the tunnel from the selected position of observation is calculated. Then the corners of the area from which the contribution to the veiling luminance is requested are traced. Then the luminance value is fed in. The programme then assesses the contribution of that part to the total veiling luminance. This process is repeated for all relevant parts of the field of view; the sum total of all these parts gives the desired value of the veiling luminance.

Daylight screens the Benelux-tunnel experiments

The Benelux-tunnel, is part of the extremely important ringroad around Rotterdam in the Netherlands. The tunnel consists of two two-lane tubes. At both entrances and both exits aluminium daylight screens over a length of about 130 m have been constructed. In the original design, these screens were "sun-tight". As a result of corrosion of the untreated aluminium the overall transmission of the screen was reduced.

Between 1979 and 1984 a series of experiments was executed in the entrance zone of this tunnel with two distinct aims: first to improve the entrance of the Benelux-tunnel itself, and second to find a more general solution for the design and construction of daylight screens. The experiments consisted of a series of different constructions. Each of the alternatives was left for quite some time to gain experience in different times of the day and different seasons. Generally speaking all experiments consisted of crosswise beams over the road, of different shape, different colour and different interdistance. All of them did represent screens that were NOT suntight: in all cases the direct sunlight could sometimes reach the road. The first seven alternatives consisted essentially of cross beams of 1.22 m high and 0.20 m wide. They were set at different interdistances. Some of these alternatives proved to be reasonable, but none of them was really satisfactory. So, as the final solution another type of beams was used; they were much smaller, having a Z-shaped cross-section with a height of 0.20 m and horizontal flaps at the top and the bottom of 0.065 m. They were painted black, and put perpendicular to the tunnel axis, that is in an East-West position. The entrance zone was subdivided in four sections each 30 m in length. The center-to-center distance of the beams decreased in each following section, being 0.6; 0.5; 0.4 and 0.3 m respectively.

In each case photometric measurements were made. Furthermore the veiling luminance was measured, taking into account the reflections and light scatter in the vehicle windscreens. In each case quite extensive subjective appraisals were made.
The fact that the screens are not suntight proved under some conditions to offer rather severe disturbance. The light scattered in the vehicle windscreen and the additional veil that resulted from the reflection of the vehicle interior in the windscreen could result in severe disturbance. It was found that these problems could not be solved as long as screens were used that were not suntight. However, the disturbance could be reduced by taking care that the luminance within the threshold zone was as high as possible - higher than the values usually quoted for adequate visibility.

It is really important to ensure that the luminance at the end of the threshold zone is reduced gradually and over a sufficient length towards the low luminance in the tunnel interior. If this is neglected, a severe "black hole" effect may result at the end of the threshold zone.

A more complete report of the results is given by Van de Brink (1984). See also Tan et al. (1983).

<u>The shape of the entrance; the Schiphol-tunnel experiments</u>

The Schiphol-tunnel is one of the major road tunnels in the Netherlands. The tunnel is under the main runway of Schiphol, the Amsterdam International airport. The road is the main freeway between Amsterdam to the North and The Hague and Rotterdam to the South. The countryside is completely flat, when approaching it the tunnel looks rather like a construction on the surface - somewhat like a large barn one has to enter. The tunnel itself consist of two tubes each containing three traffic lanes and hard shoulders at both sides.
The entrance zone consisted of a screen of aluminium grids. As the entrance zone consists of a structure on the ground, the subjective pressure on the drivers who had to enter the entrance at high speeds was considerable, particularly as the "barn door" usually seemed to be pitch-black.

The tunnel was to receive a complete "face lift". The first step in this was an investigation made by the Psychology Department of the Nijmegen University. The results of this study are presented in a report by Leeuwenberg & Boselie (1984).

The main recommendations were to discard or at least to reduce the length of the daylight screens so that the "barn door" effect was reduced as a result of the visible sidewalls. The aim was to ensure that the Schiphol-tunnel would look like other more "normal" tunnels. One may expect that drivers will be acquainted with other tunnels so that the Schiphol-tunnel will not present an unexpected sight. Furthermore the perspective view of the road leading into the tunnel will be more clearly defined.
This study is interesting not only because it suggested a considerable

improvement for the Schiphol-tunnel: it also seems to point towards a system in which the elusive notion of "visual guidance" may be operationalized.

A similar reconstruction was made in the Coen-tunnel. This twin-bore four-lane motorway tunnel to the West of Amsterdam was also opened for traffic in the late 'sixties'. Here, the daylight screens were constructed at the bottom of a deep slit and were gradually deeper under the surface. The light levels were too low. The solution was to take away the screens altogether; in this way the light level in the entrance zones was adequate and the disadvantage of direct sunlight on the road was reduced by the crossbeams and struts that were present for constructional reasons. The result is not fully satisfactory, but one feels this is about all that can be done in this tunnel. In earlier stages the facade and the area near the entrance was painted dark as to help the adaptation.

Source	Value nominal	Value altered	Resulting value of L_2/L_1'	Relative difference
L_{adef}	0	0.2	0.114	+ 46%
Age	a' = 0.142	0.07	0.091	+ 17%
Visibility	V_m = 2500	10,000	0.046	- 41%
		1000	0.139	+ 78%
Field factor	f = 3.27	2.9	0.067	- 14%
Standard field	$L_1' = 1.5L_o$	$1.3L_o$	0.090	+ 16%
Selected contrast	C = 0.2	0.3	0.048	- 38%
		0.5	0.027	- 65%
Distance	d = 150	50	0.046	- 41%
		75	0.054	- 31%
		100	0.061	- 22%
		200	0.096	+ 23%
All parameters nominal			0.078	0 %

Table 1. Variation in L_2/L_1'

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