ENTRANCE LIGHTING FOR ROAD TRAFFIC TUNNELS

Paper presented at IPLE Conference, Cambridge, September 14-16, 1982
Article IPLE Lighting Journal 48 (1983) 2 (June): 82-84

R-83-19
Dr. D.A. Schreuder
Leidschendam, 1983
Institute for Road Safety Research SWOV, The Netherlands

SYNOPSIS

The Recommendations of the CIE concentrate on the highest luminance values that are found in practice in the open and aim to provide considerable driving comfort. This leads to stringent requirements for the lighting of the entrance zone of tunnels, regarding both the luminance level in - and the length of - the threshold zone.

Practical experience and theoretical considerations suggest a different solution. Civil-engineering solutions may reduce the outside luminance so that other physiological processes become dominant. In particular, it seems that the influence of slow photochemical adaptation processes is much smaller than the influence of rapid neuronal adaptation processes.

The consequences on the practical design will be discussed, not only for the lighting of the entrance of long tunnels but also for the lighting of short tunnels and underpasses.

1. INTRODUCTION

The oldest tunnels for road traffic have been built during the first half of this century. As regards the lighting, emphasis was put upon the interior, and only little attention was given to the entrance. This was changed drastically in the late fifties and early sixties: a surge in tunnel construction in many countries made a reconsideration necessary. Contrary to the first period (the "first generation") now the results of scientific research - partly the general knowledge on physiology, partly the experimental work performed precisely for this purpose - were used. This resulted in focussing the attention on to the tunnel entrance during the day. Furthermore, the affluent, auto-minded era favoured the considerations of aesthetics and comfort of driving and vision. A large body of research has been reported; and this "second generation" culminated in the International Recommendations for Tunnel Lighting of CIE (1973) based on theoretical considerations (Schreuder, 1964) and practical experience. Very briefly, the main issues of the CIE-Recommendations are:

- At day, driving in the open results in a high constant level of adaptation of the eye. It can be expressed in luminance terms and be designated as L_1;
- Values of $L_1 > 8000$ cd/m^2 are not exceptional;
- The luminance in the first part of the tunnel (L_2) should be at least 0,1 L_1;
- L_1 is stretching to a short distance in front of the tunnel (to the adaptation point). Thus, the value of L_2 must be present in a fairly large area of the tunnel - the threshold zone;
- Further, CIE recommends a specific course of the reduction in luminance from outside to the interior. The course of the luminance throughout the tunnel can be derived from this;
- Finally, a number of additional recommendations are given regarding the interior, the exit, the design, etc. One important requirement must be mentioned: when daylight screening louvres are applied for the lighting of the threshold zone, they <u>must</u> be constructed in such a way that no direct sunlight <u>ever</u> can strike the road below under any circumstances!

However, in the late sixties and in the seventies the picture changed. Firstly it turned out that it was nearly impossible to design tunnel-entrance lighting installations, and pay for them, in accordance with the CIE-Recommendations. The tunnels that were built, were, however, quite acceptable from the point of view of lighting and visibility. Secondly, the turning tide of economics and the growing concern of energy conservation prohibited the excessive lighting, particularly as the number of tunnels grew very rapidly. And thirdly, certain important classes of tunnels (long mountain tunnels and long underpasses) were not adequately dealt with in the CIE-Recommendations. So this prompted a thorough reconsideration of the CIE document.

2. PHYSIOLOGICAL CONSIDERATIONS

When we consider the eye-adaptation, the most important is the adaptation of the fovea, the central portion of the retina, the locus of critical vision. Adaptation means the process of change of the sensitivity of the visual system; the sensitivity is adjusted to the amount of light, to the luminances in the field of view. "Adaptation" designates the adjustments in time; the equilibrium or steady state is indicated by "state of adaptation". The state of foveal adaptation is determined in the first place by the luminance of the area in the field of view that is optically projected on the fovea. This luminance is called L_f. Furthermore, as a result of light scatter, it is possible that light, coming from other areas in the field of view, inpinges on the fovea as well. This scatter may result from impurities in the atmosphere or from dust on the windscreen. Thus, a luminous veil projects itself over the field of view; the luminance of it at the location corresponding to the fovea is called L_v. A similar effect takes place within the ocular media themselves; furthermore there are photochemical and neuronal effects in the eye, which result together also in a luminous veil. The luminance of this veil is called L_{seq} - equivalent because it is not certain which part of the result is really directly caused by light scatter. So in a steady state the state of foveal adaptation can be described as follows: $L_a = L_f + L_{seq} + L_v$.
In this way, the state of adaptation is expressed as well in luminance terms, and can therefore be quantified in cd/m^2.
All this holds for steady-state situations. If, however, the luminance in the field of view is not constant, the visual system has to adapt - this is, in fact, the core of the concept adaptation. When the luminance changes slowly, the adaptation can follow; when, however, the changes in luminance are rapid, the adaptation lags behind. The result is an adaptation deficiency. This deficiency can also be expressed in luminance terms.
The dimension of the adaptation lag does not depend only on the speed in which the luminance changes. The lag is much larger when the luminance diminishes, and particularly so when the starting level is high. And here we come to the first point where the CIE-

Recommendations need to be reconsidered. In the CIE document it was stated that levels of 8000 cd/m^2 or more are not exceptional. This is true in the open; however, it is easy to avoid those excessive levels near tunnel entrances. And furthermore, it is found on the basis of both theoretical studies and practical experience that the adaptation deficiency includes an important factor of comfort. In conclusion, as a rule it turns out that for the practical situation near tunnel entrances that the adaptation deficiency can be disregarded. This conclusion is of great importance for the design of tunnel lighting installations, to such an extent that one may speak of the "third generation" of tunnel entrance lighting. The basis is, then, that in all relevant situations the adaptation can be described as $L_a = L_f + L_{seq} + L_v$.

This expression can be used for deriving the lighting requirements for both what was called the threshold zone and the transition zone - in fact it is doubtful whether it is still useful to make a distinction between these two zones.

Still, there is one point which is somewhat puzzling. It is well-known that adaptation is a matter of bleaching and regeneration of rhodopsin; for low and medium values of the luminance (say up to a few thousand cd/m^2) there is very little bleaching, so the adaptation does not need to take much time. On this basis, one should expect a rather slow and smooth increase in the time required for adaptation when the luminance is increased. The practical experience in tunnel lighting, however, suggests more a rather abrupt change from one phenomenon to another. For practical lighting design it is not important, as it is easily possible to keep the luminance below the critical value when bleaching and regeneration play an important role - in fact, it was just this fact that prompted the new research and resulted in the "third generation" lighting!

3. LIGHTING REQUIREMENTS

The most critical situation for a driver entering at day a poorly lit tunnel is closely before he reaches the portal. The adaptation level is still high (even if the tunnel portal is dark) so that the tunnel entrance looks like a "black hole". This black-hole effect can be avoided if the luminance in the tunnel entrance (called L_2) is about 0.1 of L_a; avoidance of the black-hole can be quantified by stating that an object of 7 min. of arc and a contrast of 0.2 is visible in 75% of the presentations, each of which is for 0.1 second. This particular object is used to describe the visual aspects of the task of driving a car - and even so it is questionable - but it is not rated as a critically dangerous obstacle for traffic. This value of $L_2/L_a = 0.1$ is a practical measure; it is considerably larger than the corresponding threshold value (see Schreuder, 1964).
When considering the black-hole effect, it is of great importance where the driver is looking at. Based on recordings of eye-movements it is likely that under normal conditions drivers start looking at, and into, the tunnel entrance already from a quite large distance (see Narisada & Yoshikawa, 1974). So, $L_2 = L_f$. And thus, $L_a = L_2 + L_{seq} + L_v$. Now, $L_a = 10L_2$, and therefore $L_2 = 1/9\ (L_{seq} + L_v)$.

We may go one step further. The relations we have quoted are valid for all situations; in this way the required luminance in every point in the tunnel can be determined in the same way. Call the luminance at a point x in the tunnel L_x, than, $L_x = 1/9\ (L_{seq} + L_v)$. Here, L_{seq} and L_v are determined from a point at a distance in front (against the direction of travel) of point x. It is customary to take the stopping distance for this distance; this again is usually rounded off to 100 m.
Now the picture is rather simple: at any point in the tunnel the luminance L_x should be $L_x = 1/9\ (L_{seq} + L_v)$ when L_{seq} and L_v are determined from a point 100 m in front of point x. This holds for all points near the tunnel entrance. Thus, there seems little cause for a constant luminance level in the threshold zone, nor for a distinction between threshold zone and transition zone. The major problem now is to establish L_{seq} and L_v. L_v depends exclusively on the local

circumstances, and must be measured in situ. This is often not feasible, and therefore usually L_v is neglected - in fact a queer thing to do, particularly as it is well-known from practice that L_v can be quite large. Schreuder (1964) has reported values up to 1000 cd/m^2. However, further study is needed to handle this problem properly. L_{seq} is more properly dealt with. The surroundings of the area projected on the fovea act as a glare source, and therefore L_{seq} can be assessed by applying the well-known glare formula from Stiles-Holladay, be it that an integral form must be used, as it regards here areas of high brightness and not point sources.
Moon & Spencer (1943) have indicated the way to assess L_{seq} in an analytical way; the relations can be programmed for a digital computer in a straight-forward way. In the Netherlands, research is in progress to assess L_{seq} directly from the design data of the tunnel, by calculating a perspective view of the tunnel as an intermediate step. In this way, different positions and different directions of observation can be dealt with. Also it is possible to apply more modern - and more accurate - alternatives of the Stiles-Holladay-relation (see Vos et al, 1976).
This is a good way to assess L_{seq}; however, more experience is needed. An alternative way is to measure L_{seq} directly by means of a "glare lens" that can be attached to a specific type of luminance meter (Fry et al, 1963). This is a very simple way; it can be applied only, however, in existing tunnels. Furthermore, the accuracy for this purpose is questionable.
One final remark should be made. The assessment of the lighting requirements as given here is based on the old experiments of Schreuder, resulting in $L_a = 10L_x$. It should be noted, however, that there is some doubt whether the Schreuder-experiment can be interpreted in this way. Again here, further study should be undertaken.

4. THE DESIGN OF TUNNEL ENTRANCE LIGHTING

The first thing to do near the entrance of a tunnel is to make all surfaces in view as dark and dull as possible. This may be unfavourable from the point of view of aesthetics, but it is an absolute requirement in order to ensure adequate visibility. The reason has been indicated above: only when the adaptation luminance is under some 3000 to 4000 cd/m^2 the adaptation deficiency can be neglected; and if the level is higher, this deficiency increases very dramatically. So all surfaces must be dark and dull. Furthermore, the sky - often the brightest part of the field of view - should be shielded off as far as possible, e.g. by trees or structures. In this way L_a can be reduced; it can be considerably lower than the luminance in the open (this means that the adaptation point is far ahead of the tunnel). Once more, the current CIE-Recommendations deal primarily with those circumstances when these precautions have not been made; therefore they result in very stringent requirements regarding the lighting, requirements that presently are thought to be excessive form the point of view of costs.
Next, it is necessary to assess the adaptation luminance. At present this is rather difficult because the system of calculation is not worked out in detail yet. Drawings and real models may be of help in making estimates of the adaptation levels. It is important to assess L_a for different locations, and more particularly for different times of the day and of the year in order to include as far as possible the most unfavourable position of the sun.
It is conceivable that the degree of accuracy that can be expected from the above method, is not really needed - more particularly because the conditions of sun, weather, traffic etc. may vary widely. Tan (1977) proposed a classification of tunnels according to traffic, location, compass direction, and "danger class". Such a classification may lead to considerable simplification, and deserves further research. PIARC (1979) suggests an even simpler way: they just give five examples of tunnels with estimated L_a-values; all the designer has to do, is to select the tunnel most similar to his. Again here there is no practical experience yet, but one may suspect that the PIARC system is somewhat oversimplified. When the adaptation

luminance is known, L_2 in the beginning of the tunnel can be found by applying Schreuder's formula $L_2 = 0.1\ L_a$. The restrictions of this have been indicated above.

There are two widely different methods to ensure that such a luminance is present in the first part of the tunnel. The first is to use screened daylight. As regards daylight louvres, the CIE most stringently required that no sunlight whatsoever could reach the road surface. Recent experiments, however, and the experience in several countries do suggest that this requirement is far too stringent. It seems that under certain circumstances and with certain precautions the screens do not need to be sun-tight, thus allowing a much larger transmission of the screen. More particular, it is important that the screens shield the direct sunlight from the driver's eye, and if possible also the sky. The elements should be not too large to avoid flicker effects, but not too small either so that they will not be covered by snow or rubbish. It is possible for snow to freeze under the screen but this does not seem to cause difficulties.
The second possibility is to apply artificial light. Mostly, the lamps are mounted in fitting flush with the walls and/or ceiling. The fittings usually are equipped with optical means so that the main direction of light emission is perpendicular to the direction of traffic. In this way, a maximum level of illuminance may be arrived at, but mostly not a maximum level of luminance. The counterbeam system, quite popular in Switzerland and Austria but virtually unknown elsewhere may be much more promising. By throwing the light predominantly against the direction of traffic, the luminance may be two times as high for the same illuminance as compared with the conventional (cross-wise) lighting. Furthermore, the counterbeam results in a somewhat higher contrast for obstacles on the road. Again here, further research is required, particularly regarding the resulting glare, non-uniformity and flicker (see Blaser, 1982).
L_2 must be adjusted to the prevailing light level out in the open. When screens are used, this adjustment is arrived at nearly automatically. For artificial lighting, a switching system must be installed that takes care of these adjustments. The most accurate way is to measure the adaptation luminance L_a, and to use this directly to regulate L_2 (and the lighting in the tunnel is general).

Both sun-screens and artificial lighting (traditional or counterbeam) have specific advantages and disadvantages. It depends on a number of aspects, particularly cost and energy aspects, which of the two systems is to be favoured.

5. SHORT TUNNELS

The area of short tunnels and long underpasses is neglected in the present CIE Recommendations. The general relation quoted above $L_a = L_f + L_{seq} + L_v$ may, however, be applied here as well, and may serve as a basis for more adequate recommendations.

The main difference, from a visibility point of view, between short and long tunnels is the fact that a short tunnel presents itself as a dark frame rather than as a black-hole, as the long tunnel does. The consequences of this are twofold: firstly, there is small chance for any appreciable degree of adaptation because the central area of the field of view usually does not include the dark tunnel - as in long tunnels - but the bright day-lit area behind the exit of the tunnel. Secondly, large obstacles stick out from the dark frame and therefore are quite well visible as a silhouette against the bright exit, whereas smaller objects may disappear in the dark frame. At present, research is under way regarding the relationship between the size and dimensions of this frame, its luminance and the visibility of relevant objects.

An effective way to enhance the visibility of objects in short tunnels has been indicated already by Schreuder (1964): an opening in the roof of the tunnel - or even a band of high-power light-sources may result in a bright cross-band in the tunnel, thus effectively splitting up the dark frame in two much smaller dark frames. This idea has been applied with success, both with daylight and with artificial light.

A more general approach to the lighting of short tunnels is still under consideration, focussing on two points: which tunnels require daytime lighting, and what should be the luminance in the tunnel to effectively avoid the dark frame?

REFERENCES

Blaser, P. (1982). Die Gegenstrahlbeleuchtung in der Einfahrtzone von Strassentunneln (Counterbeam lighting in tunnel entrances). Bulletin SEV (1982). In print.

CIE (1973). International Recommendations for Tunnel Lighting. Publication No. 26. Commission Internationale de l'Eclairage, Paris.

Fry, G.A.; Pritchard, B.S. & Blackwell, H.R. (1963). Design and calibration of a disability glare lens. Illuminating Engineering 58 (1963) 120-123.

Kabayama, H. (1963). Study on adaptive illumination for sudden change of brightness (In Japanese). J. Illum. Engng. Inst. Japan. 47 (1963) 488-496.

Mäder, F. & Fuchs, O. Beitrag zur Frage der Eingangsbeleuchtung von Strassentunneln. Bullletin SEV 57 (1966) 359-366.

Moon, P. & Spencer, D.E. (1943). The specification of foveal adaptation. Journ. Opt. Soc. Amer. 33 (1943) 444-456.

Narisada, K. & Yoshikawa, K. (1974). Tunnel entrance lighting; Effect of fixation point and other factors on the determination of requirements. Lighting Research & Technology 6 (1974) 9-18.

PIARC (1979). Technical Committee Report on Road Tunnels. XVIth Road World Congress PIARC, Vienna, 1979. Permanent International Association of Road Congresses, Paris, 1979.

Schreuder, D.A. (1964). The lighting of vehicular traffic tunnels. Centrex, Eindhoven.

Schreuder, D.A. (1968). Ein Vergleich von Empfehlungen für Tunneleinfahrt-Beleuchtung. Licht-technik 20 (1968) 2: 20A-21A.

Tan, T.H. (1977). Unpublished report to Subcommittee 3 on Tunnels of CIE TC-4.6.

Vos, J.J.; Walraven, J. & Van Meeteren, A. (1976). Light profiles of the foveal image of a point source. Vision Research 16 (1976) 215-219.

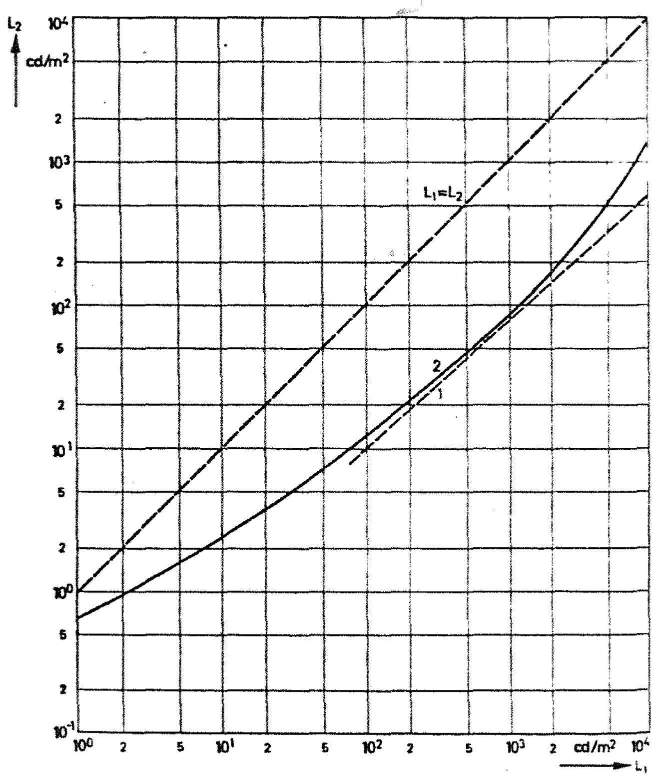

Figure 1. The relationship between the luminance in the tunnel entrance L_2 and the luminance outside the tunnel l_1. Comparison between recommended values required to avoid the "black hole" effect.

---- after Mäder & Fuchs (1966, equation 2) curve 1, and

—— Schreuder (1964, Fig. 3) curve 2.

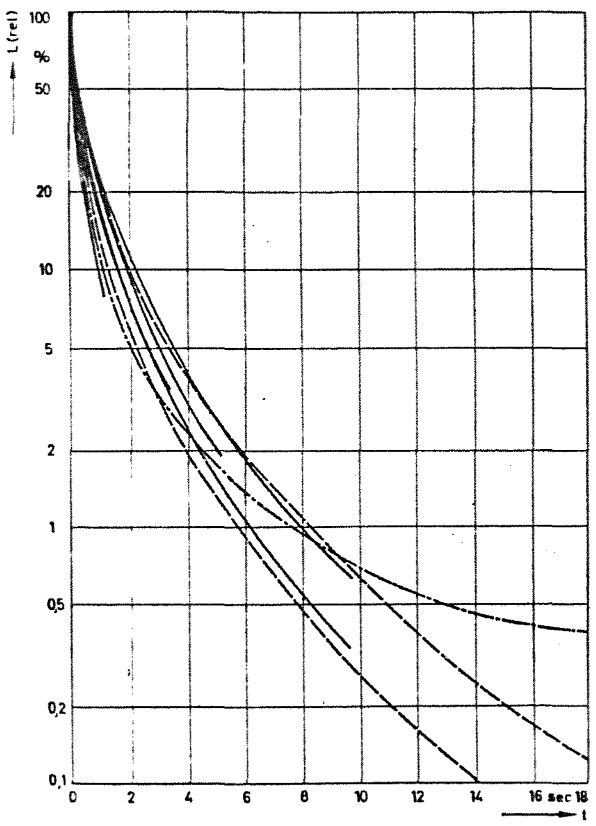

Figure 2. The acceptable degree of deduction of the luminance in a tunnel. A comparison of recommended values: L_o = 100%.
--- after Kabayama (1963, table 3) L_o : 100 ...1600 cd/m^2
- - after Schreuder (1964, table 24) L_o = 8000 cd/m^2
-.- after Mäder & Fuchs (1966, equation 3) L_o = 80 ... 6000 cd/m^2

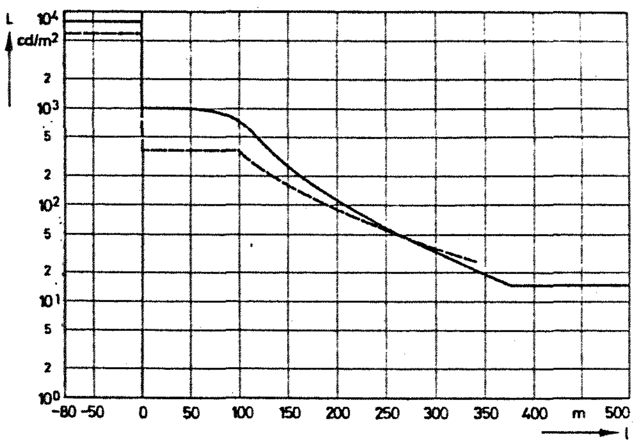

Figure 3. A compariosn of recommendations for tunnel entrance lighting: the luminance through the

--- after Schreuder (1964, fig. 25) for 72 km/h

- - after Mäder & Fuchs (1966, table II) for 80 km/h