THE LIGHTING OF TRAFFIC TUNNELS

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1. INTRODUCTION

During the day, the visual system of car drivers and cyclists is adapted to the very bright daylight. When they enter a tunnel, the visual system must adapt to the low luminance in the tunnel interior. The adaptation is usually disturbed by two factors:

- the bright surroundings of the tunnel entrance restricts the adaptation, and
- the adaptation to a relatively low luminance level may take considerable time.

The major problems for the lighting of tunnels concentrate in the daytime lighting for the first part of the tunnel directly following the entrance (the threshold zone). Other important but less crucial aspects are:

- the transition from the threshold zone to the interior
- the interior itself and
- the exit.

Additional problems are:

- flicker as a result of light sources installed in interrupted rows
- glare by daylight and by luminaires
- nighttime lighting
- emergency lighting
- the lighting problems in short tunnels and underpasses.

The presentation on tunnel lighting concentrates on the daytime entrance lighting of long tunnels.

When considering the daytime entrance lighting, one must take into account one of the peculiarities of the visual system. When the visual system is adapted in a steady-state to luminance values between 30 and 3.000 cd/m^2, adaptation to another value in this range hardly takes any time: it can be considered as being instanteneous. When, however, the steady-state adaptation level is higher than 3.000 cd/m^2, the adaptation takes time; for high values (over some 8.000 cd/m^2) it may take up to half a minute. This peculiarity leads to two distinct theoretical frameworks and to two distinct systems of tunnel lighting.

The first theoretical framework - the steady-state theory - is developed by Schreuder and Narisada. These two approaches were developed more or less independent of each other; the discrepancies that seemed to exist

between these two approaches proved to be not more than a difference in the selection of the parameters. The steady-state theory was the basis for the present CIE Recommendations (from 1977) and for many of the national codes for different countries.
The second theoretical framework - the straylight theory - is developed by Adrian; the lighting system based on it is a.o. described in the revised CIE Recommendations (in preparation).
The two approaches are often described as conflicting; they are, however, conjoint; they will be described the following chapters.

2. THE STEADY-STATE THEORY OF TUNNEL LIGHTING

When the visual system of a car driver who approaches a tunnel is adapted in a steady-state mode to a very high level of luminance L_1 (e.g. 8.000 cd/m^2 or more, corresponding to full summer sun on cement concrete, or to sun on snow), for many seconds the adaptation is almost unchanged when entering the tunnel. In order ro ensure that the driver can look into the tunnel while still outside (to avoid the "black hole effect"), the luminance in the threshold zone (L_2) must be high as well. Experiments made by Schreuder and reconfirmed by Narisada indicate that L_1/L_2 should be lower than 10 in high-speed tunnels and lower than 15 in other important tunnels. These values are taken as the basis for the current CIE Recommendations.

There seems to be a conflict between the results of the experiments of Schreuder and of Narisada. A precise analysis shows, however, that the differences in the results, and even more so the differences between the Recommendations that have been based on these experiments (the CIE and the Japanese Recommendations respectively) are mainly a difference in the selection of the parameters. As has been shown by Schreuder (Lighting Research and Technology, 1971, p. 274), the actual research results are almost identical when they are normalised as regards the time of observation, the pre-adaptation time, and the size and contrast of the object. A difference in the parameters relates to the conditions for which the research results are used. The CIE focusses on tunnels in open country where the adaptation to the dark entrance can begin only at a very short distance in front of the tunnel; the Japanese studies refer primarily to tunnels in mountainous areas, where the adaptation may begin at a much larger distance. Actually, the difference is mainly in the assumption made regarding the position of the adaptation point. We will come back on this item when discussing the details of the different recommendations.

The lenght of the threshold zone is determined by the fact that it takes some time before the adaptation begins to take effect. During this time interval the driver should be confronted by the same luminance value L_2: the threshold zone must be between 30 and 60 m in length (depending on the driving speed and the lay-out of the tunnel portal), and the luminance should be constant. In some cases - e.g. mountain tunnels in steep, wooded slopes - the approach to the tunnel is already so dark that the adaptation begins before the driver enters the tunnel.

After the threshold zone, the luminance may gradually decrease towards the tunnel interior in such a way that the light level is not below the (temporal) adaptation. Experiments have suggested that a reduction in luminance of a factor of 10 in about 2 of 3 seconds can be tolerated, although some discomfort may arise. The corresponding region is called the transition zone.

The luminance level in the interior of the tunnel can be selected over a wide range, provided the transition zone is adequate. For tunnels of intermediate length (under 1.000 m) and heavy high speed traffic a luminance level of 7 to 15 cd/m^2 is often selected; for very long mountain tunnels with moderate traffic and intermediate speed a level of 2 to 4 cd/m^2 (sometimes even 1 to 2 cd/m^2) is preferred. These levels can be accepted if adequate safety measures are provided such as escape routes, lay-by's etc. Tunnels that carry very little traffic (under about 50 vehicles per day) can stay unlit, provided that very good reflectorized road markings and delineators are installed. It should be pointed out that such tunnels are not covered by the present CIE Recommendations.

When designing the tunnel lighting, attention should be given to a number of other points. The tunnel portal should be dark to reduce the L_1. However, in the tunnel itself the surfaces of the road and of the walls should be as bright as possible in order to enhance the efficiency of the lighting system. The luminance values quoted above pertain to the road surface and the lower part of the walls. The walls and the luminaires should be cleaned with regular intervals. The luminance of the road surface and of the walls should be reasonably uniform.

When the light sources are installed in interrupted rows, disturbance by flicker may arise. The frequency between 3 and 8 c/s is particularly disturbing; flicker is absent only when the frequency is over about 50 c/s. Flicker can be a particular problem in the threshold zone when either high-power lamps or daytime louvres are applied.

Tilting the luminaires so that the light is directed mainly against the traffic may increase the luminance efficiency of the installation and may enhance the visibility of obstacles on the road as the contrast increases. This "counterbeam system" is applied with success in several European countries. Glare, lack of visual guidance and non-uniformity of the lighting of the walls may be major problems, however.

The exit presents no problem in tunnels with two-way traffic: the exit for one direction is the entrance for the other. In tunnels with one-way traffic, it is recommended to increase the interior lighting level near the exit to some 20 to 30 cd/m^2.

Special attention should be given to the lighting of tunnels with mixed traffic (cars and cyclists and/or pedestrians). The walls and the road surface will provide for a back-ground against which the objects may be seen. In such tunnels, the visual guidance by means of road markings for the separation of traffic lanes for different categories of traffic participants is essential. Further, emphasis should be placed on the uniformity of the lighting of the walls and of the road surface, whereas frequent cleaning and careful maintenance - so that there are no burn-outs - is essential as well.

3. THE STRAYLIGHT THEORY OF TUNNEL LIGHTING

When the luminance in the field of view or a driver approaching a tunnel is between about 30 and 3.000 cd/m^2, the visual system adapts very rapidly - almost instantaneously - to other luminances within that range. When the driver is close enough to the tunnel portal so that he can fix the entrance opening (at a distance of about 50 to 100 m) the visual system adapts to the luminance in the tunnel entrance - the threshold zone luminance L_2. The value of L_2 should be selected in such a way that the appropriate observations can be made, taking into account the fact that the driver has a driving task to fulfill and that the time for observation of objects is limited. L_2 can be assessed when the threshold of visibility is known, and when the "field factors" that allow for the influence of driving and of the restricted observation time, are known as well.

If one would install a lighting scheme with a value of L_2 assessed in this way, the visibility in the tunnel entrance would be so low as to be completely unacceptable. The most important factor has not yet been taken into consideration: the straylight that originates from the surroundings outside of the tunnel. That light is scattered and it forms a "veil" over the complete field of view. The veil increases all luminance values with the same amount (the equivalent veiling luminance L_s). All contrasts between objects and backgrounds decrease, and consequently objects are more difficult to see.

The veil consists of three almost equally important parts:

- the light scattered in the eye (the entopic straylight)
- the light scattered in the atmosphere and
- the light scattered in the windscreen of the vehicle.

All three parts are highly variable: the entopic stray-light depends heavily on the angle between the source of the scattered light and the line of sight, the conditions of the eyes of the observer, and on his age. The atmospheric straylight depends heavily on the transmission of the atmosphere - on the meteorological visibility, and on the type of aerosol. The windscreen scatter depends heavily on the condition of maintenance of the vehicle, the windscreen itself and the windscreen wipers and washers - and of course on the willingness of the driver to use them. In all three cases a variation of a factor of 10 can easily be found under circumstances that are otherwise perfectly normal.

The influence of the veiling luminance can be assessed as follows. One may select a contrast C_n as "nominal", that is to say the contrast of an object that is considered so important for the traffic safety that its visibility must be ensured. Further, one may define the contrast corresponding with the threshold of visibility at the particular state of adaptation as the field factors that represent changes in observation time and the fact that the observer is engaged in driving a car with f_1 and f_2. When the luminance of the object, the tunnel entrance and the overall surroundings are called L_3, L_2 and L_1 respectively, the contrast of the object is

$$C_n = \frac{L_2 - L_3}{L_2} .$$

With the veiling luminance L_s the actual contrast as presented to the driver is:

$$C' = (L_2+L_s)-(L_3+L_s)/(L_2+L_s).$$

From this follows:

$$C' = \frac{L_2}{L_2 + L_s} C_n$$

When C" is the threshold value of the contrast under the relevant situation, $C' = f_1*f_2*C"$. Thus

$$f_1*f_2*C" = \frac{L_2}{L_2 + L_s} C_n$$

$$(L_2+L_s)f_1*f_2*C" = L_2C_n$$

The object can be observed if the luminance L_2 equals at least

$$L_2 = \frac{f_1*f_2*L_s*C"}{C_n-(f_1*f_2*C")}$$

In spite of the fact that all factors in the formula indicated above are known in principle, the required value of L_2 cannot be assessed beforehand with any degree of accuracy as a result of the large variations that one may encounter in practice. Usually, one selects a number of standard or "nominal" conditions for the assessment of L_2; the selection is arbitrary to a certain extent and reflects a policy decision as to what is the borderline between acceptable and non-acceptable risk. Usually, the selection of the nominal conditions is based primarily on the practical experience with tunnel lighting schemes in nearby locations. As a point of fact, this procedure, although is does not seem to be very precise, resulted in the construction and installation of many outstanding tunnel lighting schemes!

Under the assumptions of the L_s-theory there is not an actual threshold zone: when the driver approaches the tunnel, the influence of the stray-light becomes smaller - particularly the entopic straylight and the atmospheric scatter - so that L_s diminishes. Consequently, L_2 can decrease - gradually - as well. In the same fashion the luminance in the transition zone can be assessed: when the driver is in the tunnel, the major sources for straylight disappear from the field of view, but L_s is still there.

Two major problems remain. First, it is very difficult to assess L_s in reality, and even more so in the design stage of a tunnel. The new CIE Recommendations that presently are under preparation use the L_{20} in stead.
L_{20} represent the average luminance within a cone straight ahead with an apex of 2*10 degrees. However, the correlation between L_{20} and L_s is not very strong; L_{20} can be used for the design of the lighting of individual tunnels only with some precaution. The Ministry of Transport in the Netherlands developed a computer programme that allows to calculate the entopic straylight part of L_s with a high precision. The programme can be run on a medium-sized PC; it will be made available in the near future.

A second major problem is to derive L_2 from L_s. The field factors that are needed to convert the threshold (laboratory) values into real world values are not available at present. Until the two problems are solved, the L_s-method cannot be used for the design of tunnel lighting schemes, but only for establishing the different tunnel lighting switching modes in relation to the outdoor light levels. The new CIE Recommendations apply a rule-of-thumb method (similar to that of the PIARC) where a number of drawings of tunnel portals is presented; all the designer has to do is to select that drawing that looks most like "his" tunnel; the values of L_{20} and L_2 that are written in the drawing give the basis for the design.

4. RECOMMENDATIONS FOR THE LIGHTING OF TUNNELS

4.1. General

The lighting of traffic tunnels is a fairly special field in lighting engineering. The lighting schemes usually are designed and installed by specialists. This implies that most recommendations for tunnel lighting are written for these specialists. Most countries, but not all, have codes or recommendations, usually set up either by the government or by the national lighting institution. In 1973, the CIE published International Recommendations for Tunnel Lighting (Publication No. 26). These 1973 Recommendations have been the basis for almost all national codes and regulations; the major exeption being the Japanese national tunnel lighting code. At present, the 1973 CIE Recommendations are considered as outdated; a new document (Guide for the Lighting of Road Tunnels and Underpasses) is being prepared. The two CIE documents and the Japanese code will be discussed.

Most tunnel lighting recommendations deal with the different aspects of lighting; the entrance lighting, however, usually is the major issue because it causes the most difficulties, involves the most theoretical controversies, and represents the most expensive part of the lighting installation.

4.2. The 1973 CIE Recommendations

The 1973 CIE Recommendations are still valid at present. They are based on the research by Schreuder of the early nineteen-sixties. The major issue of the entrance lighting is the principle that - as is the fact for very high adaptation luminance values - the eye of the approaching car driver is adapted to the very bright open surroundings in front of the tunnel, and that, when coming closer, the adaptation stays the same for quite some time. Only when the driver is close to the tunnel (may be only 50 to 25 m) the dark tunnel entrance will begin to influence the visual adaptation. The result is that, when approaching the tunnel, the driver must be able to look into the tunnel even when the adaptation of his eyes still corresponds to the open road. These conditions prevail when the outdoor luminance is more than about 8.000 cd/m^2 - a value that corresponds to a full summer sun on concrete, or to sun on snow. When the tunnel is not bright enough, the entrance may present itself to the driver as a "black hole". In fact, avoiding the black-hole effect while the adaption is constant is the major issue of the 1973 CIE Recommendations.

According to the Recommendations the black hole can be avoided when the luminance in the tunnel entrance L_2 is not less than about 0.1 of the outdoor luminance L_1. This luminance L_2 should be present over the full length of the threshold zone, i.e. some 50 to 100 m, depending on the driving speed and the structure and layout of the tunnel portal. After the threshold zone the luminance may be reduced at a rate of about a factor of 10 each 2 - 3 seconds. This is the "transition zone" that extends itself towards the "interior zone" of the tunnel. The interior is should be lit up to about 10 cd/m^2.

The CIE Recommendations include additional information regarding the exit, flicker effects that may result from interrupted rows of lanterns, the use of daylight screens etc.

4.3. <u>The new CIE Recommendations</u>

The CIE is in the process of preparing a new set of recommendations (Guide for the Lighting of Road Tunnels and Underpasses). The difference between de 1973 Recommendations and the new Guide refer primarily to the entrance lighting. The Guide is based on the veiling luminance concept: contrary to the 1973 Recommendations, it is assumed that the eye adaptation takes only very little time - in fact it is considered as being instantaneous. This is normaly the case when the adaptation is lower than about 3.000 cd/m^2.

In theory it is possible to assess the veiling luminance L_s, either by direct measurement (the Fry Glare Lens) or by calculation when the luminance in the different areas in the field of view are known. In the Netherlands, a computer programme has been developed, that permits to calculate the visual straylight part of L_s with high precision. This programme is based on the Vos glare formula.

Both measurement and calculation have drawbacks: the measurements cannot be made in the design stage - which is when the data are required - and the computer programme is not generally available yet. To overcome these drawbacks, the CIE Guide present several shortcuts: first, the L_{20}-concept is introduced; the average luminance in a come straight ahead with an apex of 2*10 degrees. Statistically, there is a fair correlation between L_s and L_{20}. The CIE Guide assumes that the relationship is accurate enough to for design purposes.

The CIE Guide introduces two methods to estimate the highest practical value of L_{20}. The first method takes into account the amount of sky that is visible, the stopping distance (related to the driving speed) and the overall brightness in the field of view - both for snow and no-snow conditions. By means of a table, L_{20} can be found; it is between 1.500 and 7.500 cd/m^2. The second method uses a sketch of the tunnel entrance and its surroundings to assess the arithmetical mean of the luminances in the cone of 2*10 degrees. The percentage (in area) of the sky, the road, the surroundings and the tunnel entrance are assessed, together with the luminances of these areas. As this process is rather complicated, another shortcut is introduced: the first method mentioned above can be used by estimating the sky percentage from the selection of one out of a set of eight line drawings of tunnel entrances. For each drawing, the appropriate sky percentage is added.

The CIE Guide gives values for the ratio L_2/L_{20} in order to assess the luminance in the threshold zone L_2. The ratio is given as 0.05 to 0.10 for stopping distances (depending on the driving speed) of 60 to 160 m. These values hold for "symmetric" lighting installations. In some countries the "counterbeam" system - shining most of the light in a direction opposite to the direction of traffic - is used. The Guide suggests tentative values for the ratio L_2/L_{20} between 0.04 and 0.07 for these tunnels for stopping distances between 60 and 160 m. The ratios of L_2/L_{20} given in thew Guide are not based on research but on practical experience.

It should be noted that the counterbeam system, although it clearly is superior to conventional symmetric lighting as regards lighting efficiency, is not always favoured for fear of glare, lack of visual guidance and non-uniformity.

Further practical aspects of the Guide deal with the selection of the danger class of the tunnel and the influence of the direction of the tunnel related to the North.

In most other aspects the new CIE Guide is very similar to the 1973 CIE Recommendations. After the threshold zone comes the transition zone where the luminance may decrease gradually towards the interior. Two additional differences should be mentioned: first, according to the Guide the luminance in the further half or the threshold zone may decrease as well - leaving little use for the concept of the threshold zone - and second, the Guide gives lower values for the luminance level in the interior zone; values between 1 and 15 cd/m^2 are given according to the stopping distance (speed) and the traffic flow.

4.4. The Japanese Recommendations

In 1966, the Japan Highway Public Corporation issued Recommendations for the Lighting of Vehicular Traffic Tunnels (amended in 1968). These Japanese Recommendations are based on the work of Narisada, and are adapted primarily to the typical Japanese geomorphological and traffic situations; tunnels through high mountains with steep, heavily wooded slopes, carrying heavy traffic at moderate speed. It is assumed that under these conditions the drivers will fix their gaze already at a large distance on the tunnel entrance. The result is that the "adaptation point" is far in front of the tunnel, so that there is no need for an actual threshold zone.

This factor leads to two major differences between the Japanese and the CIE Recommendations (both old and new). In the first place, according to the Japanese Recommendations, the entrance lighting is characterized by a luminance near the tunnel portal much lower than the values according to the 1973 CIE Recommendations. It is difficult to compare the Japanese values with the L_{20} values of the new Guide, but the Japanese values seem to be much lower as well: the Japanese Recommendations give L_1/L_2-values of 42:1 for 100 km/h and 117:1 for 40 km/h. Secondly, as there is no threshold zone, the Japanese Recommendations allow that the luminance may be reduced directly after the tunnel portal. In this respect, the Japanese Recommendations are similar to the CIE Guide.

At the first glance there seems to be a large difference between the Japanese Recommendations and the 1973 CIE Recommendations. It has been shown that these differences are the result of the fact that different situations have been taken into account, and not a result of differences in the basic considerations nor of the experimental data. In this connection, the 1973 CIE Recommendations can be said to be more generally applicable, whereas the Japanese Recommendations refer to a more restricted range of geomorphological and traffic situations.