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TECHNICAL REPORT

GUIDE FOR THE LIGHTING OF ROAD TUNNELS AND UNDERPASSES

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The following members of TC 4-35, "Tunnel Lighting" took part in the preparation of this technical report. The committee comes under Division 4 "Lighting and Signalling for Transport". This present publication replaces CIE 88-1990 "Guide for the lighting of road tunnels and underpasses".

Members:

Werner Adrian	Canada
Arve Augdal	Norway
Marko Bizjak	Slovenia
Peter Blaser	Switzerland
David Coatham	UK
Jan de Vlieger ✞	The Netherlands
Jean-Marie Dijon	Belgium
Marc Gillet	Belgium (Chair from Sept. 2001)
Pentti Hautala	Finland
James A. Havard	USA
Hans Huijben	The Netherlands
Jaroslav Kotek	Czech Republic
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Jean-Claude Martin	France
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Alfredo Valero Seros	Spain
Bryan Shortreed	UK
Paolo Soardo	Italy
Richard E. Stark	USA
Axel Stockmar	Germany
Luuk Swart	The Netherlands
Fernando Vila	Spain
Pieter Walraven	The Netherlands

TABLE OF CONTENTS

SUMMARY VI

RESUME VI

ZUSAMMENFASSUNG VI

FOREWORD 1
- Terms of reference 1
- Disclaimer 1

1. INTRODUCTION 1

2. THE DEFINITION OF THE PROBLEM 2

3. TRAFFIC AND VISUAL TASKS 2

4. DISTINCTION BETWEEN LONG AND SHORT TUNNELS 3

5. DEFINITIONS 4
   - 5.1 Design speed 4
   - 5.2 Reference point 4
   - 5.3 Tunnel related zones 5
   - 5.4 Tunnel lighting related terms 6
   - 5.5 Traffic 7

6. DAYTIME LIGHTING FOR LONG TUNNELS 7
   - 6.1 Lighting in the threshold zone 7
   - 6.2 The perceived contrast method 7
     - a. The influence of the atmosphere and the windscreen 8
     - b. Determination of L_{seq} 9
     - c. Minimum required perceived contrast 10
     - d. Calculation of threshold luminance 10
   - 6.3 Example of tunnel design with the perceived contrast method 11
     - a. Drawing for L_{seq} evaluation 11
     - b. L_{ij} matrix for L_{seq} evaluation 12
     - c. L_{ije} matrix for L_{seq} evaluation 15
     - d. Selection of the minimal required perceived contrast 15
     - e. Calculation of L_{th} 15
   - 6.4 Use of daylight-screens 16
   - 6.5 Length of the threshold zone 16
   - 6.6 Luminance in the transition zone 16
   - 6.7 Daytime luminance in the interior zone 17
   - 6.8. Luminance in the exit zone 18
   - 6.9 Parting zone lighting 18
   - 6.10 Lighting of the walls and the ceiling in all zones 18
   - 6.11 Uniformity of luminance 18
   - 6.12 Daylight variation and lighting control 18
   - 6.13 Glare restriction 19
   - 6.14 Restriction of the flicker effect 19

7. NIGHT-TIME LIGHTING 20

8. EMERGENCY LIGHTING 20

9. MAINTENANCE 20
   - 9.1 General 20
   - 9.2 Lamp Lumen Depreciation (*LLD*) 21
   - 9.3 Burnouts 21
   - 9.4 Luminaire Dirt Depreciation (*LDD*) 22
   - 9.5 Equipment Factors (*EF*) 22
     - 9.5.1 Ambient temperature 22
     - 9.5.2 Voltage 22
     - 9.5.3 Control gear and Lamp Factor 22
     - 9.5.4 Luminaire component depreciation 23

9.6 Maintenance of the control photometers 23
9.7 Tunnel surface reflectance depreciation 23
9.7.1 Selection of tunnel surface reflectance 23
9.7.2 Reflectance depreciation 23
9.8 Luminaire cleaning, relamping and replacement 23
9.8.1 Luminaire cleaning 23
9.8.2 Relamping 23
9.8.3 Luminaire replacement 24
9.9 Other factors 24
9.9.1 Pavement reflectance 24
9.9.2 Other reflection characteristics 24
9.9.3 Physical geometry 24
9.9.4 Errors associated with the luminaire and control gear 24

ANNEXES 26

A.1 L20 METHOD 26
Example 27
A.1.1 Evaluation of the luminance in the threshold zone with the L20 method 28

A.2 STOPPING DISTANCE 28

A.3 EVALUATION OF L_{SEQ} / CORRECT USE OF A CAMERA 30
Scope 30
Type of camera 30
Film type 30
Objective 31
Verification of distortions 31
Shooting distance 31
Evaluation of L_{seq} 31

BIBLIOGRAPHY 32

GUIDE FOR THE LIGHTING OF ROAD TUNNELS AND UNDERPASSES

SUMMARY

After having reviewed and defined the various factors to be taken into consideration with regard to the lighting of tunnels and road underpasses, the present document sets out recommendations concerning the daytime and night-time lighting. It also describes the measures to be taken into consideration in order to adapt this lighting to the fluctuations in the external lighting or in the case of failure of the normal electrical power supply of the lighting installations. Attention is also given to maintenance which has to be carried out in order to ensure the lasting quality of the installations.

It is also important to note that while this publication is part of a general activity aimed at improving road safety, safety depends on a large number of factors among which lighting is only one particular constituent. The contribution of lighting in this context is to enable the road user to perform his visual tasks by ensuring a sufficient visibility of objects.

GUIDE DE L'ECLAIRAGE DES TUNNELS ROUTIERS ET PASSAGES COUVERTS

RESUME

Après avoir passé en revue et défini les divers facteurs qui doivent être pris en compte pour l'éclairage des tunnels routiers et passages couverts, le présent document établit une série de recommandations pour l'éclairage de jour et l'éclairage de nuit. Il décrit les mesures qui doivent être prises afin d'adapter cet éclairage aux fluctuations des conditions de luminosité extérieures ou en cas de défaillance de l'alimentation électrique des installations d'éclairage. Un soin tout particulier a été apporté concernant les aspects liés à la maintenance qui doit être assurée afin de maintenir le niveau de qualité des installations.

Il est important de signaler que cette publication concerne une seule des diverses composantes visant à améliorer la sécurité routière et que cette dernière dépend d'un nombre important de facteurs dont l'éclairage. La fonction première de l'éclairage, qui a inspiré essentiellement ce document, est d'assurer une visibilité suffisante des obstacles éventuels, ce qui représente une des tâches visuelles fondamentales que l'utilisateur de la route a à exécuter.

LEITFADEN ZUR BELEUCHTUNG VON STRASSENTUNNELN UND UNTERFÜHRUNGEN

ZUSAMMENFASSUNG

Nach Prüfung und Festlegung der zu berücksichtigenden Faktoren legt dieser Leitfaden Richtlinien zur Beleuchtung von Straßentunneln und Unterführungen bei Tag und bei Nacht fest. Es werden auch die in Betracht zu ziehenden Maßnahmen zur Anpassung der Beleuchtung an die Schwankungen der Außenbeleuchtung oder bei Ausfall der normalen Stromversorgung der Beleuchtungsanlagen beschrieben. Der für die Sicherung der dauerhaften Qualität der Anlagen notwendigen Wartung wird ebenfalls Augenmerk geschenkt.

Obwohl diese Publikation Teil der allgemeinen Bemühungen zur Verbesserung der Sicherheit im Straßenverkehr ist, ist es wichtig darauf hinzuweisen, daß diese von einer Vielzahl von Faktoren abhängt, von denen die Beleuchtung nur einer ist. Für die Zwecke dieser Publikation ist die wichtigste Aufgabe der Beleuchtung, die ausreichende Sichtbarkeit von Objekten zu gewährleisten, die einen Teil der vom Straßenbenutzer zu leistenden Sehaufgabe bildet.

FOREWORD

In 1973, CIE published "International recommendations for tunnel lighting" (Publication CIE No. 26). After several years, a revision of Publication No. 26 was undertaken in two steps. In 1985 a report was published reviewing fundamental experiments concerning the daytime entrance lighting requirements (CIE 61-1984: "Tunnel entrance lighting - a survey of fundamentals for determining the luminance in the threshold zone"). With CIE 61-1984 as the background document, the recommendations were revised and published as a new document: CIE 88-1990: "Guide for the lighting of road tunnels and underpasses". That Guide was prepared in close contact with the working group "Lighting" of the Committee on Road Tunnels of PIARC (Permanent International Association of Road Congresses).

Considerable developments in the field of tunnel lighting have taken place in the last decade necessitating revisions, which could more accurately reflect recent experimental research and engineering experiences.

Terms of reference

The terms of reference are to prepare a revision of CIE 88-1990: "Guide for the lighting of road tunnels and underpasses". CIE 61-1984: "Tunnel entrance lighting: A survey of fundamentals for determining the luminance in the threshold zone" will stay on the CIE list without alterations.

Disclaimer

The primary purpose of this document is to serve as the basis for design of tunnel lighting. The document deals entirely with lighting and does not give advice on construction. Its purpose is to provide recommended practices for designing new tunnel lighting. It is not intended to be applied to existing tunnel lighting systems until such systems are redesigned.

1. INTRODUCTION

The basic principles on which CIE 88-1990 were founded, are still completely valid for the present revision. Regarding several items, however, new insight, the result of new research and the extensive practical experience from tunnels constructed over the last decade, did lead to considerable differences between CIE 88-1990 and the present revision.

The main item is the determination of the luminance in the first part of the threshold zone. According to CIE 88-1990, the L20-method was recommended and the veiling luminance method was suggested to be used in the future. Recent research allowed to base the present revision on the veiling luminance method. This change allows to determine the threshold zone luminance more accurately than according to the earlier document, more in particular in non-standard situations.

Another difference is found in the recommended values of the luminance in the interior zone of long and very long tunnels. It has followed from practical experience in the many hundreds of tunnels that were put in operation since the publication of CIE 88-1990, that the influence of the traffic volume was greater than anticipated, and that modern equipment could result in the same level of comfort and a similar level of visibility at lower levels of luminance.

The differences between CIE 88-1990 and the present revision are important but they follow directly from a further development of the principles that are laid down in CIE 88-1990.

The requirements for lighting installation of a tunnel are influenced by several critical factors which determine visibility. These conditions are eminently variable, and involve characteristics of the driver, including ability, age and personal habits; the physical conditions of the road, access to and the length of the tunnel; atmospheric conditions; traffic density, volume and speed; and type of vehicles in transit. Additional considerations include the contribution of lighting to the architectural aspect of the tunnel opening with regard to visual guidance, comfort and to the overall maintenance of the installation.

This document aims at defining a Guide intended for designers and consultants of projects.

The Guide is based on present technical possibilities and is therefore likely to be revised accordingly as these evolve. As stated above, the rules given must be considered as the minimum visibility conditions in order to obtain an installation of sufficient quality with regard to safety and comfort. If, for special reasons, the tunnel in question must be completed with particular care, stricter requirements may be imposed and some information has to be given explicitly.

As is the case for all lighting installations, the quality of tunnel lighting can vary as a function of some parameters. The minimum daytime and night-time lighting requirement is to ensure visibility conditions such that the user may travel through equally well by day and by night at a given design speed. It should provide safety, comfort and confidence at a level not lower than those that exist at the same time along the access roads to that tunnel.

In order to achieve this purpose, it is essential for road users to have, inside the tunnel, sufficient visual information regarding the geometry of the portion of the road forming the field of view, and the presence and movement of possible obstacles, the latter comprising particularly other road users. However, it is also necessary that motorists approaching the entrance of the tunnel should have the same feeling of confidence that they had along the preceding portion of the access road to the entrance.

The photometric characteristics of the lighting installation of a tunnel which define the quality of the lighting system are as follows:

- the luminance level of the road and of the lower part of the tunnel walls;
- the uniformity and distribution of the luminance of the road surface and of the walls;
- the limitation of glare produced by the light sources;
- the limitation of the flicker effect;
- the level of visibility of possible obstacles;
- the visual guidance.

All of the values specified in the present Guide are values to be maintained throughout the duration of operation of the tunnel. In order to obtain the values to be achieved for the tunnel in the brand new state it is therefore necessary to increase the specified values to take the conditions of maintenance of the installation into account. They depend on the quality of the equipment used, the frequency of maintenance and the ambient conditions of the site.

For guidance about maintenance, refer to Section 9.

2. THE DEFINITION OF THE PROBLEM

The lighting requirements of a tunnel are totally different by day and by night. At night the problem is relatively simple and consists in providing luminance levels on lit routes inside the tunnel at least equal to those outside the tunnel. The design of the lighting during daytime is particularly critical because of the human visual system. The driver outside the tunnel cannot simultaneously perceive details on the road under lighting levels existing in a highly illuminated exterior and a relatively dark interior (i.e. transient adaptation).

While the visual system can adapt to rapid reduction in ambient illumination, such as that produced when passing from daylight into the darkness of a tunnel these adjustments are not instantaneous. The adaptation process takes a certain time, depending on the amplitude of the reduction: the greater the difference, the longer the adaptation time.

For a given speed, this means that the greater the difference between the lighting level outside and that inside the tunnel, the longer will be the distance over which the visual system of the driver has to adapt.

3. TRAFFIC AND VISUAL TASKS

The visual task to be considered comprises the detection of the presence and movement of objects on the road in front of the driver.

These objects depend on the type of tunnel in question, e.g. urban tunnel, road tunnel, motorway tunnel and on the type of traffic mainly incorporated, e.g. motorized vehicles, cyclists, pedestrians, etc. The corresponding visual tasks however are too complex and too varied to be able to establish visibility criteria that can be used in the assessment of photometric requirements with regard to the lighting of tunnels.

Faced with this situation, it was agreed to use as a reference task the visibility of an object similar to that often taken into consideration in studies relating to road lighting, that is to say a target of 0,2 m x 0,2 m having a specified reflection factor. Typical reflection factor is 0,2. Actual traffic obstacles may be bigger. It is also considered that such an object, standing on the road surface, must be detected by a driver approaching the tunnel ahead of the entrance. The distance from which this object can be seen has to be equal to the stopping distance corresponding to the tunnel design speed.

The requirements relating to the lighting of tunnels and underpasses given in this document are based on this criterion. Experience shows that if a particular lighting situation is satisfactory for this visual task, it is also satisfactory for the other types of assessments.

With regard to the volume of traffic, it will be noted that the visual task defined above only applies to a situation when the distance between the vehicles following one another is greater than their stopping distance. If this is not so, the driver's visual task consists essentially in predicting the behaviour of the vehicle preceding him. It is therefore important that the driver should not be caused to make sudden operations such as unexpected braking for example. This justifies the precautions that must be taken in order to prevent the black hole effect which an insufficiently illuminated entrance of a tunnel exhibits. But the visibility of a small object is nevertheless essential.

This indicates the great influence of the traffic flow on the visibility in the practical situations that may arise at or in the tunnel. Because the traffic flow usually varies considerably over the day, and because the requirements placed on the lighting installation to guarantee the adequate visibility are more severe than those needed to guarantee adequate car-following possibilities, the Guide is based on the visibility of objects. In this respect, the speed of the vehicles is a fundamental element. The stopping distance of vehicles defines not only the point at which the observing driver must be able to detect the presence of an object but also, as shown later, the length of the entrance zone. All other things being equal, an increase in the design speed will generally result in an increase in the lighting requirements and consequently in the cost of the installations. This might suggest a call for introducing speed limits in the approach zone and whilst passing through the tunnel. In view of the continuity of the traffic stream over a traffic route, it is desirable to have the same design speed in the tunnel as on the adjacent open road.

4. DISTINCTION BETWEEN LONG AND SHORT TUNNELS

A tunnel is a covering over the road. The lighting requirements for long and short tunnels differ according to the degree to which the approaching motorist can see through the tunnel. The ability to see through the tunnel depends primarily on the length of the tunnel but also on other design parameters (width, height, horizontal and/or vertical curvatures of the tunnel, etc).

Tunnels are usually subdivided in "long tunnels" and "short tunnels". This designation refers primarily to the length of the tunnels (typically measured along the tunnel axis). Some tunnels - where the drivers cannot see the exit from a point in front of the tunnel - need to be illuminated like a long tunnel, even if their lengths would seem to make them a "short" one. These tunnels are designated as "optically long tunnels", contrary to those where approaching motorists can see through the tunnel ("optically short tunnels"). With regard to the lighting, tunnels are subdivided into three classes:

- geometrically long tunnels;
- optically long tunnels;
- short tunnels.

The distinction can be made on the basis of the diagram given in Fig. 4.1

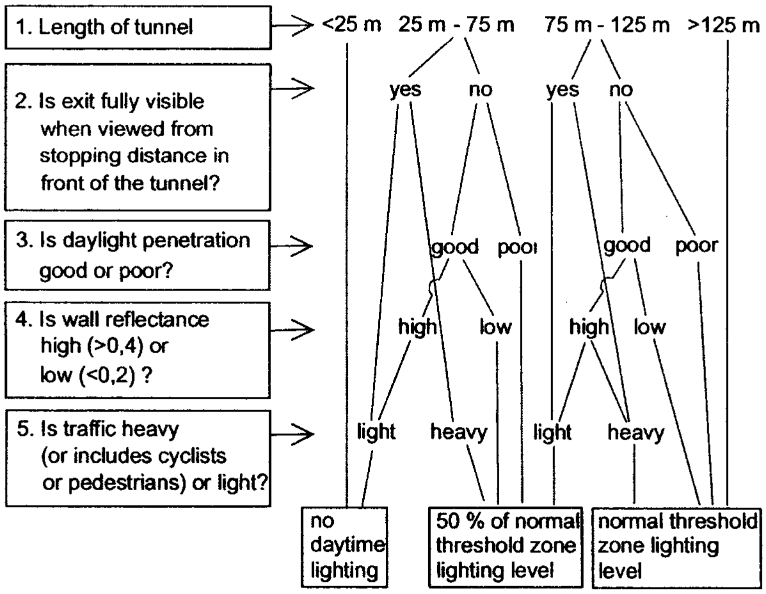


Fig. 4.1. Daytime lighting of tunnels for different tunnel lengths.

Fig. 4.1 offers a first approximation. For a detailed lighting design, the possibilities to look through the tunnel must be determined graphically.

Note: For tunnel lengths up to 75 m where no daytime lighting is recommended in Fig. 4.1, it is to be noted that at least one hour before sunset and one hour after sunrise a lighting level equal to the recommended values for the interior zone of a long tunnel should be achieved (see luminance in the interior zone). At night only the recommended value for night-time lighting is needed.

5. DEFINITIONS

This section reports the definitions of special terms used in this publication. For general terms refer to CIE 17.4-1987 International Lighting Vocabulary (CIE, 1987).

It is practical to distinguish different zones in the tunnel in order to determine the longitudinal lighting level at daytime lighting: the access zone, the threshold zone, the interior zone and the exit zone (see Fig. 5.1).

5.1 Design speed

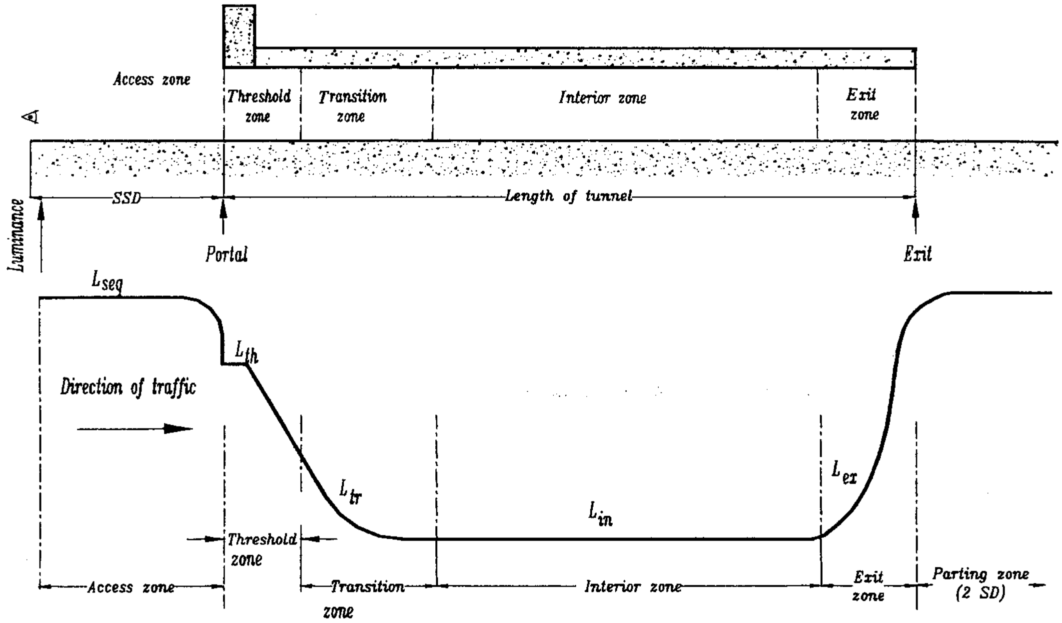
The design speed to be taken into consideration for the design of a lighting system of a tunnel must be specified by the prime contractor.

The design speed is in principle the speed for which the tunnel is laid out. It is generally accepted that this speed is the maximum speed allowed on the access roads to the tunnel. However, some people consider that a reduction of speed on the approach and passing through the tunnel is acceptable. In this case the reduction must of course be indicated ahead of the tunnel.

5.2 Reference point

The reference point is in principle the point located in the centre of the approaching lanes, at a height of 1,5 m and at a distance from the entrance of the tunnel equal to the stopping distance (*SD*) at the design speed. This stopping distance is the distance necessary to stop the vehicle moving at the speed in question in total safety. It comprises the distance covered during the reaction time and during the braking time.

The stopping distance is extremely variable and depends on the driver, his vehicle, the speed of the latter, on the gradient of the road and on the atmospheric conditions. Reference should be made to national standards. In Appendix A. 2 more explanations are given.



Typical longitudinal section of a one way tunnel

Fig. 5.1. Zones in a tunnel.

5.3 Tunnel related zones (see Fig. 5.1)

Tunnel: a structure over a roadway that restricts the normal daytime illumination of a roadway section such that the driver's capability to see is substantially diminished. In the context of this Guide, other constructions that do not restrict visibility are not relevant.

It is practical to distinguish different zones in the tunnel in order to determine the longitudinal lighting level at daytime lighting: the access zone, the threshold zone, the transition zone, the interior zone and the exit zone.

Access zone: the part of the open road immediately outside (in front of) the tunnel portal, covering the distance over which an approaching driver must be able to see into the tunnel. The access zone begins at the stopping distance point ahead of the portal and it ends at the portal.

Threshold zone: the first part of the tunnel, directly after the portal. The threshold zone starts either at the beginning of the tunnel or at the beginning of the daylight sunscreens when occurring. The length of the threshold zone is at least equal to the stopping distance.

Transition zone: the part of the tunnel following directly after the threshold zone. The transition zone begins at the end of the threshold zone. It ends at the beginning of the interior zone. In the transition zone, the lighting level is decreasing from the level at the end of the threshold zone to the level of the interior zone.

Interior zone: the part of the tunnel following directly after the transition zone. It stretches from the end of the transition zone to the beginning of the exit zone.

Exit zone: the part of the tunnel where, during the day-time, the vision of a driver approaching the exit is predominantly influenced by the brightness outside the tunnel. The exit zone begins at the end of the interior zone. It ends at the exit portal of the tunnel.

Parting zone: the first part of the open road directly after the exit portal of the tunnel. The parting zone is not a part of the tunnel, but it is closely related to the tunnel lighting. The parting zone begins at the exit portal. It is advised that the length of the parting zone equals two times the stopping distance. A length of more than 200 m is not necessary.

Entrance portal: the part of the tunnel construction that corresponds to the beginning of the covered part of the tunnel, or - when open sun-screens are used - to the beginning of the sun-screens

Exit portal: the part of the tunnel construction that corresponds to the end of the covered part of the tunnel, or - when open sun-screens are used - to the end of the sun-screens

5.4 Tunnel lighting related terms

Visual guidance: the means that ensure that motorists are given adequate information on the course of the road in the tunnel

Emergency lighting: that fraction of the lighting that is maintained under emergency conditions, e.g. failures in the main power supply

Fire emergency guidance lighting: provides visual guidance in the case of fire and smoke

Daylight screens, louvers: devices that transmit (some of) the ambient daylight, and that may be applied for the lighting of the threshold zone and/or the entrance zone of a tunnel

Sun-tight screens: screens that are constructed in such fashion that direct sunlight can never reach the road or wall surface under the screen

Contrast (*C*): the contrast between a relatively small object with sharp contours and its (immediate) background is generally defined as:

$$C(\%) = 100 \cdot (L_o - L_b) / L_b$$

with L_o the luminance of the object and L_b the luminance of the background

Equivalent veiling luminance L_{seq}: the light veil as a result of the ocular scatter, L_{seq} is quantified as a luminance

Veiling luminance: the overall luminance veil consisting of the contribution of the transient adaptation, the stray light in the optical media, in the atmosphere and in the vehicle windscreen

Threshold zone luminance L_{th} (at a specific location in the threshold zone): the average road surface luminance at that location

Transition zone luminance L_{tr} (at a particular location): the average road surface luminance in a transverse section at that particular location in the transition zone of the tunnel

Interior zone luminance L_{in} (at any location in the interior zone of the tunnel): the average road surface luminance at that location

Exit zone lighting: the lighting of the exit zone. The exit zone lighting provides the visual contact for the driver still in the tunnel with the open road beyond the tunnel.

Vertical illuminance E_v: the vertical illuminance at a particular location at a height of 0,1 m above road surface, in a plane facing and at right angles to the direction of oncoming traffic. The height of 0,1 m above the road surface is meant to represent an object of 0,2 x 0,2 m^2.

Reference obstacle: cube with a 0,2 m side and diffusing faces with a specified reflection factor ρ equal to 0,2

Contrast revealing coefficient q_c: the ratio between the luminance of the road surface and the vertical illuminance E_v at a specific location in the tunnel $q_c = L / E_v$. The method of tunnel lighting may be defined in terms of the contrast ratio in three ways: Symmetric lighting, Counter-beam lighting and Pro-beam lighting.

Symmetric lighting: the lighting where the light equally falls on objects in directions with and against the traffic. Symmetric lighting is characterized by using luminaires that show a luminous intensity distribution that is symmetric in relation to the plane normal to the direction of the traffic.

Counter-beam lighting (CBL): the lighting where the light falls on objects from an opposite direction to the traffic. Counter-beam lighting is characterized by using luminaires that show a luminous intensity distribution that is asymmetric in relation to the plane normal to the direction of the traffic, where the maximum luminous intensity is aimed against the direction of the traffic. The term refers only to the direction of normal travel.

Pro-beam lighting: the lighting where the light falls on objects in the same direction as the traffic. Pro-beam lighting is characterized by using luminaires that show a luminous intensity distribution that is asymmetric in relation to the 90/270 C-plane (the plane normal to the direction of the traffic), where the maximum luminous intensity is aimed in the same direction as the direction of the traffic.

5.5 Traffic

Traffic flow: the number of vehicles passing a specific point in a stated time in stated direction(s). In tunnel design, peak hour traffic, vehicles per hour per lane, will be used.

6. DAYTIME LIGHTING FOR LONG TUNNELS

6.1 Lighting in the threshold zone

As noted above, the necessary lighting level in the threshold zone is determined by visibility criteria or, in other words, by enough contrast. A driver can identify other road users or objects in the threshold zone from the stopping distance if the perceived contrast is equal to or higher than the minimum required contrast.

The driver's task is to determine the presence of other road users or objects in the relatively dark threshold zone while he is driving in a relatively light environment at a distance equal to the stopping distance corresponding to the tunnel design speed. This implies that the perceived contrast by a driver is different from the intrinsic contrast as can be measured from a very short distance from the object. The perceived contrast differs from the intrinsic contrast due to at least three main influences:

1. the light veil due to light scattered in the atmosphere in the line of sight;
2. the light veil due to the scattering in the windscreen (including light reflected from the dashboard) and
3. the light veil due to the scattering in the eye (from sources outside of the line of sight scattered into the fovea).

The minimum required contrast perceived at the stopping distance is not only the minimum required contrast in laboratory conditions, but also depends on the level of attention of the driver. Approaching a tunnel requires not only attention for its entrance but also for driving the car, for the road itself, for other road users at short distance, for lane changing, and so on.

6.2 The perceived contrast method

In general, the contrast is the ratio of the difference of the luminances of the object and its direct surroundings to one of the quantities. These luminances are influenced by the lighting level and the type of lighting (symmetrical, pro beam, counter beam). The daylight falling from the outside open area into the tunnel entrance cannot be disregarded. The importance of this contribution depends on different interior and exterior parameters. Its impact is that there is almost always a transition area where the contrast changes from positive towards negative, causing most objects sometimes to be invisible. Where this transition takes place and how long the transition area is, cannot be indicated in general terms. Models are available to assess the influence of the daylight (see CIE 66-1984).

The system can be seen in Fig. 6.2.1:

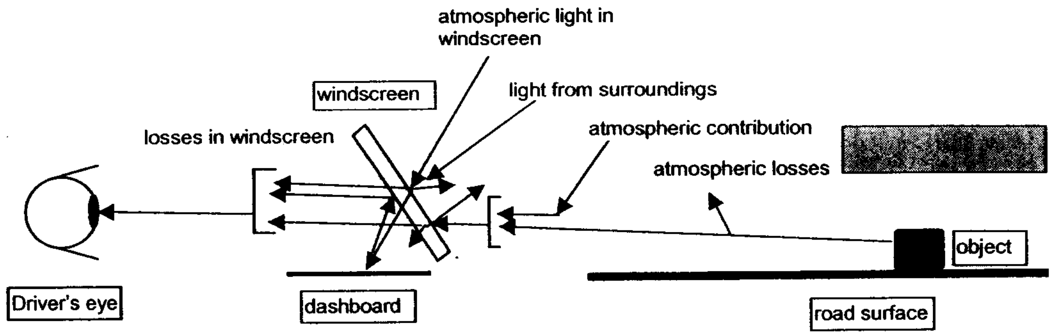


Fig. 6.2.1. The luminances of the scene.

Concerning the transmission factors τ_{ws} for the windscreen and τ_{atm} for the atmosphere this means that the perceived luminance of the object $L_{o,p}$ can be written as:

$$L_{o,p} = \tau_{ws} \cdot \tau_{atm} \cdot L_{o,intrinsic} + \tau_{ws} \cdot L_{atm} + L_{ws} + L_{seq}$$

In this equation, all the luminances are measured from inside the vehicle except the atmosphere and L_{seq}.

The same holds for the perceived luminance of the road $L_{r,p}$, i.e. the background of the object. Using the same approach:

$$L_{r,p} = \tau_{ws} \cdot \tau_{atm} \cdot L_{r,intrinsic} + \tau_{ws} \cdot L_{atm} + L_{ws} + L_{seq}$$

Other light sources surrounding the 2° cone, called glare sources, are partially scattered in the eye causing a veiling luminance which disturbs the perception of L_o and L_r. Most of these light sources are reflections by surfaces in the conical field of view of the driver.

The effect of scattered light in the eye on vision can be expressed by the equivalent veiling luminance L_{seq}. The contrast of the obstacle perceived from the stopping distance is equal to:

$$C_{perceived} = \frac{(L_{o,p} - L_{r,p})}{L_{r,p}}$$

a. The influence of the atmosphere and the windscreen

There are methods and measurements that are available to determine the luminance of the windscreen and the atmosphere. There are also many variables which cause these values to change considerably.

Table 6.2.1. Veiling levels.

Veiling levels	High	Medium	Low
Atmospheric veiling luminance (cd/m^2)	300	200	100
Windscreen veiling luminance (cd/m^2)	200	100	50

For this section we will use some typical values. Under specific circumstances higher and lower values are likely to occur.

If local data is not available, the atmospheric transmissivity (τ_{atm}) for design purposes is assumed to be 1,0 and the transmission factor for the windscreen (τ_{ws}) is assumed to be 0,8.

b. Determination of L_{seq}

Calculating L_{seq} with the highest occurring luminances of surfaces in the field of view will lead to very high levels of the threshold lighting. It is proposed to use the highest luminances likely to occur during at least 75 daytime hours per year as reference.

The equivalent veiling luminance L_{seq} can be assessed directly by means of measurements at the tunnel site with special luminance meters equipped with a "glare lens" measuring L_{seq} or with glare evaluation meters inside the car.

The equivalent veiling luminance can be determined by means of a graphical method based on the Holladay-Stiles formula as shown in Fig. 6.2.2.

This polar diagram has to be superimposed on the tunnel scene as seen from the stopping distance. The tunnel opening is to be located in the centre of the graph which represents the visual field.

The peripheral field around 2° is subdivided into sections that are considered as individual glare sources i producing stray light in the eye media proportional to E_{Gli}/θ^2_i. The size of the sections is chosen in a way that the average luminance occurring in them always produces the same amount of stray light.

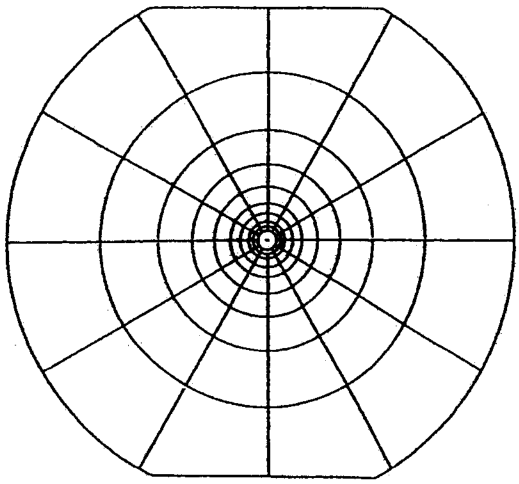


Fig. 6.2.2. Polar diagram showing zones in which the luminance produces equal amounts of stray light at the centre.

The polar diagram should be superimposed over the image using the angular relationships given in Table 6.2.2.

Table 6.2.2. Angular relationships.

Ring	Centre	1	2	3	4	5	6	7	8	9
Angle of opening	2,0°	3,0°	4,0°	5,8°	8,0°	11,6°	16,6°	24,0°	36,0°	56,8°

By summation over all sections of the visual field the total amount of the equivalent veiling luminance is obtained. The centre of the diagram should fall into the centre of the tunnel opening.

This central part of the diagram (2° circle) must be excluded in the evaluation of L_{seq}. However, it affects the foveal adaptation.

The average luminances in the different sections of Fig. 6.2.2 have to be added. The total equivalent veiling luminance is found from:

$$L_{seq} = 5{,}1 \cdot 10^{-4}\, \Sigma\, L_{ije}$$

with $L_{ije} = (\tau_{ws} \cdot L_{ij}) + L_{ws}$

and L_{ij} as stated in Table 6.2.3.

where:

L_{seq} = the total equivalent veiling luminance in cd/m².

L_{ije} = the luminance of each section in cd/m² in front of the eye.

L_{ij} = the average luminance of each section in cd/m² (measured outside the car, in front of the windscreen).

L_{ws} may often be neglected in the previous equation.

In case no measured luminances of the tunnel environment are available the reference data in Table 6.2.3 may be used, paying attention to local conditions.

Table 6.2.3. Examples of luminances at tunnel portals.

Driving direction (Northern hemisphere)	L_c (sky) kcd/m²	L_r (road) kcd/m²	L_e (environment) kcd/m²			
			Rocks	Buildings	Snow	Meadows
N	8	3	3	8	15 (V) 15 (H)	2
E-W	12	4	2	6	10 (V) 15 (H)	2
S	16	5	1	4	5 (V) 15 (H)	2

(V) Mountainous country with mainly steep surfaces facing drivers

(H) Flat, more or less horizontal, country

NOTE: In the southern hemisphere N and S should be interchanged.

c. Minimum required perceived contrast

There are several methods of determining the minimum required contrast and much study has been done in this area. For the purpose of the design in this section, 28% is recommended as the level of minimum required perceived contrast.

d. Calculation of threshold luminance

From the three first equations of the present section 6.2, it can be deduced that:

$$L_{th} = \frac{L_m}{\frac{1}{C_m}\left(\frac{\rho}{\pi \cdot q_c} - 1\right) - 1}$$

with

$$L_m = \frac{\left(\tau_{ws} \cdot L_{atm} + L_{ws} + L_{seq}\right)}{\left(\tau_{ws} \cdot \tau_{atm}\right)}$$

C_m is the minimum required perceived contrast (see previous sub-section where 28% is recommended). This contrast may mostly be considered as negative (for any q_c being greater than 0,06 with a reflectance factor of the target equal to 0,2).

In order to find out the threshold road luminance, the designer should start from the standardised figures for contrast revealing coefficient (either 0,2 for symmetrical systems or 0,6 for CBL systems).

In order to find a more precise value of the threshold luminance an iterative process is necessary. After having selected an initial estimated figure for the average q_c of the installation and having calculated the correlated L_{th}, it may be necessary to calculate the real average q_c of the installation in order to verify initial assumptions.

6.3 Example of tunnel design with the perceived contrast method

In order to perform a design using the method described in this section certain steps should be taken and are illustrated in the following example.

a. Drawing for L_{seq} evaluation

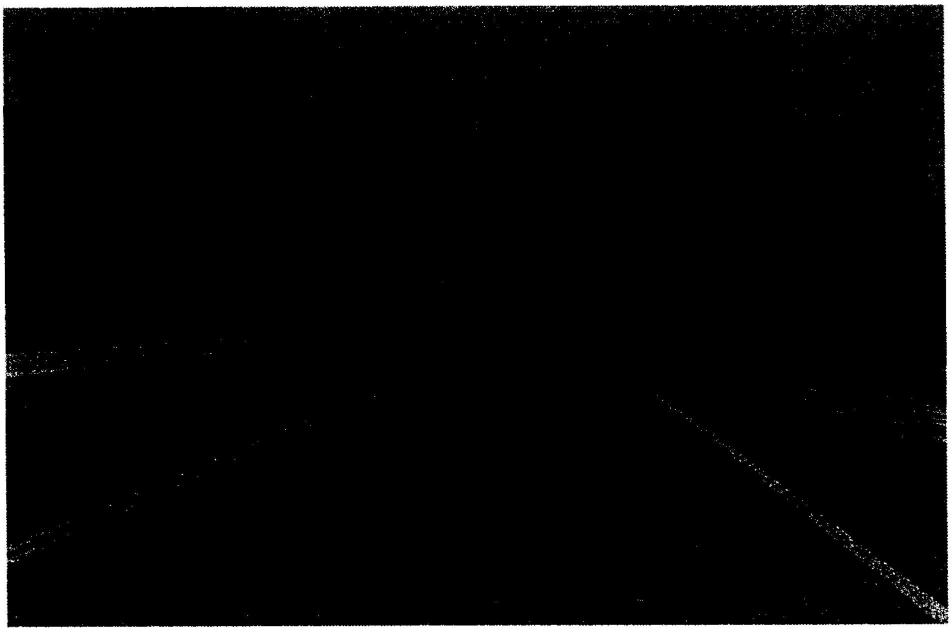


Fig. 6.3.1. L_{seq} evaluation's diagram.

Figures for the cells of the matrix are taken from Table 6.2.3. The example is in the Northern hemisphere and driving direction is North. For information, the 20° circle appears as the fourth ring starting from the periphery and is not taken into consideration when doing the design with the perceived contrast method. In the present example, the two highest and the two lowest patches are not taken into account because they are out of the field of vision. Also, the luminance of the portal which is taken into consideration is equal to zero because it is negligible when compared with the other surfaces' luminances.

b. L_{ij} matrix for L_{seq} evaluation (luminances in kcd/m²)

Table 6.3.1. Detailed calculation of L_{ij} matrix for L_{seq} evaluation.

RINGS / From Inside Out / Center Circle Is Not Included

1	1	2	3	4	5	6	7	8	9
	8,00	8,00	8,00	8,00	8,00	6,20	4,10	8,00	0,00
Sky							20%	100%	Not Calculated :01
Road									
Rocks									
Building	100%	100%	100%	100%	100%	70%	15%		
Snow									
Meadows						30%	65%		
Tunnel									
	100%	100%	100%	100%	100%	100%	100%	100%	

2	1	2	3	4	5	6	7	8	9
	5,36	8,00	8,00	8,00	6,20	3,50	2,00	5,00	7,70
Sky								50%	95%
Road									
Rocks									
Building	67%	100%	100%	100%	70%	25%			
Snow									
Meadows					30%	75%	100%	50%	5%
Tunnel	33%								
	100%	100%	100%	100%	100%	100%	100%	100%	100%

3	1	2	3	4	5	6	7	8	9
	0,00	6,40	8,00	8,00	3,20	2,00	2,00	2,00	3,20
Sky									20%
Road									
Rocks									
Building		80%	100%	100%	20%				
Snow									
Meadows					80%	100%	100%	100%	80%
Tunnel	100%	20%							
	100%	100%	100%	100%	100%	100%	100%	100%	100%

4	1	2	3	4	5	6	7	8	9
	0,00	5,50	5,00	5,00	2,60	2,70	2,70	2,65	2,55
Sky									
Road		50%	60%	60%	60%	70%	70%	65%	55%
Rocks									
Building		50%	40%	40%					
Snow									
Meadows					40%	30%	30%	35%	45%
Tunnel	100%								
	100%	100%	100%	100%	100%	100%	100%	100%	100%

SECTIONS: Clockwise from Noon

Table 6.3.1 continued.

RINGS / From Inside Out / Center Circle Is Not Included

Section		1	2	3	4	5	6	7	8	9
5		3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
	Sky									
	Road	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Rocks									
	Building									
	Snow									
	Meadows									
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	100%
6		3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	
	Sky									
	Road	100%	100%	100%	100%	100%	100%	100%	100%	NC :06
	Rocks									
	Building									
	Snow									
	Meadows									
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	
7		3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
	Sky									
	Road	100%	100%	100%	100%	100%	100%	100%	100%	NC :07
	Rocks									
	Building									
	Snow									
	Meadows									
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	
8		3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
	Sky									
	Road	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Rocks									
	Building									
	Snow									
	Meadows									
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	100%

SECTIONS: Clockwise from Noon

Table 6.3.1 continued.

RINGS / From Inside Out / Center Circle Is Not Included

Section		1	2	3	4	5	6	7	8	9
9		0,00	1,20	3,25	4,37	2,95	2,50	2,60	2,70	2,80
	Sky									
	Road		40%	25%	33%	35%	50%	60%	70%	80%
	Rocks									
	Building			25%	34%	10%				
	Snow									
	Meadows			25%	33%	55%	50%	40%	30%	20%
	Tunnel	100%	60%	25%						
		100%	100%	100%	100%	100%	100%	100%	100%	100%
10		0,80	0,80	4,80	8,00	4,40	2,00	2,00	0,80	2,00
	Sky									
	Road									
	Rocks									
	Building	10%	10%	60%	100%	40%			10%	
	Snow									
	Meadows					60%	100%	100%		100%
	Tunnel	90%	90%	40%					90%	
		100%	100%	100%	100%	100%	100%	100%	100%	100%
11		8,00	8,00	8,00	8,00	7,40	3,80	2,00	2,90	5,60
	Sky								15%	60%
	Road									
	Rocks									
	Building	100%	100%	100%	100%	90%	30%			
	Snow									
	Meadows					10%	70%	100%	85%	40%
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	100%
12		8,00	8,00	8,00	8,00	8,00	6,20	3,80	7,10	0,00
	Sky							15%	85%	NC :12
	Road									
	Rocks									
	Building	100%	100%	100%	100%	100%	70%	15%		
	Snow									
	Meadows						30%	70%	15%	
	Tunnel									
		100%	100%	100%	100%	100%	100%	100%	100%	

SECTIONS: Clockwise from Noon

Table 6.3.2. Final L_{ij} matrix for L_{seq} evaluation.

AVERAGE LUMINANCE OVER EACH RING SECTION

	RING NUMBER									
SECTION	1	2	3	4	5	6	7	8	9	SUM
1	8,00	8,00	8,00	8,00	8,00	6,20	4,10	8,00	not calculated	58,30 kcd/m²
2	5.36	8,00	8,00	8,00	6,20	3,50	2,00	5,00	7,70	53,76 kcd/m²
3	0,00	6,40	8,00	8,00	3,20	2,00	2,00	2,00	3,20	34,80 kcd/m²
4	0,00	5,50	5,00	5,00	2,60	2,70	2,70	2,65	2,55	28,70 kcd/m²
5	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	27,00 kcd/m²
6	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	[illegible]	24,00 kcd/m²
7	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	[illegible]	24,00 kcd/m²
8	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	27,00 kcd/m²
9	0,00	1,20	3,25	4,37	2,95	2,50	2,60	2,70	2,80	22,37 kcd/m²
10	0,80	0,80	4,80	8,00	4,40	2,00	2,00	0,80	2,00	25,60 kcd/m²
11	8,00	8,00	8,00	8,00	7,40	3,80	2,00	2,90	5,60	53,70 kcd/m²
12	8,00	8,00	8,00	8,00	8,00	6,20	3,80	7,10	[illegible]	57,10 kcd/m²
									L_{ij}=	436,33 kcd/m²

c. L_{ije} matrix for L_{seq} evaluation

Each term of the previous matrix is multiplied by 0,8 (τ_{ws}) and increased by the windscreen luminance. We consider the veiling luminances as medium i.e. L_{ws} = 100 cd/m² and L_{atm} = 200 cd/m².

Table 6.3.3. L_{ij} matrix with L_{atm} and L_{ws} contributions.

SECTION	1	2	3	4	5	6	7	8	9	SUM
1	6,5	6,5	6,5	6,5	6,5	5,06	3,38	6,5	[illegible]	47,44 kcd/m²
2	4,39	6,50	6,50	6,50	5,06	2,90	1,70	4,10	6,26	43,91 kcd/m²
3	0,1	5,22	6,5	6,5	2,66	1,7	1,7	1,7	2,66	28,74 kcd/m²
4	0,1	4,5	4,1	4,1	2,18	2,26	2,26	2,22	2,14	23,86 kcd/m²
5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	22,50 kcd/m²
6	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	[illegible]	20,00 kcd/m²
7	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	[illegible]	20,00 kcd/m²
8	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	22,50 kcd/m²
9	0,1	1,06	2,7	3,596	2,46	2,1	2,18	2,26	2,34	18,80 kcd/m²
10	0,74	0,74	3,94	6,5	3,62	1,7	1,7	0,74	1,7	21,38 kcd/m²
11	6,5	6,5	6,5	6,5	6,02	3,14	1,7	2,42	4,58	43,86 kcd/m²
12	6,5	6,5	6,5	6,5	6,5	5,06	3,14	5,78	[illegible]	46,48 kcd/m²
										359,46 kcd/m²

Therefore $L_{seq} = 5{,}1 \cdot 10^{-4} \times 359{,}46$ kcd/m² = 183 cd/m²

d. Selection of the minimal required perceived contrast

In the present example, we will calculate L_{th} for both counter-beam and symmetrical lighting distributions. We consider these solutions will lead to q_c figures higher than 0,06 therefore leading to a negative perceived contrast (for a reflection factor of the target equal to 0,2). We therefore assume C_m being equal to (-0,28).

e. Calculation of L_{th}

We can calculate L_{th} from the above equations:

$$L_m = [(0{,}8 \times 200) + 100 + 183] / (0{,}8 \times 1) = 554 \text{ cd/m}^2$$

and

in the case of a counter-beam lighting installation:

$$L_{th} = \frac{554}{\frac{1}{(-0{,}28)}\left(\frac{0{,}2}{\pi \cdot 0{,}6} - 1\right) - 1} = 253 \text{ cd/m}^2$$

In the case of a symmetric lighting installation

$$L_{th} = \frac{554}{\frac{1}{(-0{,}28)}\left(\frac{0{,}2}{\pi \cdot 0{,}2} - 1\right) - 1} = 386 \text{ cd/m}^2$$

6.4 Use of daylight-screens

In some countries, daylight provided by screens over the tunnel entrance is used on a wide scale. Regarding the luminance levels, the daylight has to fulfil the same requirements as the artificial lighting. The contrast ratio L/E_v, shall be determined in the same way as for artificial light. For lighting design purposes, the position of the portal is considered at the beginning of the screens.

The contribution of the interreflected light shall be included in the calculation.

Depending on the tunnel location and its construction, the daylight screens can be part of the tunnel ceiling or of the walls, or both. It is recommended for daylight screens in the tunnel ceiling not to apply sun-tight louvers, because practice has shown that with current design methods and materials, it is not possible to ensure a light transmission high enough to fulfill the requirements. For non-sun-tight louvers it is recommended that L_{th}/L_{seq} shall be at least 2 for all tunnel classes. A higher value of L_{th}/L_{seq} is recommended. The maximum value of L_{th}/L_{seq} shall be 6. That figure refers to the fact that the light transmission of non-sun-tight louvers usually depends on the weather conditions. In sunny conditions a high value of L_{th}/L_{seq} (up to 6) is preferred. For cloudy skies the value of L_{th}/L_{seq} must be at least 2. For daylight screens in the tunnel ceiling specific requirements are given in order to avoid the nuisance from flicker (see Section 6.14).

For non-sun-tight screens in tunnel walls, such as horizontal louvers or windows or vertical galleries, specific care must be taken to avoid disturbing flicker effects, which usually cannot be avoided altogether. For this reason it is preferable to use non-sun-tight louvers in the tunnel ceiling and not in the tunnel walls.

6.5 Length of the threshold zone

The total length of the threshold zone must be at least equal to the stopping distance. Over the first half of the distance, the luminance level must be equal to L_{th} (the value at the beginning of the threshold zone). It is recommended that from half the stopping distance onwards, the lighting level may gradually and linearly decrease (linear scale) to a value, at the end of the threshold zone, equal to 0,4 L_{th}. See Fig. 6.6. The gradual reduction over the last half of the threshold zone may also be in steps. However, the luminance levels should not fall below the values corresponding to a gradual decrease, as drawn on the figure.

6.6 Luminance in the transition zone

The reduction of the luminance of the road in the transition zone follows, in principle, the curve shown in Fig. 6.6.

The transition zone starts at the end of the threshold zone (t = 0).

This curve can be replaced by a stepped curve with levels that should never fall below the continuous curve. The maximum luminance ratio permitted on passing from one step to another is 3. The last step should not be greater than 2 times the interior zone luminance.

As the field of view of the driver is made up by the tunnel interior, a longer transition zone may be advisable in order to counteract a second black hole effect.

For additional driving comfort, in the case of the stepped curve, the length of the transition zone may, at its end, be extended for 1 to 2 seconds over the length that follows from the CIE-curve.

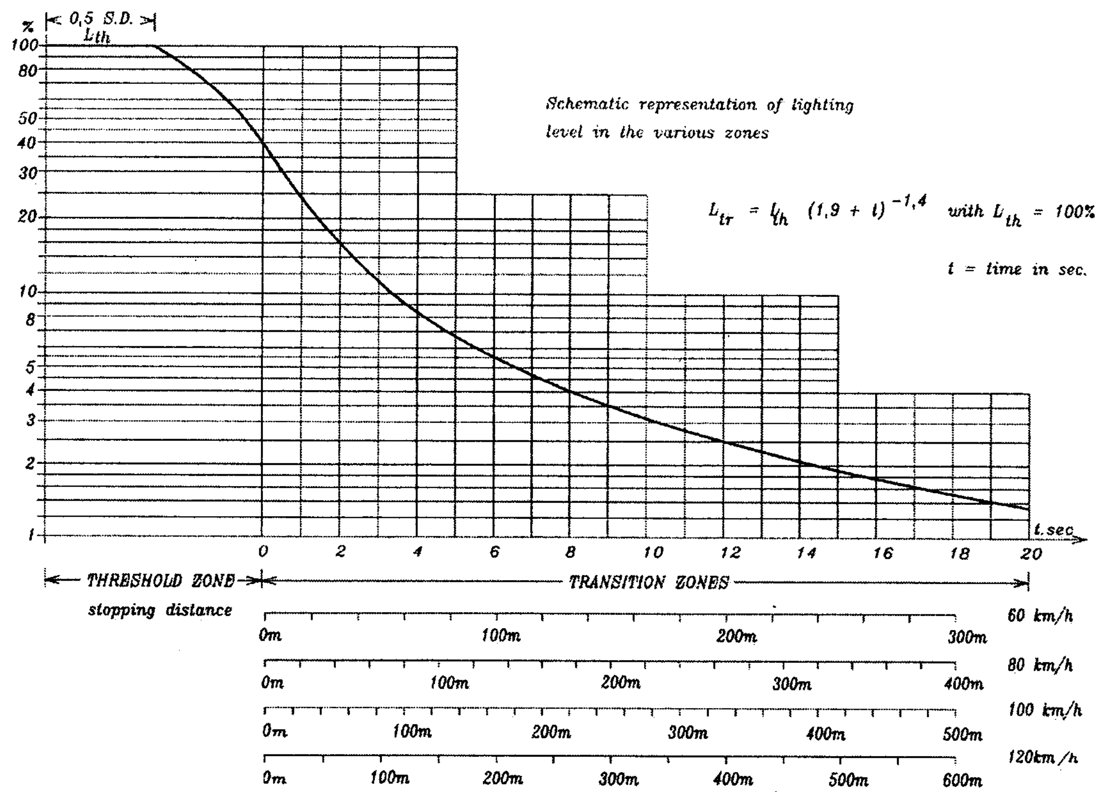


Fig. 6.6. Luminance evolution along the tunnel.

6.7 Daytime luminance in the interior zone

The average luminance of the road in the interior zone of the tunnel is given below as a function of the stopping distance *SD* and of the traffic flow. Very long tunnel's interior zone consists of two different sub zones. The first sub zone corresponds to the length which is covered in 30 seconds and should be illuminated with the "long tunnels" levels. The second sub zone corresponds to the remaining length and should be illuminated with the "very long tunnels" levels.

Table 6.7.1. Luminance values in cd/m² in the interior zone (long tunnels).

Stopping Distance (m)	LONG TUNNELS Traffic flow [vehicles/hour/lane]	
	Low	Heavy
160 m	6	10
60 m	3	6

Table 6.7.2. Luminance values in cd/m² in the second part of the interior zone (very long tunnels).

Stopping Distance (m)	VERY LONG TUNNELS Traffic flow [vehicles/hour/lane]	
	Low	Heavy
160 m	2,5	4,5
60 m	1	2

For stopping distances lying between the stated figures and intermediate traffic flows (between low and heavy), linear interpolation may be used.

Traffic flow used in the previous tables may be defined as follows:

Table 6.7.3. Traffic flow classification.

Traffic flow (see definition in section 5.5)	**One way traffic**	**Two way traffic**
High	> 1500	> 400
Low	< 500	< 100

6.8. Luminance in the exit zone

In order to ensure adequate direct illumination of small vehicles and sufficient rear vision via mirrors, the exit zone should be illuminated in the same way as the interior zone of the tunnel. In situations where additional hazards are expected near the exit of the tunnel and in tunnels where the interior zone is long, it is recommended that the daytime luminance in the exit zone increases linearly over a length equal to the *SD* (before the exit portal), from the level of the interior zone to a level five times that of the interior zone at a distance of 20 m from the exit portal.

6.9 Parting zone lighting

In case the tunnel is part of an unlit road and the speed of driving is higher than 50 km/h, night-time lighting of the parting zone is recommended:

- if the night-time lighting level in the tunnel is more than 1 cd/m^2;
- if different weather conditions are likely to appear at the entrance and at the exit of the tunnel.

Road lighting in the parting zone shall be provided over the length of two stopping distances with road luminance not lower than 1/3 of the night-time luminance in the interior zone of the tunnel.

6.10 Lighting of the walls and the ceiling in all zones

Tunnel walls form part of the background for the detection of obstacles in the tunnel; they contribute to the adaptation level and to the visual guidance. Therefore, the luminance of the tunnel walls is an important component for the quality of the tunnel lighting. The average luminance of the tunnel walls, up to at least a height of 2 m, must be at least 60% of the average road surface luminance at the relevant location.

6.11 Uniformity of luminance

Good uniformity of luminance must be provided on the road surface and on the walls up to a height of 2 m. The lower parts of the walls act as a background for traffic, as does the road. So both must be considered in the same way. A ratio of 0,4 for the minimum to the average value of luminance on the road surface and on the walls up to 2 m in height in clean conditions of the tunnel is recommended. A longitudinal uniformity of 0,6 along the centre of each lane is recommended for the road. Such values of uniformity must be verified for all dimming steps of the lighting installation. Moreover, in the transition zone, as well as in the second half of the threshold zone (and in the exit zone if existing), the luminance uniformity shall be calculated and measured in the central part of each step replacing the continuous variation curve. It is recommended that the above values shall be reached, independently, on the length of the step.

Note: The values of 0,4 and 0,6 are those corresponding to the values for normal road lighting given in CIE 115-1995.

6.12 Daylight variation and lighting control

The access zone luminance varies with changes in daylight conditions.

As the luminance levels in the threshold and transition zones are constant percentages of the access zone luminance, it is necessary to provide control of the lighting in these zones. When screened daylight is used for the entrance zone lighting, the control is automatic. It should be noted, however, that, depending on the transmission characteristics of the screens, the luminance under the screens, is not always linearly correlated to the outdoor light level. For artificial lighting a system that provides control is needed. The control may be done through continuously dimming devices or by switching in separate steps. Many modern tunnels have up to 6 steps, including those for night-time operation. An instantaneous reduction by a factor of not more than 3 is recommended because of economic and comfort reasons.

For adequate light control the access zone light level must be monitored continuously. The method used for lighting control can be different from the method for the lighting design.

The luminance meter that is applied for these measurements is placed at the stopping distance and aimed at the tunnel portal. For maintenance reasons, the luminance meter should be mounted between 2 m and 5 m high above the pavement or hard shoulder on the near side of the street if the road does not curve towards the near side. In the latter case, the luminance meter should be positioned over the central reservation or on the off side of the road. Its sensitivity to temperature should be minimal and the long-term stability should be good as well.

From the momentary access luminance value, the instantaneous luminance required in the threshold zone (L_{th}) is derived. In order to be able to correct for short-term disturbances (e.g. the burning out of lamps) as well as the long-term deterioration (e.g. soiling and corrosion of the tunnel walls and the luminaires) it is recommended to measure the interior luminance with a (second) luminance meter. Again here, it is not possible to measure the luminance from the position of the driver's eye. For practical reasons the mounting height of the luminance meter has to be greater than that of the highest truck i.e. above 4,5 m. Therefore the measured value is different from the luminance seen by the driver. A (constant) correction factor has to be applied.

In general, the difference between the actual and the preferred luminance in the threshold zone should be as small as possible. For each installation, the most economic solution has to be considered on the basis of the energy, lamp and labour cost.

6.13 Glare restriction

As glare reduces visibility, it is important to minimize it. In tunnel lighting the physiological (disability) glare has to be considered. Disability glare effects are quantified by the Threshold Increment *TI* as described in CIE 31-1976 "Glare and uniformity in street lighting".

The threshold increment *TI* must be less than 15% for the threshold, the transition and the interior zones of the tunnel at daytime and night-time. For the exit zone during daytime no restriction is given. The following formula shall be used to calculate *TI*:

$TI = 65\ (L_v\ /\ L_r^{0,8})$ for $L_r \leq 5$ cd/m²

$TI = 95\ (L_v\ /\ L_r^{1,05})$ for $L_r > 5$ cd/m²

with: L_r average road surface luminance

and L_v veiling luminance created by all luminaires in the field of view where the axis of fixation is 1° down from the horizontal at the relevant location. The calculations shall be made on the base of the initial values and with a full cut-off angle of 20° above the axis of observation due to the roof of the car. At present, it is not possible to give a numerical value for the restriction of the glare in the transition zone.

6.14 Restriction of the flicker effect

Flicker sensations are seen when driving through spatially periodic changes in luminance, such as those produced by daylight screens (both sun-tight and non-sun-tight) or luminaires that are mounted separately. Under specific conditions, the flicker may cause discomfort that sometimes can be severe.

The degree of visual discomfort experienced due to flicker depends upon:

(a) the number of luminance changes per second (flicker frequency);

(b) the total duration of the experience;

(c) the ratio of peak (light) to trough (dark) luminance within each period (luminance modulation depth) and the steepness in the increase (rise-time).

(a), (b) and (c) depend upon vehicle speed and luminaire spacing. (c) also depends upon the photometric characteristics and the spacing of the luminaires. In near-continuous line lighting, where the distance between the end of one luminaire and the beginning of the next luminaire is less than the length of the luminaires, flicker discomfort is rendered independent of the frequency. The flicker frequency can be easily established by dividing the velocity (in m/s) by the luminaire spacing (center-to-center; in m). For example: for a speed of 60 km/h (= 16,6 m/s) and luminaire spacing of 4 m, the flicker frequency is 16,6/4 = 4,2 Hz.

In general, the flicker effect is negligible at frequencies below 2,5 Hz and above 15 Hz. When the frequency is between 4 Hz and 11 Hz, and has duration of more than 20 s, discomfort may arise provided no other measures are taken. It is recommended that, in installations where the duration is more than 20 s, the frequency range between 4 Hz and 11 Hz be avoided, particularly when small light sources with a sharp run-back are used. Large size luminaires with low gradients in the light distribution (like e.g. length-wise mounted luminaires with fluorescent tubes) usually will lead to little discomfort. In view of the high luminance of the elements, it is recommended to avoid for non-suntight daylight screens all frequencies below the flicker-fusion frequency, - e.g. > 50 Hz - independent of the length of the screens.

7. NIGHT-TIME LIGHTING

(a) If the tunnel is on a section of an illuminated road, the quality of the lighting inside the tunnel should be at least equal to the level, uniformities and glare of the access road. The uniformity at night of tunnels shall fulfil the same requirements as the daytime lighting.

(b) If the tunnel is a part of an unlit road, the average road surface luminance inside must not be less than 1 cd/m², the overall uniformity at least 40% and the longitudinal uniformity at least 60%.

8. EMERGENCY LIGHTING

In the event of a failure in the normal power source that supplies the lighting system, it is recommended that an emergency non interruptible power supply is employed to energize sufficient system luminaires. Conventionally the "emergency" luminaires form a part of stage 1 being the normal night-time level throughout the tunnel. The emergency configuration by example could consist of: one lamp from a selection of the system luminaires, forming a linear symmetrical and inter spaced series of emergency luminaires, being energized from the non interruptible power supply source. It is recommended that the average illuminance level of the emergency lighting should be at least 10 lx with 2 lx being the minimum level at any location within the tunnel. For recommendations relating to escape lighting in the event of a fire, appropriate references and standards should be sought by the reader (e.g. EN 1838), as it is not intended for this document to cover the specific demands required by such circumstances.

9. MAINTENANCE

9.1 General

When planning and designing a tunnel lighting system, the engineers and designers should take into consideration all matters concerning maintenance. The lighting designer should determine and influence, if possible, the cleaning policy, schedule and methods the owner plans to use for periodically restoring tunnel surface reflectivity.

A good lighting system maintenance plan is one which not only provides acceptable initial results, but which also enables the maintenance staff to keep system performance in good condition throughout the expected equipment life. A plan, whose operating policy emphasizes regular maintenance, is particularly important with regard to energy conservation. This maintenance plan, once incorporated into the design, should be carried out to insure that the system performs as expected.

Cleaning tunnel walls of various surfaces requires the use of chemical solvents, pressurized super heated water and mechanical cleaning devices that may have a deleterious effect on the tunnel lighting system. Some types of luminaires may be prone to premature failure due to their inability to maintain water tightness and dust tightness, features required in the tunnel environment. In selecting the equipment, designers should consider its capability to withstand washing when high-pressure spray and mechanical brushes are applied.

Materials and finishes used in the luminaire manufacture are of specific importance and should be carefully considered when selecting equipment for tunnel applications. Dissimilar materials need to be positively isolated from each other. As an example, aluminium and carbon or stainless steel components exposed to moisture and chemicals may allow galvanic reactions that cause early deterioration of the equipment. The same considerations also apply to the materials used to locate and secure the lighting system to the tunnel. Chemicals in concrete must be isolated from some metals, such as aluminium, and other materials subject to corrosion.

Maintenance in tunnels is difficult under regular traffic conditions or partial lane closures as it can cause severe traffic backups and may increase the potential for accidents. Repair of the lighting system and its components must be accomplished with minimal time spent in the tunnel.

The light levels obtained when the system is initialized will decrease due to a number of related items. Since the recommended luminance levels in this Guide represent the lowest-in-service values that should be maintained throughout the operating life of the system, it is therefore of the utmost importance that the initial luminance figures be higher to compensate for Lamp Lumen Depreciation (*LLD*), Luminaire Dirt Depreciation (*LDD*), Equipment Factor (*EF*) and the tunnel surface (wall and ceiling) reflectance depreciation. These factors, which change with time after installation, may be combined into a single multiplying factor for inclusion in calculations. This Total Maintenance Factor (*TMF*) is composed of the above-mentioned factors, each of which is controlled and evaluated separately. A few factors are beyond the control of the lighting system owner or operator and depend upon actions of others, such as the system voltage regulation, or the control of emissions into the atmosphere. It is, however, the task of the system designer to determine and apply a realistic *TMF* factor to all design calculations as follows:

$$\text{Initial Luminance Level} = \frac{\text{Lowest In-Service Maintained Luminance Level}}{\text{Total Maintenance Factor}}$$

9.2 Lamp Lumen Depreciation (*LLD*)

The luminous flux produced by light sources generally decreases with time. The *LLD* factor will depend on the type of light source used for the tunnel lighting. Lumen output characteristics for the different lamps (Fluorescent, Compact Fluorescent, LPS, HPS, MH, Induction or Electrodeless) vary due to aging. Information about the chosen lamp and its lumen depreciation and mortality are available from lamp manufacturers' tables and graphs. Rated average life should be determined for the specific hours per start. From these facts, a practical group relamping cycle should be established and then, based on the hours elapsed to lamp removal, the specific *LLD* factor can be determined. Consult manufacturers' data for *LLD* factors. Additionally, monitoring the change of light output after the lighting system is installed will help to further refine the optimum relamping cycle. Systematic group relamping is to be preferred.

9.3 Burnouts

Unreplaced burned-out lamps will vary in quantity, depending on the kinds of lamps and the relamping program used. Manufacturers' lamp mortality statistics should be consulted for the performance of each lamp type so that the number of burnouts can be determined before the time of planned replacement is reached. For applications where maintained illumination is critical, rigorous record keeping of lamp burnout performance is recommended.

9.4 Luminaire Dirt Depreciation (*LDD*)

The *LDD* factor relates to the depreciation of luminaire lumen output due to dirt deposits on lenses, refractors, lamps and reflecting mirrors. This accumulation of dirt results in a change in the photometric distribution emanating from the luminaire and a loss in light output on the roadway. *LDD* must be considered in calculating maintained luminance values specified for the service life of the lighting system.

To a large extent, the value of the *LDD* factor is dependent, in inverse proportion, to the owner's investment in quality of material and manufacture of luminaires, and commitment to regular cleaning of plastic or glassware, lenses, lamps, and reflecting mirrors. However, if the luminaires are sufficiently sealed against the ingress of dirt, then cleaning of the front glasses of the luminaires should be enough to maintain the light output. One system currently in use determines the Ingress Protection (IP) rating for luminaire enclosures. The International Electrotechnical Commission standard, IEC 60598, provides the test methodologies to determine the degree of protection against ingress of dust, solid objects and moisture in accordance with the classification of the luminaire and the IP number marked on the luminaire. For luminaires in tunnels, the minimum class for dirt / moisture protection is contained in the IP65 rating. The intervals between cleaning may vary greatly in order to maintain the required performances. Conversely, if the intervals of cleaning are fixed, the use of a luminaire that in service stays cleaner may permit the designer to use a lower wattage to achieve the same lighting results.

Decisions about *LDD* factor value, and its relation to the number and wattage of fixtures required to meet maintained service levels, and the commitment of resources to regular maintenance should be considered in a life cycle cost analysis.

9.5 Equipment Factors (*EF*)

Light loss factors, that are not dependent on time, relate mostly to the characteristics of the specific equipment selected. While some may not be correctable, it is possible that one or more may have an important effect upon the light level produced. Care should be taken in selecting equipment appropriate to the service conditions.

9.5.1 Ambient temperature

The effect of ambient temperature on the output of some lamps may be considerable. Each particular lamp-luminaire combination has its own distinctive characteristic of light output versus ambient temperature. To apply a factor for light loss due to the environmental ambient temperature site characteristics, the designer must know the highest and lowest temperatures expected and to have data showing variation in light output with changes in ambient temperature for the specific lamp in the specific luminaire to be used.

9.5.2 Voltage

In-service voltage is difficult to predict. However, if voltage fluctuations are expected then certain control gear types can be selected which compensate for voltage variations. Conductor size affects voltage drop and the trade-off between using smaller conductors and control gear types that compensate for voltage variations should be evaluated.

9.5.3 Control gear and Lamp Factor

Information is available as to the relationship of the control gear circuit type, lamp type, and other factors to the rated versus actual light output of various lamps and control gears. Certain circuits can minimize line voltage variation; others can minimize lamp tolerances while still others can compensate for lamp aging. Photometric data is based on rated lamp output under laboratory conditions. Under field conditions circuits and component tolerances in both the control gear and the lamp cause variations between any individual lamp control gear combination and rated output.

9.5.4 Luminaire component depreciation

Surface depreciation results from adverse changes in metal, paint, plastic components, and gaskets, which reduce light output. Because of the complex relationship between the light controlling elements of luminaires using more than one type of material, it is difficult to predict losses due to deterioration of materials. Also for various luminaire surfaces, the type of atmosphere to which they are exposed will differentially affect the losses. Lack of cleaning greatly impacts system deterioration.

9.6 Maintenance of the control photometers

It is important that the control photometers in the access and threshold zones are checked and cleaned periodically. It is recommended that the control photometers be calibrated on a yearly basis.

9.7 Tunnel surface reflectance depreciation

The main purpose of cleaning the walls is to ensure a high light level on the wall i.e. high wall luminance as well as good road luminance. High wall reflectance is important because the walls contribute to the inter-reflected light and also the lighting of the walls provides a significant contribution to the visual guidance for the motorist.

9.7.1 Selection of tunnel surface reflectance

Selection of tunnel surface reflectance has a significant impact upon effectiveness of light fixtures in meeting the lighting design criteria. Reflectance characteristics (specular, diffuse, and others) will have significant effect on the effective use of light.

9.7.2 Reflectance depreciation

Tunnel surfaces will collect dirt, soot, chemicals such as salt, grime, and moisture deposits from vehicle exhaust, vehicle spray and atmospheric and subterranean causes. This will result in depreciation of the surface reflectance utilized in the lighting design for the original surface. This should be taken into consideration for calculations utilizing surface reflectances.

9.8 Luminaire cleaning, relamping and replacement

Good lighting and visibility play an important role in the prevention of accidents in tunnels and the potential secondary effect of explosion, fire, or the generation of noxious fumes.

Repair and maintenance of lighting fixtures in tunnels usually requires lane closures, which should be minimized by the selection of good equipment and a well-developed cleaning and relamping schedule.

9.8.1 Luminaire cleaning

Regular cleaning of reflecting mirrors and lenses, is particularly important in tunnels because these components are constantly subjected to atmospheric pollutants.

Periodic cleaning of both external and internal surfaces is required. The internal cleaning requirements will vary depending on ambient conditions and luminaire construction. Proposed cleaning schedules and the initial cost of higher quality fixtures should be included in the life-cycle economic analysis. Cleaning schedules should be coordinated with relamping schedules as much as possible to minimize lane closures.

9.8.2 Relamping

Consideration of group relamping is more critical in tunnel lighting maintenance programs than for most other lighting systems because of traffic restrictions required in tunnels.

Easy, quick relamping (as well as internal cleaning) is affected by the construction, latching, sealing and accessibility of fixtures. These factors should be thoroughly considered in design. Poor designs relative to location, accessibility to the fixture, or ability of workmen (with gloves) to open, service, and close fixtures will significantly affect operating costs. An example of poor design from a maintenance viewpoint is the location of luminaires over the centre of a very wide roadway.

9.8.3 Luminaire replacement

Consideration should be given to luminaire selection and mounting to allow very rapid replacement of the total luminaire or its components. This approach should attempt to minimize the amount of time required for lane closures.

9.9 Other factors

A number of other factors should also be considered in the overall calculations of tunnel lighting design. Not all of these will result in any reduction of the lighting system quality, but should be considered as necessary. This is particularly important when disparities arise between calculations and field measurements.

9.9.1 Pavement reflectance

The pavement is other than R1, R2 or R3 as used in calculations:

a) real pavement reflectance is typically some variant of the assumed standard and for accuracy should be measured;

b) pavement is rarely uniformly polished;

c) layers of construction dust obscure the real reflection characteristics.

9.9.2 Other reflection characteristics

Bi-directional reflection characteristics are needed to accurately predict light reflections from the road, wall and ceiling surfaces.

9.9.3 Physical geometry

Physical geometry is not the same as assumed in the design due to typical construction differences such as tunnel size, luminaire location and / or aiming, etc.

9.9.4 Errors associated with the luminaire and control gear

a) Photometric variations:
   1. beam placement is incorrect;
   2. beam shape is incorrect;
   3. efficiency is other than published.

b) Lamp manufacturing variations:
   1. lamp does not meet lumen rating;
   2. incorrect light centre;
   3. arc tubes are not concentric with lamp base (out of plumb arc tube, base or socket);
   4. HPS arc voltage design is shifted up or down

      Up = high light level & shorter lamp life

      Down = lower light level & longer lamp life.

c) HID choke or reactor type control gear permit significant changes in light level. Example a 1% change in voltage = 2,5% change in light level.

d) Control gear is not nominal due to manufacturing tolerances:
   1. low output produces low light level;
   2. high output produces short lamp life.

e) Luminaire manufacturing variations such as incorrect socket position, etc.

When designing tunnel lighting installations, we recommend the use of a total maintenance factor in function of the frequency of the maintenance and the quality of the materials:

- 0,35 to be used when poor maintenance and material quality are considered;
- 0,50 to be used when normal maintenance and material quality are considered;
- 0,70 to be used when intensive maintenance and high quality material are considered;
- higher or lower values may be used depending on the foreseen maintenance schedule and quality material.

ANNEXES

A.1 L20 METHOD

The luminance L_{20} in the access zone is defined as the average of the luminance values measured in a conical field of view, subtending an angle of 20° (2 x 10°), by an observer located at the reference point and looking towards a centered point at a height equal to one quarter of the height of the tunnel opening. See Fig. A.1.2.

This average luminance is conventionally considered as representative of the state of adaptation of the eye of a driver approaching the entrance of the tunnel when he finds himself at the reference point and is used as a basis for computing the luminance in the entrance zone. Preferably, it can be calculated or it can be measured by means of a luminance meter having a 20° angle of aperture.

This method can be used if one has an image taken at the stopping distance from the portal of the tunnel. In this method, the evaluation of L_{20}, is obtained from a sketch of the environment of the entrance of the tunnel and is calculated by means of the following formula:

$$L_{20} = \gamma \cdot L_c + \rho \cdot L_r + \varepsilon \cdot L_e + \tau \cdot L_{th} \qquad \text{(A.1.1)}$$

where:

L_c =	luminance of the sky:	γ = % of sky in the 20° field
L_r =	luminance of the road:	ρ = % of road
L_e =	luminance of the surroundings:	ε = % of surroundings
L_{th} =	luminance of the threshold zone:	τ = % of tunnel entrance

and

$$\gamma + \rho + \varepsilon + \tau = 1 \qquad \text{(A.1.2)}$$

In this formula the value of L_{th} is the unknown to be determined. For stopping distances longer than 100 m, the value of τ is low (below 10%) and given that L_{th} is already low with respect to the other values of luminance, the L_{th} term is negligible.

For a stopping distance of 60 m the following expression can apply:

$$L_{20} = (\gamma \cdot L_c + \rho \cdot L_r + \varepsilon \cdot L_e + \tau \cdot L_{th}) / (1 - k) \qquad \text{(A.1.3)}$$

As k (see Section A.1.1 and Equ. A.1.5) can never be greater than 0,1, the product $\tau \cdot k$ is negligible and the expression can be written as follows:

$$L_{20} = \gamma \cdot L_c + \rho \cdot L_r + \varepsilon \cdot L_e \qquad \text{(A.1.4)}$$

where

$$\gamma + \rho + \varepsilon < 1$$

If no L values of the surroundings are available, the data for L_c, L_r and L_e (expressed in kcd/m^2) are given in Table 6.2.3.

In order to estimate the percentages of the components of L_{20}, it is appropriate to take a photograph of the entrance of the tunnel from the reference point, the axis of the line of sight being oriented towards a point in the centre of the entrance at a height equal to one quarter of the height of the tunnel opening.

The circle of intersection of the cone of observation with the vertical plane of the portal is then marked on the photograph and the zones of the components are delineated, their luminances being calculated as a percentage of the area of the circle. The radius of the circle can be calculated, at the scale of the photograph, on the basis of a known dimension of the picture, for example the height of the portal of the tunnel.

Example (see Fig. A.1.2.)

Stopping distance: *SD* = 100 m

Portal height = 5 m (13,7 mm on the photograph)

The sought radius R = *SD* · tg 10° = 0,176 · *SD*

On the scale of the plane of the portal, *SD* = 100 x 13,7/5 = 274 mm

Therefore R = 0,176 x 274 = 48,3mm

In this case, the skyline must not be modified during the construction. Otherwise it will be appropriate to make use of a scale drawing. The photograph or the drawing can be compared with the most similar sketch in Fig. A.1.1, whose specific sky percentage is known.

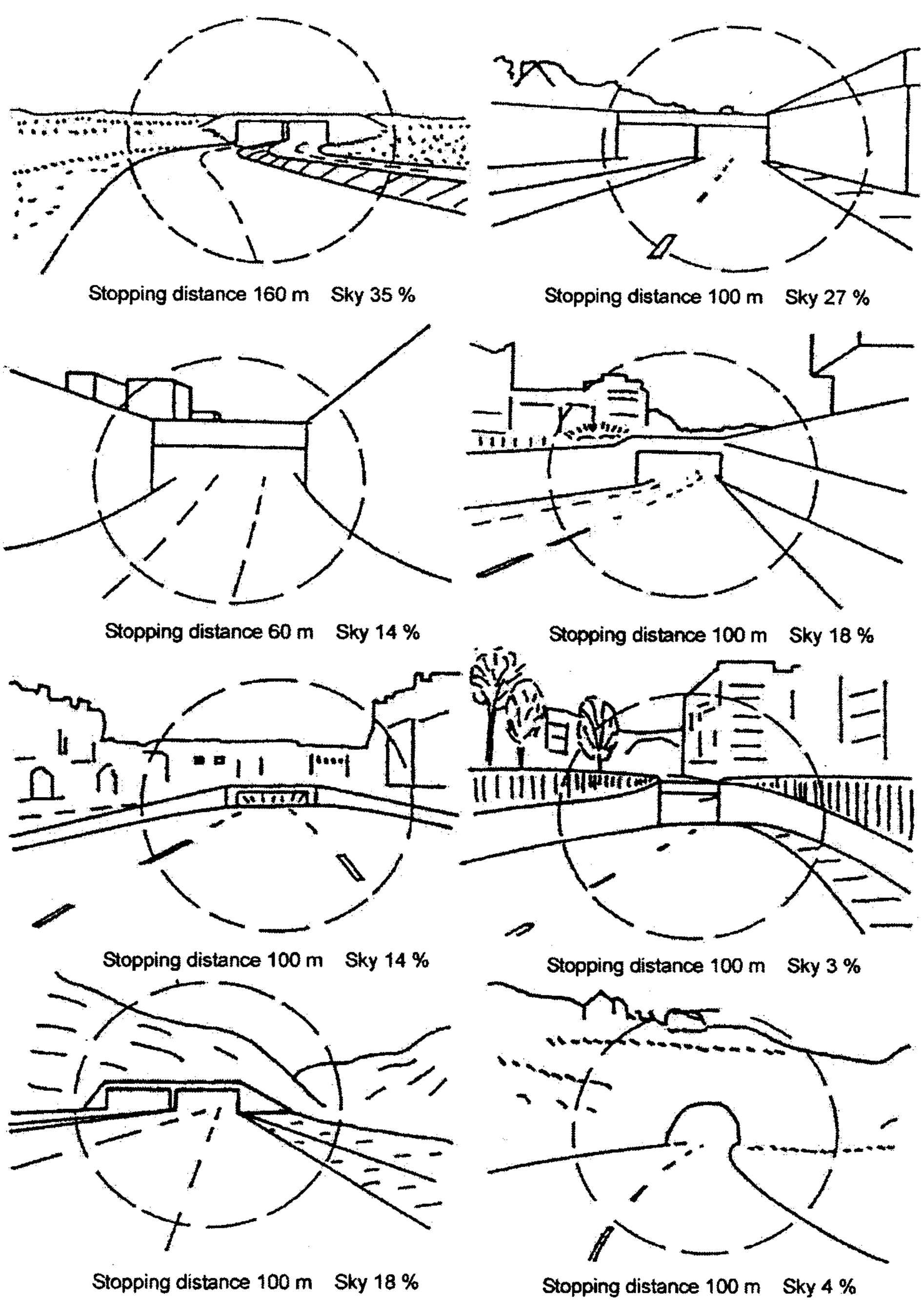


Fig. A.1.1. Sky percentages for several configurations.

A.1.1 Evaluation of the luminance in the threshold zone with the L20 method

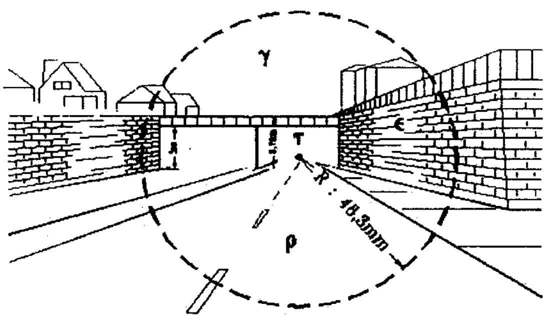


Fig. A.1.2. Perspective view of tunnel entrance with superimposed 20° subtended circle.

In order to prevent the sensation of a black hole and to create minimum luminance conditions to obtain sufficient visibility of objects in the threshold zone, the luminance of the road in the threshold zone must reach certain minimum values. These depend on the luminance in the access zone. In practice it is necessary to distinguish a first half within the threshold zone where the luminance of the road is constant and called the threshold luminance (L_{th}).

L_{th} can be expressed as a fraction k of L_{20}

$$L_{th} = k \cdot L_{20} \qquad (A.1.5)$$

As the proportion taken by the view of the entrance is a function of the length of the access zone, the minimum value of k to be complied with also depends on the stopping distance according to the Table A.1.3.

Table A.1.3. L_{th}/L_{20} ratio's for various speeds.

Speed (km/h)	$k = L_{th} / L_{20}$
<= 60 km/h	0,05
80 km/h	0,06
120 km/h	0,10

A.2 STOPPING DISTANCE

Important parameters for the design of tunnel lighting installations include the speed, volume and composition of traffic flow entering, and passing through the tunnel. A method is included as part of this Annex but national practices should take precedence.

There is a strong, but non-linear relationship between the traffic flow and the accident risk: higher volumes show a higher accident risk (with the exception of very low or very high traffic flows). The extra risk can be counteracted, at least in part, by increasing the light level. This relationship is established for many types of open roads, and it is assumed that it also holds for tunnels.

One of the most important factors is speed. In practice, road and tunnel designs are such that speed and flow usually are interrelated, as a high design speed is selected for roads for which a high flow is expected. High speeds require better visibility and therefore generally a higher luminance level.

The stopping distance *SD* that often has to be evaluated for the correct design of the lighting is the sum of two stretches of road:

- the x_o distance covered during the reaction time;
- the x distance covered during the braking time.

If u is the travelling speed, constant at the beginning of the stopping action,

$$x_o = u \cdot t_o \tag{A.2.1}$$

where t_o is the reaction time.

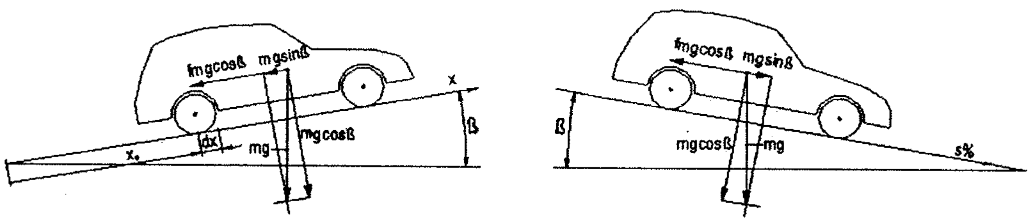


Fig. A 2.1. Forces acting on a vehicle with different slopes.

The x distance can be calculated comparing the impulse for a dt time with the momentum

$$-(f \cdot m \cdot g \cdot \cos\beta \pm m \cdot g \cdot \sin\beta) \cdot \mathrm{d}t = m \cdot \mathrm{d}u \tag{A.2.2}$$

where:

f = friction coefficient tire-pavement

m = mass of the vehicle

g = gravity acceleration

the + sign must be considered for ascending slope; the – sign for descending slope.

The time dt can be expressed as dx/u. Introducing the slope $s = \tan\beta$, Equ. A.2.2 becomes:

$$-\cos\beta \cdot g \cdot (f \pm s)\,\mathrm{d}x / u = \mathrm{d}u \qquad \text{or}$$

$$\mathrm{d}x = -\frac{u}{\cos\beta \cdot g \cdot (f \pm s)}\mathrm{d}u$$

As cosβ always close to the unit, it can be neglected.

Integrating the left-hand member between the distance 0 and x, the right-hand member must be integrated between the speed u and the speed 0. So

$$\int_0^x \mathrm{d}x = -\int_u^0 \frac{u}{g \cdot (f \pm s)}\mathrm{d}u \tag{A.2.3}$$

The integration of the right-hand member is impossible because the friction coefficient f is an unknown function of the speed and other parameters depending on the speed, such as the atmospheric conditions, the tires condition and so on.

But assuming f as a constant versus u Equ. A.2.3 gives:

$$x = \frac{u^2}{2 \cdot g \cdot (f \pm s)} \tag{A.2.4}$$

With this hypothesis formula Equ. A.2.4 can be used to determine x if the friction coefficient is assessed by practical tests and reported in a graph as a function of the speed.

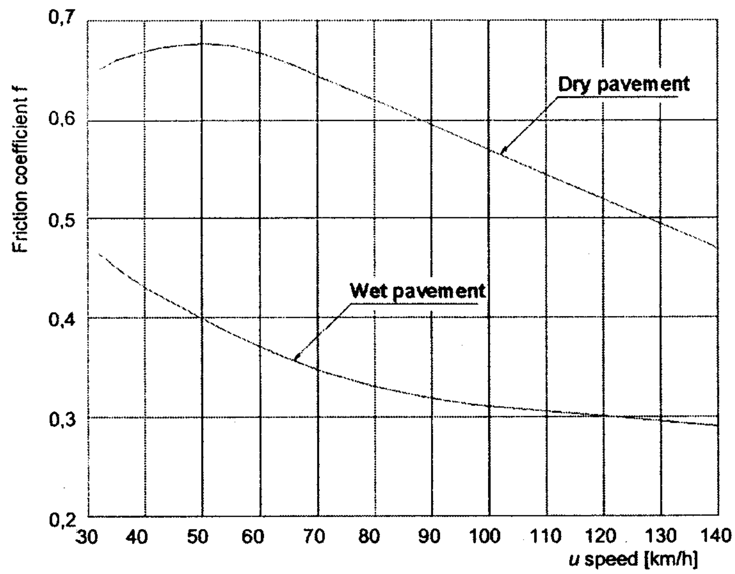


Fig A.2.2. Typical diagrams of the friction coefficient as a function of the speed for dry and wet pavement.

Summing the reaction distance (Equ. A.2.1) and the braking distance (Equ. A.2.4) the general formula of the stopping distance is obtained :

$$SD = u \cdot t_o + \frac{u^2}{2 \cdot g \cdot (f \pm s)}$$

Without any particular value, t_o can be assumed equal to 1 s and f taken from the curve of Fig. A.2.2 for wet pavement as a function of the design speed.

A.3 EVALUATION OF L_{SEQ} / CORRECT USE OF A CAMERA

Scope

Section 6.2 suggests using a photograph for the estimation of L_{seq}. In this appendix indications are given for the correct use of the camera.

Type of camera

Any type of camera is allowed, both traditional and electronic, provided that they meet the criteria outlined below. However, since a quicker evaluation of L_{seq} requires exportation of the picture in an electronic format, electronic cameras are advisable. Electronic cameras permit an immediate transfer of the pictures to a PC without the use of a scanner. Also motion picture cameras can be used, provided that they have facilities to capture still pictures and transfer them to a PC.

Film type

For traditional cameras, negative films are advisable, since the large print size is more suitable for the scanner, which is necessary for transferring the picture into the PC.

There is no preferred film format: e.g. type 135 (picture size 36 mm x 24 mm), type 120 or 220 (picture size 60 mm x 60 mm or 70 mm x 60 mm) are equally suitable, with any film sensitivity, provided it is sufficient for a good picture. Colour films are preferable, because they permit an easier recognition of details of both foreground and background for the use of Section 6.2.

Objective

In principle, any focal length is permitted for the objective lens, provided that it covers at least 57° horizontally and 40° vertically, in order to comply with the extension of the diagram of Fig. 6.2.2. Actually, angular relationships are invariant through a "perfect" lens between object (the scene) and image (the picture). However, many commercial lenses, especially wide angle ones, show large distortions, either pin-cushion or barrel, which make them unsuitable for the evaluation of L_{seq}. This is especially the case for low cost zoom lenses, frequently used in electronic cameras.

Thus, it is advisable to restrict the field of view to the minimum requested, because distortions are normally minimized. For example, a 35 mm lens for film format 135 (field 54° x 38°) and a 60 mm one for film formats 120 or 220 (field 53° x 53°) are a bit under the limits, but still acceptable. If the contribution to L_{seq} of the external sectors of Fig. 6.2.2 is disregarded, then a 50 mm lens (field 39° x 27°) for the 135 format and 80 mm (field 41° x 41°) for the 120 or 220 format, i.e. the "normal" lenses for both formats, can also be accepted. Lower focal lengths can always be used, provided that distortions are kept low.

Some zoom lenses of electronic cameras show the focal lens equivalent to the 135 film format (36 mm x 24 mm), making the set up of the correct focal length easy. In some other cases, no such indication is given. In this case the set-up of the focal length of the zoom lens should be done preliminary looking in the electronic view finder, or even better in the LCD screen which normally equips the camera, at a rigid meter placed vertically in front of the camera: 1 m at a distance of 2,7 m covers 40°.

Verification of distortions

Before using a camera for the first time, the distortion of a lens should be verified. For this purpose, a photograph should be taken of a horizontal object (e.g. the alignment of the upper sides of the windows of a large building or the top of large roof) placed at the top of the picture with the lens focused at infinity (the object should be at a distance of at least 10 m). On the print of the picture it is easy to discover whether there is an important distortion or not.

Shooting distance

The camera should be placed at the stopping distance from the threshold of the tunnel, corresponding to the design speed of the tunnel, with the optical axis of the objective placed above the axis of the running lane of the road at a height of 1,25 m and aimed at the centre of the threshold section of the running lane.

However, this is not always possible, especially if a picture is to be taken on an existing tunnel without interrupting the traffic. While a camera placed on one side of the running lane at a normal height (e.g. 1,5 m - 1,8 m) does not introduce appreciable errors, more care should be placed on the distance to the tunnel, because the angular relationships between the points of the scene on the plane of the tunnel threshold and the points closer or further (e.g. the sky) are altered and difficult to recover on the picture. Either way, a tolerance of ±10% of the stopping distance can be tolerated, since it generates an error of at most 1° on the azimuth angles in Fig 6.2.2.

Evaluation of L_{seq}

The picture of the tunnel taken will be superposed to the diagram of Fig. 6.2.2 of Section 6.2. This can be best accomplished on the electronic images on the screen of a PC or, if an electronic image is not available, through a transparent sheet. Either the picture or the diagram shall be scaled so that the 2° aperture circle of the diagram corresponds to the same aperture on the picture. To this aim, since both the width of the tunnel opening W_T and the stopping distance SD are known, it is sufficient to calculate the observation angle α (in degrees) subtended by the tunnel opening as:

$$\alpha = 2 \cdot \text{arctg}\,[W_T / (2\,SD)] \sim 57 \cdot W_T / SD$$

and then scale the picture, or the diagram, up or down in order to make them compatible, taking account that the central circle of the diagram subtends 2°.

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