Wout van Bommel

Road Lighting

Fundamentals, Technology and Application

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Dedicated to: *the many students and attendees of conferences who, through their critical questions and participation in discussions, helped me over a period of some 40 years in learning how to explain lighting.*

Preface

This is my second book on the subject of road lighting. The first, also titled "Road Lighting", appeared in 1980 in the series "Philips Technical Library" published by Kluwer, with co-author Prof. J.B. de Boer. Since that time, the technology of road lighting has progressed to keep up with the changes in lamp and lighting technology, in traffic and automobile technology, and especially in the thinking about energy and the environment. The introduction of solid-state light sources (LEDs) has provided the possibility to design innovative, truly-sustainable lighting installations that are adaptable to changing circumstances such as traffic density and weather conditions. To avoid pitfalls when designing such installations, a detailed knowledge of the typical characteristics of the many different light sources, and especially also of all the aspects determining the final quality of road lighting, is essential. Completely-new fundamental research on vision and new application research on visual performance and comfort, conducted at many different research institutions at many different places all over the world, is now available as a basis for the specification and the design of effective, energy-friendly and sustainable road-lighting installations.

The purpose of this present book, which represents a completely-fresh approach to the subject, is to outline the underlying principles on which modern road lighting is based and to leave the reader with an understanding of the background to the subject and a knowledge of how these principles should be applied in practice.

The book is divided into three parts. Part One discusses the lighting of open roads for motorised traffic as well as for cyclists, pedestrians and residents. The first chapters deal with the purpose of road lighting, visual performance, including the effects of mesopic vision and of the aging eye, and visual comfort. Traffic safety, personal security and pleasantness are the main issues here. Following chapters describe the relevant lighting criteria for good and efficient road lighting and show and discuss the international, European and North American standards and recommendations for road lighting. Next, lamps and luminaires are reviewed in terms of their practical properties and features, the intention being to facilitate a proper selection of this equipment for the various application fields. The road surface, as a means to reflect light towards the road user, must in fact be seen as part of the equipment of a road-lighting installation. Road-surface reflection properties are therefore dealt with in one of the "Equipment" chapters. The chapter "Design Aspects" provides the link between theory and practice and supplies the reader with the knowledge needed for effective lighting design. The sustainability aspects of road lighting that have to be taken into consideration by the lighting manufacturer as well as by the lighting designer are also discussed in this chapter. The last chapter of part one deals with road-lighting calculations and measurements.

Part Two of the book is devoted entirely to the subject of light pollution. Lighting that lights not only the area intended but that spreads out uncontrolled into the surrounding areas and into the sky is an annoyance to society. The disturbing effects to residents, to motorised and slow-moving traffic, to astronomers and to wildlife and natural vegetation are described. The zoning and curfewing tactics that are employed to restrict light pollution are explained, and lighting criteria that can be used by the lighting specifier and the lighting designer to guarantee that installations will stay within acceptable light pollution limits are defined. International, European and North American standards and recommendations on the restriction of light pollution are listed and discussed. The last Chapter of this Part 2 deals with that lighting equipment that is specifically suitable to limit light pollution. It also provides practical design guidelines on controlling light pollution.

The subject of the third and final part of the book is tunnel and underpass lighting. The structure of this part is largely the same as that of part One. It has chapters discussing the purpose, the visual-performance fundamentals, the lighting criteria and the standards and recommendations for tunnel lighting. The concluding chapter deals with tunnel-lighting equipment and tunnel-lighting design aspects.

This book is not aimed solely at the road-lighting designer and road-lighting engineer in municipalities and local governments or the student of lighting design and engineering; there is much of interest here too for the town planner, town traffic engineer and environmental specialist, as well as for the lamp and luminaire developers and manufacturers.

I am much indebted to Derek Parker who did a great job editing this book, just as he did for the previous Road Lighting book, back in 1980.

Contents

List of Abbreviation

Organizations

ANSI	American National Standards Institute
CEN	European Normalization Commission
CIE	International Lighting Commission
DOE	Department of Energy (USA)
EC	European Commission
GLF	Global Lighting Forum
IAU	International Astronomical Union
IDA	International Dark sky Association
IEC	International Electrotechnical Commission
IESNA	Illuminating Engineering Society of North America
ISO	International Standardization Organization
PIARC	World Road Association
Zhaga	International Consortium developing interface specifications that enable interchangeability of LED light sources

About the Author

Prof. Wout van Bommel MSc worked for more than 35 years with the head office of Philips Lighting in the Netherlands in different lighting application functions. He became responsible for the company's international lighting application know-how centre. He has carried out research into many different lighting subjects. Some concepts now used in international standards for lighting are based on his research work.

For the period 2003–2007 Wout van Bommel has been President of the International Lighting Commission (CIE). He was on the Board of the International Dark-sky Association (IDA) between 2008 and 2010. He was president and still is Board member of the Dutch "Light and Health Research Foundation" (SOLG).

Wout van Bommel was appointed Consulting Professor at the Fudan University of Shanghai in 2004 and for the period 2008–2012 External Examiner of the Master Course "Light and Lighting" at the University College of London (UCL- Bartlett Institute).

He has published many papers in national and international lighting journals in different languages. All over the world he has presented papers, has taught at universities and schools and has given invited lectures at conferences.

After his retirement from Philips Lighting, he teaches in Shanghai 1 month per year and throughout the year at other Institutions. He advices, as an independent Lighting Consultant, lighting designers, researchers, companies, municipalities and governmental bodies.

Part I
Road Lighting

Chapter 1
Purpose and Benefits of Road Lighting

Abstract Decisions to invest in road-lighting installations can only be made sensibly if there is a clear insight into the purpose and benefits of road lighting. For motorized traffic, road lighting should provide visual performance and visual comfort and help to keep the driver alert. Many different studies have shown that good road lighting can reduce night-time accidents. In countries with peak hours in the hours of darkness, road lighting can increase the capacity of a motorway. In built-up and residential areas, road lighting should also provide visual information for slow-moving traffic such as pedestrians, cyclists and moped users so that they can find their path without the risk of colliding with or stumbling over potentially dangerous hazards. In these areas road lighting should also be aimed at discouraging violence, vandalism and crime. Indeed, crime statistics indicate that there exists a relation between road lighting and crime reduction. Good road lighting can also contribute to the feeling of security of residents. This is important in preventing social isolation, especially of the elderly and young women. Finally, well-designed road lighting can contribute to the attractiveness of an area.

The safety and comfort of a road user deteriorate considerably with the onset of darkness, particularly on those roads not provided with a well-designed and maintained lighting installation. Driving involves a continuous decision-making process based on information that reaches our senses. More than 80 % of this input is visual information. Good lighting is essential in keeping our visual performance at a high enough level during the hours of darkness. By visual performance is meant the ability of a motorist to continuously select and process, more or less subconsciously, that part of the visual information presented to him that is necessary for the safe control of his vehicle. For a high level of visual performance to be maintained, especially when driving for a long time, the road user must also feel comfortable in the visual environment. This also helps to keep the level of fatigue low. Road lighting during the hours of darkness can enhance visual comfort. Many night-time accidents involve drivers that were sleepy or even asleep prior to the accident. Lighting may also contribute in keeping drivers alert because of its neurological influence.

The basic purpose of lighting for motorised traffic is thus to enhance the motorist's:

- visual performance
- visual comfort
- alertness

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Studies in many countries and by many different institutions have shown that road lighting can help to reduce the number of night-time accidents by more than 30 % (CIE 1993; Elvik 1995; Elvik et al. 2009; Wanvik 2009). At some 60 %, the reduction of fatal accidents and of accidents involving serious injury is even greater. An analysis of the accident database containing all fatal accidents in the USA on both urban and rural roads, showed that of the various types of fatal accident, the type involving pedestrians increases most under conditions of low lighting level (Sullivan and Flannagan 2007). Thus, those traffic roads with many pedestrians seem to benefit most from good road lighting.

Recently, a direct link has been established between visual performance obtained from different road lighting installations at intersections in Minnesota (USA) and the reduction in traffic accidents at night (Rea 2012; Bullough and Rea 2011) . Where the so-called relative visual performance (RVP— see Sect. 3.3.3) increases from less than 0.7 to between 0.8 and 0.9, the percentage of traffic accidents is reduced by approximately 15 %. A long time ago, in the UK, detailed lighting measurements of 100 different urban road sections (speed limit 50 km/h), each with a minimum length of 1 km, were linked with the night/daytime accident ratios, which were recorded over a 3 year period on the same road sections (Hargroves and Scott 1979). There where the average lighting level on the road surface (one of the parameters that positively influence visual performance) was higher, the night/daytime accident ratio was lower. Roads with an average luminance level in the category 1.2–2 cd/m^2 showed 20–30 % lower accident ratios than roads in the category 0.3–1.2 cd/m^2. Gibbons and Lutkevitch (2014) collected the accident rates from seven US States, over a 5 year period. With a mobile laboratory, They made in-situ illuminance measurements on stretches of road where accidents occurred. The accident rates will subsequently be correlated with the lighting level. Preliminary results show a significant decrease in the night/daytime accident ratio with increasing road-lighting level. Visual performance does, indeed, directly affect traffic safety.

Sometimes it is suggested that the presence of road lighting encourages motorists to drive faster. Even if this were to be the case, it does not change the fact that road lighting reduces accidents. It would mean that the above-mentioned accident-reduction figures would have been even greater had there been no such increase in speed. Research into a possible speed-increasing effect of road lighting however shows that the effect is limited to some 1–3 km/h (Folles et al. 1999; Assum et al. 1999; Hogema et al. 2005) or that it is non-existent (Remande 2009) .

Road lighting can increase the capacity of a motorway during the hours of darkness. This could be of practical benefit in those countries where, during the winter, the traffic peaks after sunset or before sunrise. Van Goeverden et al. (1998) showed that the capacity increase, expressed in “passenger car equivalents/hour”, on a two-lane motorway amounts to 2.5 %, and on a three lane motorway to 1.7 %.

In built-up and residential areas the lighting should serve not only the visual performance of motorists but also that of slow-moving traffic participants, such as pedestrians, cyclists and moped riders. The lighting should enable them to orientate themselves in the environment and to follow their path without the risk of stumbling, colliding with or falling over potentially dangerous obstacles or hazards.

Especially in residential areas (but also in industrial areas), road lighting also serves to discourage violence, vandalism and crime in general. Many studies are carried out into the relation between improved road lighting and crime prevention, some of them with conflicting results and some of them of poor research quality. On the basis of extensive literature study, Welsh and Farrington (2008) made a meta-analysis[1], including only those studies that fulfilled minimum quality of research requirements. From this meta-analysis, based on 13 USA and UK studies, they concluded that improved road lighting (the quality of which, unfortunately, is not always clearly quantified) has a significant effect on crime reduction. Crime (property and violent) decreased by 21 % in the areas with improved lighting compared to the control areas without improved lighting.

Yet another aspect to which good road lighting should contribute, is the feeling of security of residents. Perceived insecurity after dark in the urban space limits mobility, especially that of young women and the elderly (Banister and Bowling 2004; Blöbaum and Henecke 2005; Johansson et al. 2011) . It restricts their participation in social life and can lead to social isolation. Fotios et al. (2014) introduced in this context the term "reassurance" to describe the confidence a pedestrian might gain from road lighting to walk along a road. A feeling of insecurity especially arises when an easy escape possibility is not available, or would seem not to be available. It is therefore essential that the road lighting is harmonised with a proper design of the outdoor environment, so as to make escape possibilities clearly visible during the hours of darkness. Ease of recognition of faces during encounters between people in the street, may further increase the sense of security. If the subjective feeling of security is good, people will be encouraged to go out, which in turn, improves the actual security of the area because a street with more people out on the street is more secure than a street devoid of people.

Finally, road lighting can increase the attractiveness of a whole city or a neighbourhood, both for local residents and visitors alike. This is especially so if it is integrated with specific urban decorative lighting of buildings and monuments.

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[1] Meta-analysis is a statistical analysis of several separate but similar studies in order to test their combined data for a statistically significant statement. Some of these studies may individually be too small for making a significant statement.

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Chapter 2
Basic Lighting Quantities

Abstract The first thing to determine is which are the lighting parameters that positively influence the visual performance and comfort of the users of road lighting. For this it is necessary to define those basic lighting quantities that play a dominant role in the seeing process of motorists, pedestrians and residents, namely: illuminance or luminance. For motorized traffic it is the luminance of the road surface that forms the background to possible objects on the road. For the normal directions of view of motorists, the reflection properties of road surfaces, needed for the determination of road-surface luminance, can be photometrically characterized. Therefore, road surface luminance can and is indeed used as the basic lighting quantity for road lighting for motorized traffic. Since the directions of view of slow-moving traffic such as pedestrians and cyclists are more varied and the reflection properties of surfaces of interest are widely different, we have to fall back on illuminance as the basic lighting parameter for road lighting specifically meant for non-motorized road users. The basic measure here for the lighting of the road and pavement is the horizontal illuminance; for the lighting of facades it is the vertical illuminance and for the lighting of faces of persons in the street it is the semicylindrical illuminance.

2.1 Road-Surface Luminance for Motorized Traffic

A surface is made visible by virtue of light being reflected from it and entering the eye of the observer: the greater the amount of light entering the eye, the stronger will be the visual sensation experienced. Thus, the illuminance on a road surface, which refers only to the amount of light reaching that surface, gives no indication of how strong the visual sensation will be; or in other words, how bright the surface will appear. The brightness of the road surface will depend on the amount of light reflected from it in the direction of the observer (Fig. 2.1).

The photometric measure for this is the luminance (L) of the surface. That it is the luminance and not the illuminance that determines the brightness is illustrated by way of the four photographs of one and the same road-lighting installation shown in Fig. 2.2.

The illuminance pattern on the road is the same in each photograph because the road-lighting luminaires and their configuration are the same—it is the changes in the reflection properties of the road surface which results in changes in the luminance

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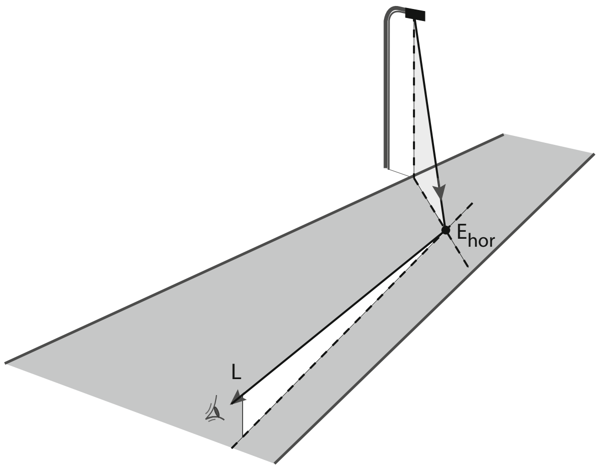

Fig. 2.1 Light incident towards the road results in the horizontal illuminance, E_{hor} on the road, while the light reflected from the road surface results in the road-surface luminance, L

pattern and, in turn, in differences in brightness. Since brightness is finally determined not by illuminance but by luminance, the visual performance and visual comfort of a road user are directly influenced by the complex pattern of luminances existing in his view of the road ahead. The refection properties of cars, bicycles, pedestrians, obstacles and other objects in the field of view vary widely. Dry road surfaces, on the other hand, have relatively similar reflection properties for the normal viewing directions of a motorist towards the road area some 50–150 m in front of him. The road-surface luminance, as achieved from a particular road-lighting installation, can therefore be accurately predicted. The road surface often forms the background to objects on or close to the road. This is why the road-surface luminance concept is usually better suited than the (horizontal) illuminance concept for use in defining the visual performance and comfort of the motorized road user.

2.2 Illuminance for Pedestrians, Cyclists and Residents

The viewing directions of pedestrians and cyclists are far more varied than those of a motorist. The surface of interest to the former is not only the surface of the road but also that of the pavement (sidewalk in America), the facades, and the faces of other people in the street. For these two reasons it is not possible to work with standard reflection properties for this category of road users. For road lighting specifically meant for non-motorized road users we therefore fall back on the illuminance as the basic lighting parameter.

Fig. 2.2 The influence of road-surface reflectance on perceived brightness, with illuminances constant: **a** smooth dry surface; **b** smooth wet surface; **c** rough dry surface; **d** rough wet surface. (Van Bommel and De Boer 1980)

2.2.1 Horizontal and Hemi-spherical Illuminance

It is important for pedestrians and cyclists that the lighting reveals potentially dangerous obstacles lying in their path and any irregularities in this. The horizontal illuminance is therefore usually used as the basic lighting parameter (Fig. 2.3). Since most objects are not flat but three dimensional, some road lighting standards specify the strength of the lighting at ground level in terms of the hemispherical illuminance rather than the horizontal illuminance (see again Fig. 2.3). Appendix A gives the calculation formulas for horizontal and hemi-spherical illuminance.

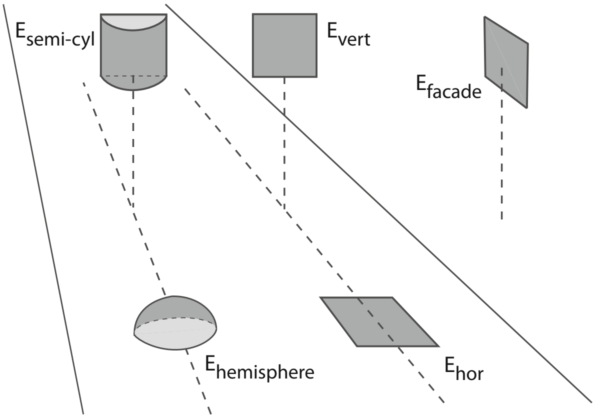

Fig. 2.3 The terms horizontal illuminance (E_{hor}), hemispherical illuminance ($E_{hemisphere}$), vertical illuminance (E_{vert}), façade illuminance (E_{facade}) and semi-cylindrical illuminance ($E_{semi\text{-}cyl}$) refer to the illuminances on an (infinitely small) body of the shape illustrated

2.2.2 Vertical and Semi-cylindrical Illuminance

For security reasons, it is important to be able to identify one another on meeting in the street. It is for this reason that the vertical illuminance at face height is sometimes used as the basic lighting parameter. It has been shown, however, that the semi-cylindrical illuminance at face height is an even better basic parameter for this purpose (see again Fig. 2.3). This is, as will be discussed in more detail in Chap. 5, because the human face is not flat, and light incident on the sides of the face contributes to its visibility. It is the vertical illuminances on the facades bordering the street that actually determine how well these facades can be seen. Appendix A gives the calculation formulas for vertical and semi-cylindrical illuminance.

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Chapter 3
Visual Performance for Motorists

Abstract A motorist's visual performance can be assessed using a number of different performance criteria. The visibility of static objects (obstacles) and dynamic objects (other road users, including pedestrians) and the visibility of changes in the visual scene and the detection of relative movement are examples of important criteria. Detection just on the threshold of visibility is often not enough for safe driving: good supra-threshold visibility increases the chance of a motorist reacting in time. Another aspect, important for decreasing reaction time, is peripheral vision: noticing something out of the corner of the eye, "off" the line of sight, that needs attention. As will be explained in this chapter, peripheral vision is different in the mesopic vision range as compared to the photopic vision range.

In order to be able to draw conclusions as to what lighting quality is needed under different situations, the individual relationships between photometric lighting parameters and the different performance criteria, such as revealing power, total revealing power, visibility level, small target visibility and relative visual performance, have to be studied. Fortunately, there are many research results on the relationships between the most important performance criteria and the various lighting parameters. These will be dealt with here. The impact of adverse weather conditions and of the effect of vehicle lighting on the visual quality obtained from fixed road lighting, are other items dealt with here. Finally, the neurological influence that lighting could possibly have in helping to keep the motorist alert will be discussed.

3.1 Object Contrast

3.1.1 Contrast and Contrast Threshold

At the relatively low lighting levels common in road lighting, colour vision is poor and visual detection is made possible more by the difference in luminance between an object and its background (viz. the luminance contrast), than by any difference in colour. An object has a luminance contrast (C) defined by:

$$C = \frac{L_o - L_b}{L_b}$$

in which L_o is the luminance of the object itself and L_b the luminance of the background against which it is seen. If an object is darker than its background it will be

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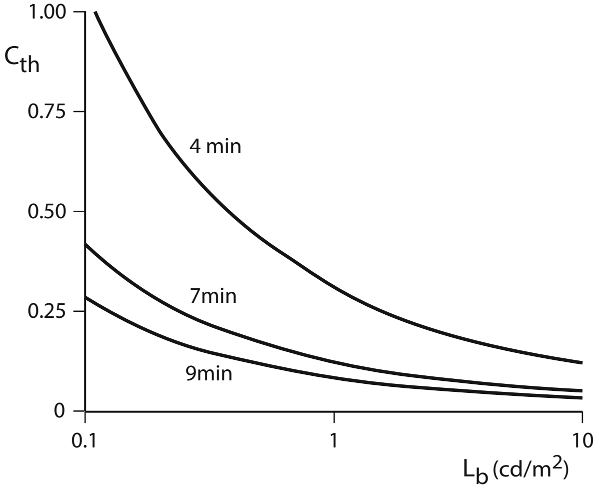


Fig. 3.1 Decrease in threshold contrast, C_{th}, with increase in background luminance, L_b for objects subtending an angle of 4, 7 and 9 min of arc. Positive contrast, observation time 0.2 s, observer age 30 years. (Adrian 1989)

seen in silhouette and its contrast is negative; if, on the other hand, it is brighter than its background its luminance contrast is said to be positive. The luminance contrast needed for an object to become visible depends, amongst other things, on the luminances surrounding the object, as it is these that determine the adaptation condition of the observer's eye. This is illustrated in Fig. 3.1, which gives the relation between the just-perceivable contrast—termed the threshold contrast, C_{th}—and the background luminance for three different sizes of objects (seen under a visual angle of 4, 7 and 9 min, respectively). The figure shows that the threshold contrast C_{th} decreases as the background luminance and the size of the visual angle increase. Increasing the background luminance, viz. the luminance of the road surface, thus increases the chances of the object being detected, because the threshold contrast for objects is decreased. Another way of expressing this positive effect of background luminance on contrast seeing is by saying that a larger adaptation luminance increases the contrast sensitivity of the eye.

When the contrast threshold for a situation is known, it is possible to calculate whether or not an object with given size and reflectance factor is visible. For this purpose Adrian (1989) published a comprehensive set of formulae with which the contrast threshold can be calculated depending on, amongst other things, the background luminance, the degree of glare, the object size, the observation time and the age of the observer. This set of formulae, sometimes called "the Adrian model", is given in Appendix B. The effect of age can also be calculated from these formulae. The actual effect on visual performance of these age factors will be demonstrated in a further section of this chapter, while Chap. 7 will explain the reasons for the loss of vision with age.

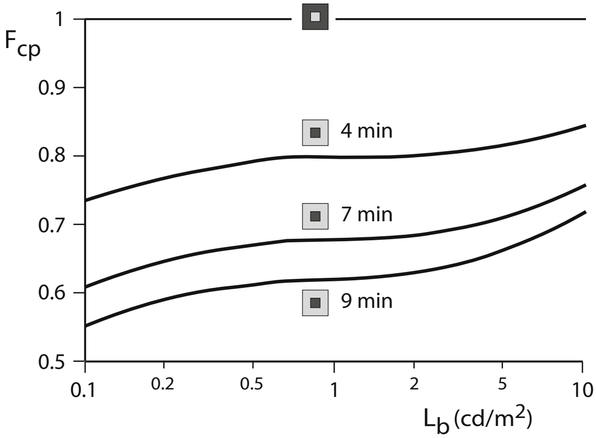


Fig. 3.2 Contrast threshold polarity factor, F_{cp}, depending on background luminance, L_b, for objects seen under different angles. (Based on Adrian 1989)

3.1.1.1 Field Factor

Contrast thresholds are, and were, normally determined under laboratory conditions in which the test persons were instructed to signal the presence of an object that appeared at a defined position in the laboratory model. Unlike with these observers, motorists are not alerted to the appearance of an object—it just "appears" unexpectedly at an unforeseen position. Moreover, a motorist has to carry out a multitude of different driving tasks, so an object that is just visible under laboratory conditions is therefore not visible under actual driving conditions (Mayeur et al. 2008). This means that a so-called field factor, which increases the laboratory contrast threshold, has to be applied to arrive at a contrast threshold value valid for realistic driving conditions. The value of the field factor is dependent on the actual driving task and the alertness and the motivation of the driver (Schreuder 1998). Field-factor values of 3 to more than 5 have been reported (Narisada and Karasawa 2001; CIE 2013; Adrian 1989; Schreuder 1998). In this book, where the field factor is relevant, we assign it the conservative value of 3.

3.1.1.2 Contrast Polarity

Most of the contrast threshold measurements concerned laboratory objects with positive contrast only, viz. objects brighter than their background (Blackwell 1946; CIE 1981; Adrian 1989). In road lighting, many objects are seen in negative contrast viz. they are darker than their background. Comparing same-contrast values with positive and negative contrasts, the latter are more easily visible and thus have smaller contrast thresholds (Adrian 1989; Okada 2003; Ito et al. 2007). Adrian determined the contrast threshold polarity factor (F_{cp}), which indicates the factor difference between positive and negative contrast threshold. Figure 3.2 shows that the value of the polarity factor is dependent on both the background luminance and the visual angle

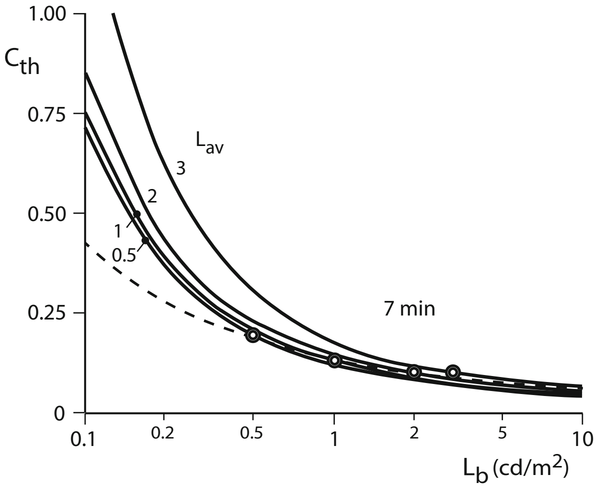


Fig. 3.3 Contrast threshold, C_{th} as a function of the momentary background luminance, L_b, for different values of the average road surface luminance, L_{av}, presentation time 0.125 s. (Based on Narisada et al. 2003). Broken line: Adrian's threshold for a uniform luminance

under which the object is seen. Appendix B gives the formulae needed to calculate the contrast threshold polarity factor for each situation.

3.1.1.3 Adaptation Luminance Under Non-uniform Conditions

Contrast-threshold curves such as those of Fig. 3.1 are normally obtained under conditions where an object is perceived against a large area having uniform luminance. Here the adaptation luminance is equal to the background luminance. In road-lighting practice the road surface luminance is not uniform. A motorist scans, partly unconsciously and partly consciously, different areas of the road in front of him. In the practical situation of a non-uniform road-surface luminance, his eyes cannot completely adapt instantaneously to the various points he is looking at. The average road surface luminance is often used as the adaptation luminance. Indeed, Brémond et al. (2011) suggest, on the basis of visibility tests on a test road, that averaging the luminances of many different positions on the road give the better results. Narisada et al. (1997, 2003) used some of their earlier laboratory experiments (Narisada and Yoshimura 1977; Narisada 2009) to show the combined influence of the actual background luminance and the average road surface luminance on the visibility threshold. Based on Narisada's results, Fig. 3.3 gives the contrast sensitivity curve for a 7-min object in dependence of the background luminance for different average road-surface luminances. The open circles indicate situations where the average road-surface luminance equals the background luminance, viz. a situation of uniform luminance. The broken line is the contrast threshold for uniform luminance, also for a 7-min object, as determined by Adrian and given earlier in Fig. 3.1. By comparing the open circles with the broken-line curve, it is evident that Narisada's results are very much in line with those of Adrian. For a background range from slightly less than 0.5 cd/m^2

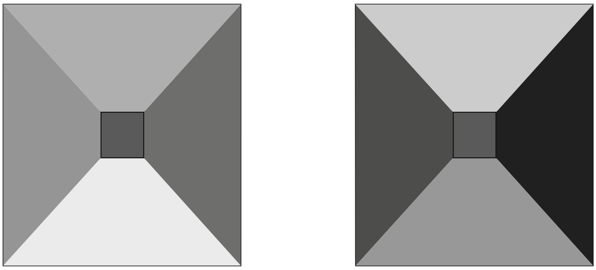


Fig. 3.4 Schematic illustration of different background luminances around an object on a road surface with non-uniform luminance. On the right: the average luminance at the sides of the target is equal to the object luminance itself

to 10 cd/m^2, the influence of the non-uniformity of the road-surface luminance is small. It can be neglected for average road surface luminances smaller than or equal to 2 cd/m^2.

3.1.1.4 Background Luminance Under Non-uniform Conditions

That in road-lighting practice the road surface luminance is not uniform, leads to the question "what constitutes the background luminance of the object?". Different methods for setting the background luminance of a target on a road surface with a non-uniform luminance distribution may be employed: viz. the background luminance at the bottom of the object, at the top of the object, or the background luminance on that side of the object that leads to the highest contrast (Fig. 3.4). This is called the maximum contrast method.

Sometimes the average background luminance of the bottom and top or of the four sides of the object is used. However, from a visibility point of view, such an averaging procedure is not realistic: it is quite possible that on all sides of the object the background luminance is quite different from the object luminance itself, while the average value is the same as the object luminance. This suggests, incorrectly, that the object is invisible (Fig. 3.4 right). Some investigations show that for practical road lighting situations the differences between the various methods are negligible for visibility evaluations (Lecocq 1991). A recent study suggests, on the basis of comparing detection possibilities of objects on a test road with contrast calculations, that the maximum contrast method gives the better results (Brémond et al. 2011).

3.1.1.5 Object Shape

In most laboratory investigations concerning threshold contrast, and also in road lighting visibility tests, flat objects have been used. In practice, however, any obstacles found on a road are seldom flat. Flat objects, however, are more difficult to see than are three dimensional ones (Lecocq 1991; Dijon and Justin 1999). Flat objects can therefore be considered as the more critical obstacles. In contrast to a flat object the luminance over a three dimensional object is usually not uniform under road lighting conditions (Fig. 3.5, left). One part of the object will receive more light

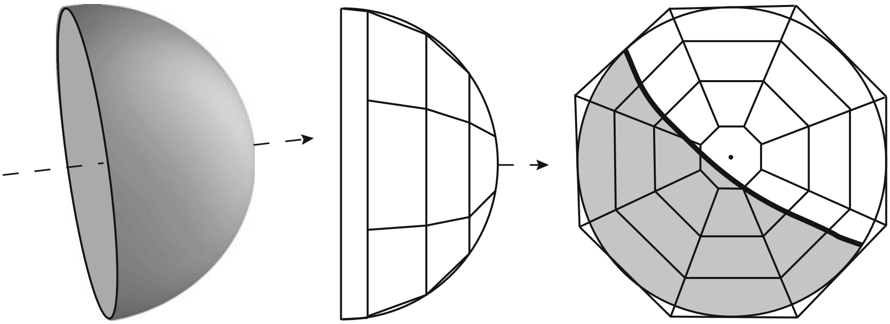


Fig. 3.5 Hemispherical object and Lecocq's multi-faceted hemisphere, with on the right an example of the calculated sharp border between the brighter and darker parts

from the luminaires than the other part, the difference being dependent of the actual luminaire positions relative to the object. If the border between the brighter and darker part of the object is sharp and the difference in luminance is great enough, the object may be detected just because of this luminance difference (intrinsic contrast), independent of the background luminance ("self-visibility" of the object). Lecocq (1991, 1999) introduced a three-dimensional hemispherical object with its curved top turned towards the observer. Calculation of the luminance distribution over the surface of the hemisphere is very difficult. Therefore Lecocq divides the curved body of the hemisphere into 25 flat faces (Fig. 3.5). The calculated luminance of each face is the basis for defining the location of the border between the brighter and darker part and of their average luminances. Self-visibility is checked on the basis of "normal" flat-object threshold curves. If self-visibility does not occur, the parts are treated as two separate flat objects and their visibility is checked on the basis of flat-object threshold curves.

3.1.2 Silhouette Principle of Road Lighting

Fixed road lighting aims at making objects visible as dark silhouettes against the bright road surface. The higher the luminance of the road surface, the greater the number of objects that will be seen in silhouette. We therefore speak of the luminance concept of road lighting. The silhouette principle of road lighting for a limited set of objects, with reflectance factors typical for pedestrian clothing, is illustrated in Fig. 3.6 for three different situations with increasing luminance of the road surface that forms the background to the objects. Only in the situation with the highest background luminance will all objects be visible, most of them in silhouette, viz. in negative contrast.

The silhouette principle of road lighting was demonstrated as long ago as the beginning of the last century by the British researcher Waldram—one of the very

Fig. 3.6 A set of objects with reflectance factors typical of those found in a pedestrian's clothing (*top*), seen against three different road-surface backgrounds, in order of increasing luminance. With good road lighting most of the objects are seen in negative contrast (silhouette vision)

Fig. 3.7 Photograph taken by Waldram at the beginning of the last century to illustrate the silhouette effect of road lighting. A white and a black cat are seen as dark silhouettes against the bright road surface of high luminance. (Waldram 1938)

early researchers investigating the luminance concept of road lighting. Figure 3.7 shows one of Waldram's original photographs. The white and black cats are seen as grey and black silhouettes against the bright road surface.

Of course, the road surface is barely visible as a background whilst stuck in a traffic jam. But because of the slow traffic speeds and short distances over which visibility is required, poor visibility is not really then a problem. Once the traffic moves on and speeds increase and visibility over greater distances is again required, the road surface again forms the background to most objects on the road (Fig. 3.7).

To ensure sufficiently-high contrasts and thus a sufficient visual performance at all locations on the road, the difference between the average and the minimum road-surface luminance should not be too great. This can be ensured by having a high enough ratio of minimum-to-average road surface luminance. This luminance ratio of L_{min} to L_{av} is called the overall uniformity, U_o. The smaller this ratio (i.e. the poorer

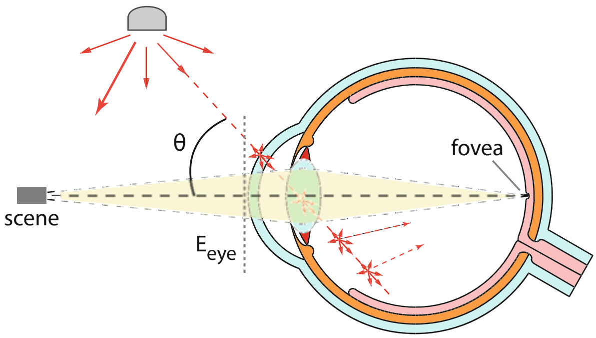


Fig. 3.8 Light scatter in the eye due to glare

the uniformity), the worse will be the visual performance for objects seen against the low-luminance part of the road surface, which is where the contrast value is low and the contrast threshold is high. As an extra negative effect, large luminance differences in the field of view also result in a lowering of the contrast sensitivity of the eye, and give rise to so-called transient adaptation problems. This effect can be explained by considering the brighter parts as forming glare sources for an observer looking towards the darker parts of the road surface (Adrian and Eberbach 1968/1969).

3.1.3 Contrast and Glare

3.1.3.1 Disability Glare

Glare can take either of two forms: disability glare and discomfort glare. Disability glare is the form that is responsible for a negative influence of glare on visual performance. The mechanism by which the loss of visual performance due to the presence of glare takes place can best be understood by considering the light scatter taking place in the eye of the observer, Fig. 3.8).

A sharp image of the scene in the direct field of view is focused on the retina of the eye, the resulting visual sensation being determined by the luminance of the scene. At the same time, however, light coming from a glare source that is too close to the direct line of sight is partly scattered in the eye lens and eyeball. Part of the scattered light is re-directed towards the fovea, where it interacts negatively with the image of the road ahead: it reduces its contrast. It acts as a bright veil drawn across the field of vision. This veil can be considered as having a luminance—the equivalent veiling luminance (L_{veil})—proportional to the quantity of light scattered in the direction of the retina. The overall effect on visual performance is then determined by two components: scene luminance and equivalent veiling luminance. Holladay (1927) found, on the basis of visibility tests, the latter component to be dependent upon the illuminance (E_{eye}) on the eye and the angle (θ) between the viewing direction and the direction of light incidence from the glare source and on the age (A) of the observer.

For the range of luminances normally occurring in road lighting and for θ within the range 1.5–60°, veiling luminance can be given by the empirical formula:

$$L_{veil} = 9.86 * \frac{E_{eye}}{\theta^2}\left\{1 + \left(\frac{A}{66.4}\right)^4\right\}$$

This formula is recommended by CIE (1976, 2000) for use in road lighting. The upper limit of θ will be met so long as the observer's direction of view is towards the road surface, and provided screening of glaring light by the car roof is taken into account. The screening angle is standardised by the CIE (1976) at 20°. For mounting heights lower than some 6 m the angle θ may become smaller than the lower limit of 1.5°. In that case the contribution to the veiling luminance corresponding to angles between 0.1 and 1.5° can, according to CIE (2002), be calculated from:

$$L_{veil} = E_{eye} * \left[\frac{10}{\theta^3} + \left(\frac{5}{\theta^2}\right) * \left\{1 + \left(\frac{A}{62.5}\right)^4\right\}\right]$$

Using imaging techniques employing a pupilometer apparatus, it is now possible to directly measure the scatter in the eye. From that scatter pattern, the actual veiling luminance of each individual test person can be calculated for different glare situations. This gives a more accurate result than that obtained from the empirical formulas given above (Davoudian et al. 2013). This method can help future disability-glare research.

Crawford (1936) showed that for multiple glare sources the total equivalent veiling luminance can be described by adding the equivalent veiling luminances of the individual sources, thus

$$L_{veil} = \sum_{1}^{n} L_{veil,\,i}$$

The overall effect of glare on visual performance can now be determined by first adding the total equivalent veiling luminance to each of the two luminances forming the contrast of the task object (L_o and L_b). The result of this is twofold.

Firstly, the effective contrast of the target object decreases from C_o to C_{eff}:

$$C_o = \frac{L_o - L_b}{L_o} \; to \; C_{eff} = \frac{(L_o + L_{veil}) - (L_b + L_{veil})}{(L_b + L_{veil})} = C_o \frac{L_b}{L_b + L_{veil}}$$

See Fig. 3.9, where the contrast threshold curve of Fig. 3.1 shown earlier is used to demonstrate this effect: the decrease in effective contrast corresponds to the decrease from point a to point b.

Secondly, the contrast threshold of the task object decreases due to the increase in effective background luminance, from:

$$L_b \; to \; L_b + L_{veil}$$

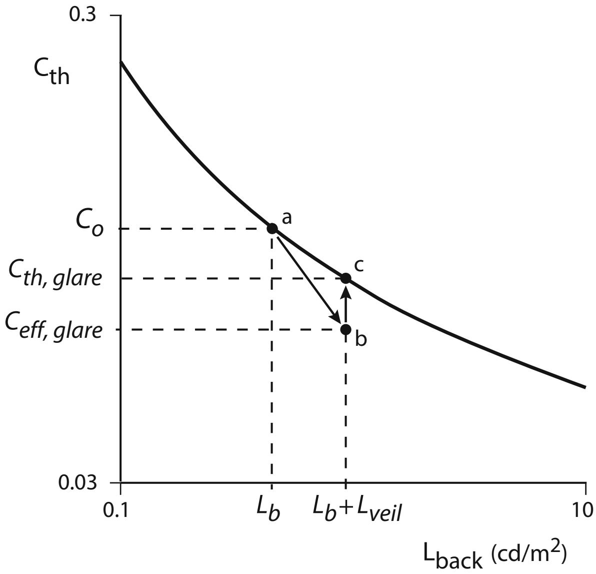


Fig. 3.9 Contrast threshold curve and influence of the veiling luminance on both the threshold value and the effective contrast with and without glare

In the figure this corresponds to the decrease from point a to point c.

The decrease in loss of effective contrast is larger than the decrease in threshold contrast. In other words, an object that can just be seen when there is no glare (threshold contrast) cannot be seen when glare is present unless the actual contrast is increased. This "masking" effect forms the basis of the measure for loss of visual performance due to glare: the so-called threshold increment, TI. This is defined as the amount of extra contrast required to again just make the object visible under glare conditions, relative to the effective contrast. This corresponds in Fig. 3.9 to:

$$TI = \frac{c - b}{b}$$

CIE (1976) prescribes that the threshold increment should be determined on the basis of the perception of an object that subtends an angle of 8 min of arc at the eye of the observer.

In practice, of course, contrasts will not be increased, and the value of the threshold increment then indicates the loss of visual performance due to glare. For each different background luminance, that is to say for each part of the road surface viewed by an observer, the effect of glare on visual performance will be different, and a different value for the threshold increment will be obtained. CIE (1976) recommends employing as an overall measure of disability glare the relative threshold increment (TI) based on the average road-surface luminance value as background luminance. CIE states that for the luminance range $0.05\ cd/m^2 < L_{av} < 5\ cd/m^2$ the threshold increment is approximated with the formula:

$$TI = 65 * \frac{L_{veil}}{L_{av}^{0,8}}$$

where:

TI is in percent;

L_{veil} for an observer looking straight ahead in a direction parallel to the road axis and 1° down from the horizontal;

3.1.3.2 Spectrum and Disability Glare

Research into a possible wavelength effect on disability glare has shown that there is no or only a very marginal effect (Jainski 1962; Wooten and Geri 1987; Davoudian et al. 2013; Niedling et al. 2013). As will be discussed in Chap. 4, the same cannot be said for discomfort glare.

3.1.3.3 LEDs and Disability Glare

LED road lighting luminaires consist of an array of numerous small bright LEDs (see Chap. 10). The consequence is that these luminaires have a much more pronounced non-uniform luminance over their light-emitting surface as compared to luminaires using more conventional light sources. As has already been explained, the disability effect of glare is caused by scattering of light within the eye that leads to a bright veil, that in turn masks the field of view. Considering this process, one may not expect a large difference in disability glare effects for LEDs and conventional light sources. However, recent research indicates that the pronounced non-uniformity of the light-emitting surface of LED luminaires has an influence on discomfort glare. Where in the past it was often reasoned that by limiting disability glare discomfort glare would also be restricted to a large enough extent, this may no longer be true in the case of LED luminaires (see Chap. 4).

3.1.4 Contrast and Vertical Illuminance

As we have seen, the principle of silhouette seeing, on which road lighting is based, requires sufficiently high negative contrasts. This in turn means that the vertical illuminance on the side of objects facing oncoming motorists should be restricted.

3.1.4.1 Vertical Illuminance and Glare Restriction

For symmetrical luminaires (relative to the longitudinal axis of the road) good glare restriction automatically limits the vertical illuminance on objects provided by light from the luminaires. Provided the glare restriction specification is good, there is therefore usually no need to also specify the limitation of vertical illuminance provided by the luminaires.

3.1.4.2 Vertical Illuminance and Reflection from the Road Surface

Light from the luminaires not directly aimed at the object but at the area of road surface in front of an object, contributes to the vertical illuminance at the target by the light reflected from that road-surface area. This indirect contribution decreases the value of the negative contrast of that object. The contribution is, of course, larger for flat objects than for three-dimensional ones, where the reflected light from the road surface cannot reach their upper sides. Adrian and Gibbons (1993, 1999) showed that the (negative) impact of the reflected light from actual road lighting installations is, for certain object positions on the road, for flat objects, not negligible. Although the same authors introduced a provisional calculation system for the indirect contribution, a generally-applicable system is not yet available. This means that visibility calculations based on contrast seeing, give a slightly too optimistic result.

3.2 Threshold Visibility

3.2.1 Revealing Power

The number of objects out of a defined set that are just detectable at various points on a road can be calculated from the lighting values obtained from a road-lighting installation. "Just detectable" means that they are at the threshold of visibility. If the set of objects is chosen so as to represent the probability of the occurrence of reflectance factors of pedestrian clothing, the percentage of objects detectable at each point on the road is called "the revealing power " of the lighting installation (Waldram 1938). The probability of occurrence of reflectance factors of pedestrian winter cloth has been measured by Smith (1938) and later by Hansen and Larsen (1979). Hansen and Larsen measured the reflectance factors of cloth of 1024 pedestrians randomly chosen on the street. In Japan, the number of objects larger than 10 cm found on actual express ways, have been measured together with their reflectance. Around 1300 objects were analysed (Hirakawa et al. 2007). Figure 3.10 shows the results for both clothing and objects.

Figure 3.11 (left) shows a rough representation of the reflectance factor occurrence of Hansen and Larsen's clothing. The same figure (right) shows the objects that may be visible under a road-lighting installation of not-too-good quality: many of the darker, but only some of the brighter objects are visible against the bright road surface. This is typical for a poor road-lighting installation: objects in the range of moderate-to-high reflectance factors are invisible.

Revealing power is eminently suitable to provide an insight into how the different aspects of road lighting, such as average road surface luminance (L_{av}), uniformity (expressed as overall uniformity U_o) and glare restriction (expressed as threshold increment TI), influence visibility. In order to provide a fundamental insight into how these basic parameters influence visual performance, revealing power values for

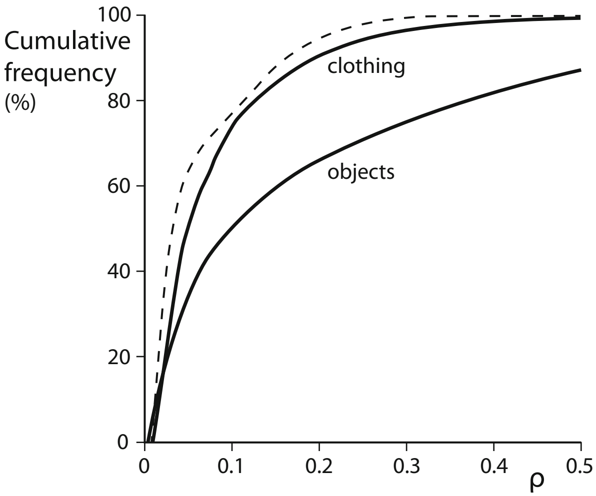


Fig. 3.10 Cumulative percentage of occurrence of reflectance factors of pedestrian's clothing and of objects dropped on express ways. Solid lines: clothing of Hansen and Larsen and objects of Hirakawa et al. Broken line: clothing of Smith

the darkest position on the road (local minimum road-surface luminance) have been calculated for different combinations of L_{av}, U_o and TI. The basis for the calculations are the contrast-threshold curves calculated from Adrian's formulae (Appendix B) for a 30-year-old person and an object seen under an angle of 7 min (observation time 0.2 s). The angle of 7 min corresponds to an object of 20 × 20 cm seen from a distance of 100 m, which in turn corresponds to the stopping distance of a car at a driving speed of some 100 km/h to 120 km/h. A field factor of 3 has been applied (see Sect. 3.1.1.1). A common road lighting installation with a TI value of 10 and 30 % will produce a vertical illuminance value that is numerically equal to about respectively 5 and 7.5 times the value of the average luminance, respectively. The vertical illuminance values following from this relationship have therefore been used in the calculations.

Figure 3.12 shows the results for a 30-year-old person for both the cloth (Hansen and Larson) and the brighter objects (Hirakawa et al.) and for a good overall uniformity of $U_o = 0.4$ and a good glare restriction of TI = 10. With this good uniformity and glare restriction, the revealing power RP is only 50–60% at a lighting level of $L_{av} = 0.5$ cd/m^2. It increases to 70–80 % at a lighting level of 1 cd/m^2 and to 80–90 % at 2 cd/m^2. This shows that at the lower end of the range 0.5 cd/m^2 to 2 cd/m^2 (shaded area in the figure), revealing power is not good enough and that at the higher end of that same range, revealing power scarcely improves further. Good road lighting, for high speed roads, requires lighting levels of between 1 and 2 cd/m^2 for 30-year-old motorists. The fact that in this range, the revealing power of the brighter objects is lower than that of the darker cloth, once again illustrates the silhouette concept of road lighting. In both cases the majority of the objects are seen in silhouette (negative contrast). In the case of the brighter objects more of these shift into the invisible area between negative and positive contrasts, leading to a loss of negative-contrast vision.

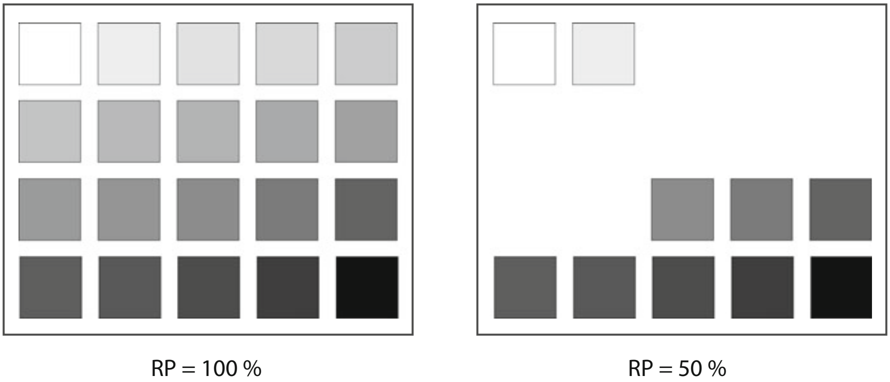


Fig. 3.11 *Left*: objects with a reflectance factor distribution typical for pedestrian clothing. *Right*: those objects that remain visible under relatively poor road-lighting conditions (revealing power of 50 %)

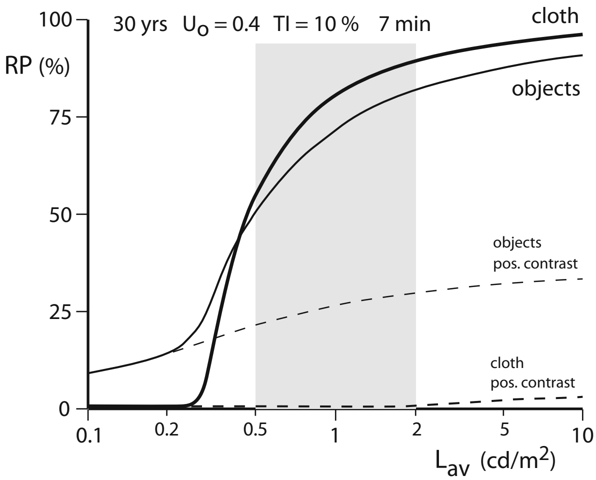


Fig. 3.12 Revealing power (RP) of cloth and objects at the darkest location on the road as a function of the average road-surface luminance (L_{av}) for $U_o = 0.4$ and TI = 10 %. Thin broken lines: contribution of objects seen in positive contrast. Visual angel 7 min, age 30 years

That more objects become visible in positive contrast (see broken lines in Fig. 3.12) is not enough to compensate for this loss.

The influence that uniformity and glare restriction have on visual performance becomes evident from Fig. 3.13 where, for the cloth targets, the revealing power values are given for three different combinations of uniformity and glare restriction:

- $U_o = 0.40$ and TI = 10 % representative for "good" road lighting
- $U_o = 0.25$ and TI = 10 % representative for bad overall uniformity
- $U_o = 0.40$ and TI = 30 % representative for too much glare.

When the uniformity decreases from $U_o = 0.40$ to only 0.25, the revealing power will, at a lighting level of 1 cd/m^2, fall back from 80 % to only a poor 43 %. That

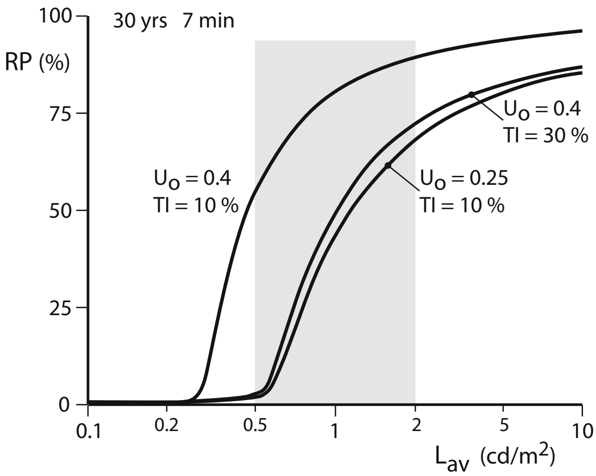


Fig. 3.13 Revealing power (RP) of cloth targets at the darkest location on the road as a function of the average road-surface luminance (L_{av}) for different U_o and TI combinations. Visual angle 7 min, age 30 years

glare too has a negative effect on visual performance is clear when comparing (at the same lighting level of 1 cd/m^2) a TI value of 10 % (good glare restriction) with a value of TI of 30 %: the revealing power (at good uniformity of 0.40) decreases from 80 to 50 %. In both the case of low uniformity and that of poor glare restriction the revealing power is close to zero at a lighting level of 0.5 cd/m^2.

The eye deteriorates with age as will be shown in Chap. 7. In that same chapter the dramatic effect of age on visual performance will be demonstrated with the aid of the results of revealing power calculations for 50- and 65-year-old persons.

3.2.2 Total Revealing Power

As has been mentioned, the revealing-power calculations shown in the previous section are valid for a single point on the road surface: the darkest position on the road. It is also possible to calculate the revealing power at all grid points on the road surface. This is called the "total revealing power". Figure 3.14 shows, as an illustration of this, revealing power results at nine grid points. In practice of course far more grid points are used.

As a characteristic value of the general level of revealing power, Narisada et al. (1997) introduced the "area ratio", defined as the percentage of road area at which the revealing power is higher than 90 %. They considered an area ratio of 70 % as acceptable for road lighting for important roads. In the example of Fig. 3.14 the area ratio is 6/9 = 67 %. The concept of total revealing power gives a clear insight into the effect on visual performance of some road-lighting design parameters, such as type of luminaire arrangement, mounting height, and type of road surface. As an example of this Fig. 3.15 gives the area ratio for an actual road lighting installation, using luminaires with moderate glare control, as a function of the average road surface

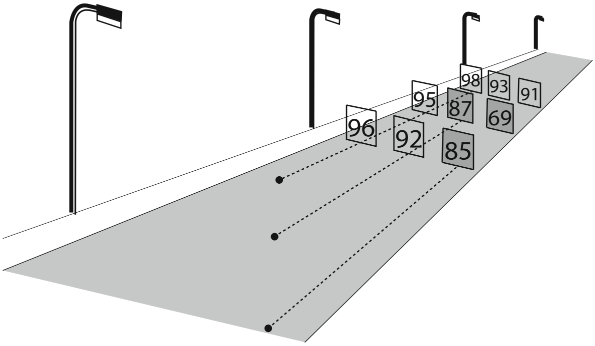


Fig. 3.14 Revealing power values at all grid points between a luminaire span. Black dots indicate the lengthwise observer positions for the different rows of grid points. Values below 90 % are shown in a darker shade

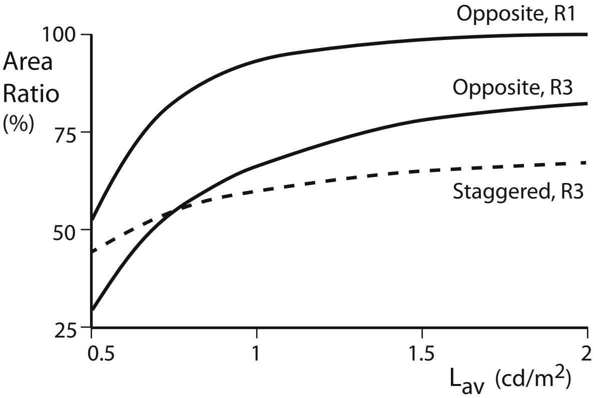


Fig. 3.15 Area ratio as a function of average road surface luminance L_{av}. Visual angle 7 min, field factor 3 and age 28 years. Two-lane road with opposite and staggered arrangements and a light (CIE R1) and darker (CIE R3) road surface. Mounting height 10 m. (Based on Narisada and Karasawa 2001)

luminance. Results are given for luminaire arrangements on both sides of a two lane road in an opposite and staggered arrangement and for two different types of road surface (a diffuse light one, R1, and a darker somewhat more glossy one, R3).

As with the revealing-power curves shown in the previous section, a pronounced increase in visual performance (area ratio) is obtained when the average road surface luminance increases from 0.5 cd/m^2 to 1 cd/m^2. Here too, the curves level off between 1.5 cd/m^2 and 2 cd/m^2. That the staggered arrangement results in lower visual performance is a consequence of the lower uniformity that accompanies such an arrangement. It is important to note that the lighter road surface R1 results in considerably higher visual performance than that provided by the darker surface R3. This is because for the same average road surface luminance level the ratio of vertical illuminance to road surface luminance is smaller with lighter road surfaces, so that silhouette vision is improved. Section 12.6 will elaborate on this effect.

3.3 Supra-Threshold Visibility

The revealing power concept dealt with in the previous section concerns threshold visibility. The visual performance of a driver, however, will only be adequate from the traffic-safety point of view if he is able to detect obstacles in his path quickly and with the minimum of effort; only then will he be able to react in time to the presence of an obstacle in his path. For this it does not suffice for visibility to be on its threshold. Supra-threshold visibility conditions are required. Different ways of measuring supra-threshold visibility have been developed.

3.3.1 Visibility Level

The so-called visibility level, VL, is a measure that indicates how far the visibility of an object of defined size, shape and reflectance, is above the threshold of visibility. It is defined as[1]:

$$VL = \frac{C_{actual}}{C_{th}}$$

where: C_{actual} is the real contrast between the object on the road and its background (the road-surface luminance), and C_{th} is the contrast threshold needed between the object (same size, shape and reflectance as the actual object) and its background for it to be just visible.

If VL equals 1 the object is exactly at the threshold of vision as defined for laboratory conditions. If VL equals 3 it is at the threshold of vision taking a field factor of 3 into account corresponding to realistic driving conditions. All values above 3 are representative for supra-threshold vision conditions under realistic driving conditions.

Just as revealing power values can be calculated for different road-lighting situations, so can visibility level be calculated from the Adrian threshold contrast formulas (Appendix B) as well. It has been shown that there exists a good relationship between the actual detection distance of an object under dynamic conditions and the calculated visibility level of that object (Janoff 1990). Other studies have shown that there is also a good relationship between the calculated visibility level of an object and the subjective rating of visibility of a group of static observers (Janoff 1992; Ménard and Cariou 1994; Dijon and Justin 1999; Bacelar et al. 2000). Figure 3.16 shows such relationship for both a flat and a hemispherical target. The 5-point visibility assessment rating scale ranges from 0 to 4 with the meaning, 0 = target not visible, 1 = target weakly visible, 2 = passable visibility, 3 = satisfactory visibility, 4 = good visibility.

[1] It is the same as $VL = \Delta L_{actual} / \Delta L_{th}$ with ΔL being the luminance difference between object and background.

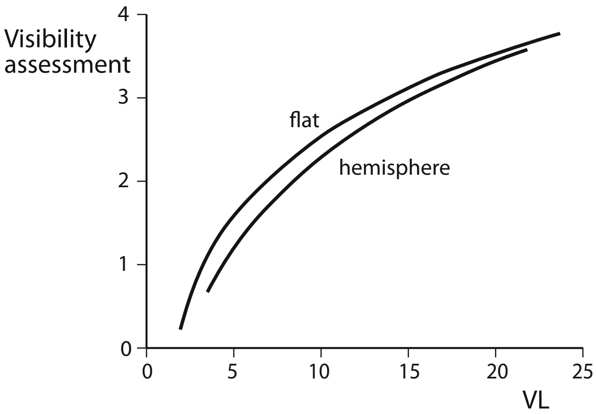


Fig. 3.16 Calculated visibility level, VL, for flat and multi-facetted hemispherical objects as a function of the visibility assessment for flat and hemispherical objects positioned 83 m from static observers on a test road. Object 20 × 20 cm with 0.20 reflectance factor. (Bacelar et al. 2000)

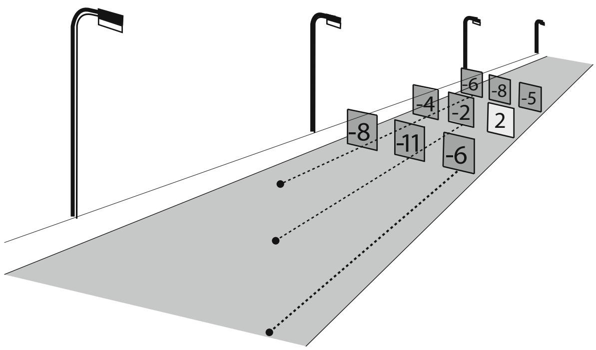


Fig. 3.17 Visibility level values, VL, for objects with the same reflectance factor. Negative values: objects seen in negative contrast (silhouette). *Black* dots indicate the lengthwise observer positions for the different rows of grid points

From the figure we learn that for the assessment "passable visibility" a visibility level of 7 to 8 is required.

For a defined object size and shape and for a fixed reflectance factor, visibility level values can be calculated for the various positions of a defined road lighting installation (Fig. 3.17).

Contrary to the concept discussed earlier of total revealing power, the visibility level value at each point is only valid for one single reflectance factor. If a different reflectance factor is chosen, the distribution of the visibility-level value over the various positions may be completely different. This makes it difficult to make statements about the quality of a road lighting installation on the basis of one set of visibility levels only. Visibility level is therefore less suitable for providing an insight into how the different aspects of road lighting influence visibility. Different proposals have been made for defining one critical reflectance value to overcome this problem (CIE 1995; ANSI/IESNA 2000). This has led to a concept named "small-target visibility".

3.3.2 Small-Target Visibility

Small-target visibility, or STV, is the visibility level, VL, calculated according to strictly-defined conditions. The conditions are defined by (IES, ANSI/IESNA 2000, 2014) as follows:

- flat target with diffuse reflectance factor of 0.50
- target size: 18 cm $\times$ 18 cm seen from a distance of 83 m (visual angle 7.45 min),
- observer-to-target sight line: parallel to the road-axis line,
- observer age: 60 years,
- contrast threshold according to Adrian's model (Appendix B) for an observation time of 0.2 s,
- observation height: 1.45 m (the target at 83 m is seen with a downward viewing angle of 1°),
- background luminance: average of the point luminance at the bottom of the object and at the top of the object (as seen from the observation position),
- regular calculation grid starting at 83 m from the observer, between a span of luminaires.

In the original proposal of IES the value of the reflectance factor was 0.20. However, it was realized that under most road lighting conditions such a value certainly does not represent the most critical reflectance factor, because that value will often lead to good silhouette vision. Wrong conclusions regarding the quality of a road lighting installation could be the result. In a later update by IES, some conditions were changed to more critical ones. The reflectance factor was changed from 0.20 to 0.50 and the age of the observer from 23 to 60 years (ANSI/IESNA 2000). These changes improved the concept of small target visibility. Nevertheless, the fact that the system is based on a single reflectance factor only, may still sometimes lead to misleading conclusions. It should also be noted that a reflectance value of 0.5 seldom occurs in practice.

The idea behind the development of the concept of small-target visibility was not to provide an insight into how the different aspects of road lighting influence visibility of objects. Small target visibility has been developed to become a design metric for good-quality road lighting installations. For this, it is necessary to define from the visibility level values at the different calculation grid points, one single value, representative for quality of the road lighting installation. IES defined for this purpose a weighted average visibility index from all the grid VL values, which then is called small-target visibility, or STV. The method of weighting is such that large VL values are not counted as heavily as small ones, since such high VL values at some positions do not compensate for the low values at other locations. The weighting formula for STV is given in Appendix B. For the example illustrated in Fig. 3.17 the arithmetic average is 5.8 and the weighted average is 5.0. Since this weighted average does not always guarantee sufficient visibility everywhere on the road, others propose the use of the minimum visibility level (absolute value) of all grid points

(2.0 for the example of Fig. 3.17) as the metric for the quality of the road-lighting installation (Lecocq 1991; AFE 2002).

In 2006, the roadway lighting committee of IESNA decided to withdraw STV as a design metric, but to retain it as a comparison or fine-tuning tool for road-lighting installations that have been designed on the basis of luminance criteria but that can benefit from further optimization. The concept of total revealing power, discussed in a previous section (Sect. 3.2.2), offers an alternative for this. With it, unlike as with small target visibility, different reflectance factors are taken into consideration.

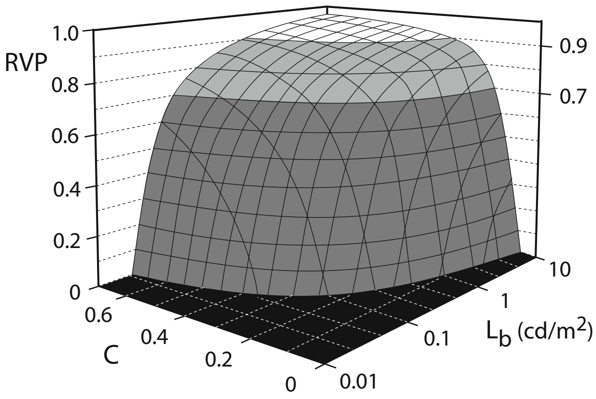
3.3.3 Relative Visual Performance

As has been shown, the starting point for supra-visibility measures is the threshold contrast of visibility. Measurements of threshold contrast, even when determined under laboratory conditions, show a large spread, even when determined repeatedly with the same observer. Apparently, the border between vision and non-vision is not such a sharp one. Rea and Ouellette (1988) therefore developed a supra-threshold measure, called relative visual performance, or RVP, based on reaction times for detecting objects. Both the contrast thresholds and the level of supra-visibility are derived from these reaction-time experiments. The authors claim that their contrast thresholds are therefore more representative than those derived using conventional methods.

The RVP model was originally developed for indoor lighting applications from experiments measuring speed and accuracy of reading-tasks (Smith and Rea 1982). The reaction-speed experiments with objects have extended the RVP model for use in road-lighting applications. RVP, like visibility index, can be calculated from the contrast and size of the object, the luminance of the background, the glare and the age of the observer. Appendix B gives the formulas for the calculation of RVP from the photometric values of road lighting installations for different object sizes and reflectances, the latter being required for the calculation of the contrast (Rea and Ouellette 1991). The reaction performance tests on which the model is based were carried out with both positive-contrast and negative-contrast objects. The conclusion from these tests was that the difference in contrast threshold for positive and negative contrasts is negligible. This is contrary to the results of Adrian, used for the calculation of visibility level and small-target visibility. It should be noted, therefore, that the reaction performance tests for the lower lighting levels were only carried out with positive-contrast objects.

Visibility level is not linearly proportional to visibility. For example, a visibility level, VL, of 10 does not correspond to a situation that is twice as visible as one with a visibility level of 5. Often the level of visibility becomes saturated at VL levels higher than 10 to 15. This saturation of visibility is not directly apparent from the VL values. By contrast, RVP values are proportional to the speed and accuracy of the visual processing. Figure 3.18 shows the results of RVP calculations for one object size (7 min of visual angle).

Fig. 3.18 Relative visual performance, RVP, as a function of object contrast, C, and background luminance L_b. Flat, square object; visual angle: 7 min; observer age: 30 years; no glare; a calculation variant different from but based on Rea (2012)



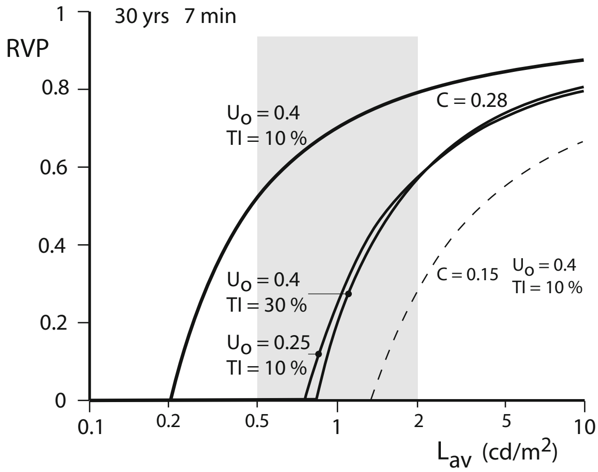
RVP, or the speed and accuracy of visual processing (vertical axis), is given as a function of the object contrast, C, and the background luminance, L_b. The higher the lighting level and the higher the contrast, the larger are the RVP values. RVP values higher than some 0.9 correspond to the plateau of the RVP body (displayed in white): the area where saturation of visibility occurs and further improvements in contrast or background luminance have hardly any effect on improvements in visibility. RVP values lower than 0.7 correspond to the area on the steep downwards slope (escarpment). Small reductions in contrast and/or background luminance have a strong negative effect on RVP and thus on the speed and accuracy of visual processing. Good and efficient road lighting should be such that the RVP values correspond to the top of the slightly-sloped area, dark grey-shaded in the Fig. (RVP between 0.7 and 0.9). The bottom of the RVP body, i.e. RVP values equal to zero corresponds, of course, to no visibility (black shaded area).

To give insight into RVP values of road-lighting installations with differing quality, RVP values for the darkest position on the road (local minimum road-surface luminance) have been calculated for different combinations of L_{av}, U_o and TI. This is similar to what was done previously for revealing power, and as shown in Sect. 3.2.1 The same three different combinations of uniformity and glare restriction have been analysed:

- $U_o = 0.40$ and $TI = 10\,\%$ representative for “good” road lighting
- $U_o = 0.25$ and $TI = 10\,\%$ representative for bad overall uniformity
- $U_o = 0.40$ and $TI = 30\,\%$ representative for too much glare.

The calculations have been made for an object seen under an angle 7 min of arc, corresponding to an object size of 20×20 cm at a distance of 100 m, and an observer age of 30 years—again, the same as for the revealing-power calculations. Figure 3.19 gives the results for an object contrast of 0.28. Object contrasts between 0.2 and 0.3 are often considered as the critical contrasts in road lighting. A contrast of 0.28 is the critical contrast that is recommended for use as a basis for tunnel lighting (CIE 2004).

Fig. 3.19 Calculated RVP values for objects at the darkest location on the road as a function of the average road-surface luminance (L_{av}) for different U_o and TI combinations. Object seen under an angle of 7 min of arc with a contrast of 0.28. Observer age 30 years



The results are very much similar to those of revealing power displayed in Fig. 3.13. At good uniformity and glare restriction, RVP values between 0.7 and 0.8 are obtained at lighting levels of between 1 cd/m^2 and 2 cd/m^2. When the uniformity decreases from $U_o = 0.4$ to only 0.25, the RVP values decrease from 0.7 at 1 cd/m^2 to a poor value of about 0.1 at the same lighting level of 1 cd/m^2. The same holds true for the change from good uniformity ($U_o = 0.4$) and glare restriction (TI = 10 %) to good uniformity ($U_o = 0.4$) and bad glare restriction (TI = 30 %). To show that the results are, of course, different for different object contrasts, and thus for different reflectance factors, the thin broken curve gives the RVP results for a small contrast of 0.15. Objects with such a small contrast are invisible at a lighting level of 1 cd/m^2, even with good uniformity and glare restriction.

A provisional direct link has been established between relative visual performance calculated for different road-lighting installations at intersections in Minnesota (USA) and the reduction in night-time road accidents at those same intersections (Rea 2012). Where RVP increases from less than 0.7 (viz. on the descending slope of the RVP body) to the range 0.8–0.9 (the light grey area close to the plateau of the RVP body), the percentage of traffic accidents reduces by approximately 15 %. More experimental data is needed before such a link can be made statistically significant.

The relative-visual-performance model, like small-target visibility, has not been developed merely to give an insight in how the different aspects of road lighting influence visual processing of objects. It is also proposed as a design-visibility metric for good-quality road lighting installations. The author of this book believes that visibility metrics cannot replace the purely photometric-based metrics, such as road surface and veiling luminance, as a design metric for road-lighting installations. One reason for this is that such a metric is always based on only one type or one set of objects. Another reason is that the driving task concerns much more than trying to see and react to relatively small objects on the carriageway. As mentioned already, visibility metrics such as small-target visibility, total revealing power, and now also relative visual performance can be important as a comparison or fine-tuning tool for road-lighting installations that have been designed on the basis of pure photometric criteria but that can benefit from further optimization Another example of the use of these tools is analysing lighting effects at locations, such as pedestrian crossings and road intersections, where clearly-defined, specific visibility tasks are key (Rea et al. 2010).

3.4 Visibility on Road Surrounds

One of the many vision-related tasks of a driver concerns the detection of objects that are not on the road but in the adjacent areas of the road. He must be able to decide whether or not these are moving towards or into his line of travel. Road lighting can, and should, facilitate this task.

An example of the work carried out concerning this aspect of road lighting is the study conducted at Philips 2nd generation open-air road-lighting laboratory (Fig. 3.20) (Van Bommel and Tekelenburg 1986). Each of ten drivers was asked to drive along the laboratory's test road, where they were called upon to react to the presence of pedestrians by actuating a micro-switch on the steering wheel. The pedestrians were instructed to appear at random positions, not on the traffic lane but three metres from its border on the adjacent surroundings of the road (road verge). This test thus involves peripheral or off-line vision. Plastic cones were used to make the narrow driving lane slightly less than straight so that the drivers were obliged to keep their eyes on the traffic lane ahead. The detection of the pedestrians on the surrounds was therefore indeed "off" the line of vision. From the point where the drivers reacted to the presence of a pedestrian, the remaining distance to the pedestrian was determined. The tests were carried out for different luminances of the road and for two different situations of the lighting of the road verge: one where the verge was lit to 40 % of the illuminance on the traffic lane itself ("bright surrounds") and another one with no verge lighting ("dark surrounds")—see Fig. 3.21. The results are shown in Fig. 3.22 where the average remaining distance at the moment of reaction, d_{remain}, is given as a function of the average luminance of the traffic lane, L_{av}. For the situation with the bright road-side surrounds a clear trend is evident: the higher the average luminance of the traffic lane, the greater the remaining distance to the pedestrians at the moment the drivers reacted.

For the situations with dark road-side surroundings, increasing the lighting level on the traffic lane itself has no positive effect on the detection distance of the pedestrians. As will be shown later in the section on Lighting Quality Parameters (Chap. 8), this is why many standards and recommendations require a minimum amount of light on a stretch of some 3–5 m adjacent to the carriageway itself.

One series of tests was carried out without any fixed road lighting but with dipped car headlights only. This result is also shown in Fig. 3.22. It can be seen that poor road lighting (0.3 cd/m^2 or 1 cd/m^2 with the dark surroundings) is no better than the

Fig. 3.20 Philips' open-air road-lighting laboratories—from first to third generation. The third generation is today's laboratory in France. (Photo: Pierre Crouzet)

use of dipped car headlights only. From this we can conclude that poor road lighting is a waste of money and energy. Note that all tests have been performed with the same high-pressure sodium type of lamp. Effects of different spectra on peripheral vision will be discussed in Chap. 6 "Mesopic Vision".

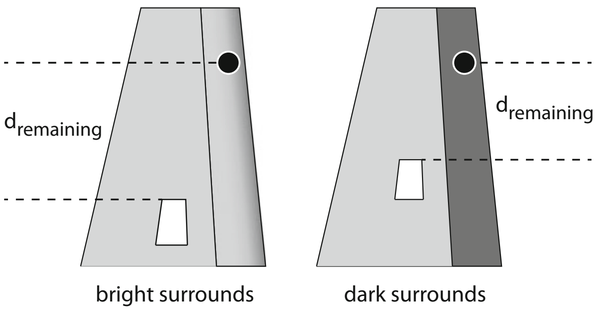


Fig. 3.21 Test situation at the open-air road-lighting laboratory. Driver's car equipped with dipped European beam

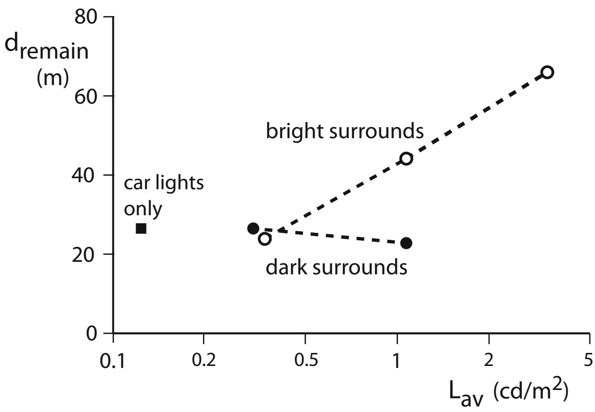


Fig. 3.22 Remaining distance, d_{remain}, after the reaction to the presence of pedestrians positioned three metres away from the border of a traffic lane, as a function of the average traffic-lane luminance, L_{av}. Uniformity, $U_o > 0.4$ and glare, $TI < 10$. (Van Bommel and Tekelenburg 1986)

The importance of appropriate lighting for the surrounds of a road is confirmed by the accident study referred to in the first chapter of this book, in which the authors reported that higher road-surface luminances result in lower accident ratios (Hargroves and Scott 1979). Apart from the importance of a sufficiently-high road surface luminance, they also reported that accident ratios were 20–30 % less on roads falling in the group with surround luminances between 0.5 cd/m^2 and 1.2 cd/m^2 than on roads in the group with surround luminances lower than 0.5 cd/m^2.

3.5 Traffic Flow

Position-keeping in the traffic stream is another important safety aspect of the driving task. Road lighting can also help in this respect. Night-time motorway driving tests carried out over a distance of 50 km in a road simulator showed that motorists react to the presence of a broken-truck on the emergency lane differently according to whether there is lighting or no lighting. Figure 3.23 shows that on lighted motorways, approaching motorists already started changing traffic lane some 360 m before the breakdown, compared to a distance of only 130 m where there was no motorway

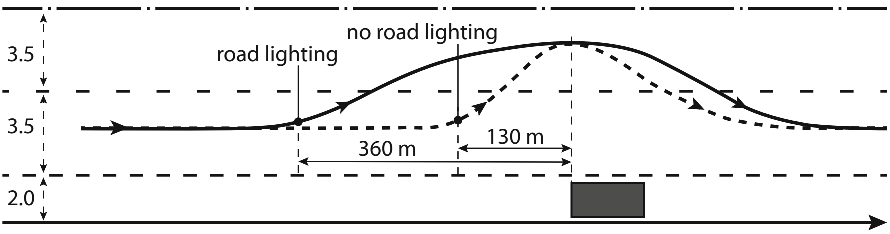


Fig. 3.23 Night-time reaction of drivers in a road simulator to the presence of a parked truck on the emergency lane of a motorway after 45 km of driving. Average of 14 drivers aged 25–40 years. (Remande 2009)

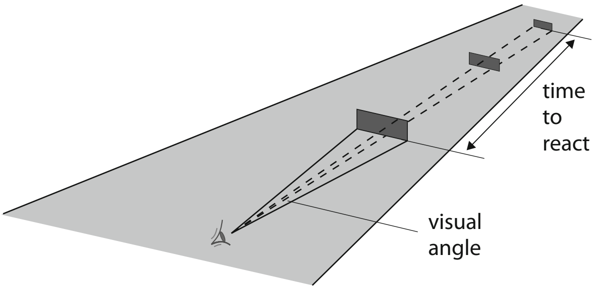


Fig. 3.24 Change of visual angle of a leading car that is slowing down permits a driver behind that car to detect that the lead car is slowing down

lighting (Muzet 2003; Remande 2009). The earlier initiated, more gradual, reaction in the case of lighting allows other motorists to anticipate in plenty of time, which has a positive influence on traffic flow and avoids sudden, dangerous snowball-type reactions.

Detection of the change in the angular size of cars driving in front of a motorist is also an important visual element of the position-keeping driving task. The change indicates whether a car in front is accelerating, slowing down or braking (Fig. 3.24). Quite some time ago the time needed to react to a change in this visual angle was studied in a laboratory simulation (Fisher and Hall 1976, 1978). With today's dense traffic, the results are probably more important than they were at the time of the study. Figure 3.25 gives the time needed to react to the change in visual angle of a simulated lead car that starts slowing down, as a function of the average road-surface luminance, L_{av}. for a simulated initial distance between the test driver and lead vehicle of 40 m and for two deceleration rates. It can be seen that for low values of L_{av} the reaction time (t) is relatively large and decreases rapidly as L_{av} is increased. If the difficulty of the task is increased (viz. if the deceleration rate of the lead car is decreased), the reaction time at a given value of L_{av} will be that much larger, although the same systematic decrease of reaction time with increasing luminance level is found, both the curves levelling out as L_{av} approaches 10 cd/m^2. The effect may reduce the number of so-called "ghost traffic jams" during dark hours. Ghost traffic jams are those that occur because of unnecessary, sudden braking or lane-changing and the

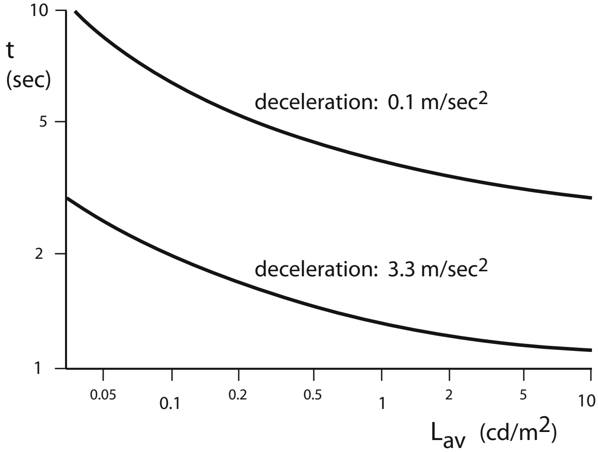


Fig. 3.25 Time *t*, taken to react to change in visual angle of a lead vehicle that starts slowing down, as a function of the average road-surface luminance, L_{av}, for two deceleration rates of the lead vehicle. (Fisher and Hall 1976)

subsequent chain reactions by following drivers. They get their name from the fact that there is no apparent reason for the traffic jam.

3.6 Adverse Weather Conditions

A road-lighting installation can give rise to bad, and thus dangerous, visual situations due to the presence of rain, fog or snow. At the same time, a snow-covered road surface can also improve visibility. The most important factors having a bearing on road - lighting quality under adverse weather conditions will be discussed here. Guidance on the design of road-lighting installations to minimize negative consequences during adverse weather conditions will be given in Chap. 13 “Design Aspects”.

3.6.1 Wet Weather

When it is raining, a certain amount of the light directed towards the road from a road-lighting installation never reaches it: some is lost through absorption in the rain drops and some is scattered by these same droplets in all directions. However, the resultant loss of visibility, although troublesome while the rain lasts, is usually mild compared with that caused by the wetting of the road surface, which remains wet for some time after the rain has stopped.

The influence that a wet road surface has on the visibility is a direct result of the changed nature of that surface’s reflection properties. Light coming from the road-lighting luminaires and reflected specularly by the wet road toward a road user

Fig. 3.26 Bright and dark patches on a wet road surface

will produce very bright patches on its surface alternating with large dark patches (Fig. 3.26).

The bright patches can have luminance values of more than ten times the values at the same area during dry conditions (Ekrias et al. 2007). The result is that the average luminance of the surface increases while the overall and longitudinal luminance uniformities decrease. While the increase in average road-surface luminance has a positive effect on the adaptation state of the driver's eyes, the decrease in uniformity has a much larger negative effect on overall visual performance. The most important influence on the wet-weather quality of the road lighting is without doubt that exerted by the nature of the road surface itself, although the light distribution of the luminaires and the type of lighting arrangement also have a, somewhat smaller, influence. Open-structure road surfaces that easily drain away water remain diffusely reflecting even when wet, and thus have only a small negative impact on wet-weather road-lighting quality. As will be shown in the Section "Standards and Recommendations", some standards give specific requirements for the value of the overall uniformity U_o under wet road-surface conditions.

3.6.2 Snow

When it is snowing, much of the light from the road-lighting luminaires is lost through absorption in the snow flakes and some is scattered in the direction of the driver, giving rise to glare. When the road is covered with snow, the average road-surface luminance increases by a factor of 4 to 5 while, due to the diffuse character of snow, the uniformity does not deteriorate much (Ekrias et al. 2007). If the installation permits of dimming, the lighting level can be reduced as long as the settled snow remains clean.

3.6.3 Fog

The poor visibility that occurs on a lighted road during foggy weather can be attributed to light being absorbed and scattered by the fog-producing water droplets, which often contain dirt particles, suspended in the atmosphere. Some of this light is lost, and some is reflected towards the road user in the form of a bright veil of fog that obscures details on the road ahead. (In vehicle lighting, this is commonly known as the 'white-wall effect'.) Nothing can be done regarding the loss of light. The degree to which fog scatters light in the direction of the driver's eyes decreases if more of the light of the installation is radiated across instead of along the road. The visual guidance obtained from the road-lighting installation can be important under foggy weather conditions as it enables the motorist to see the run of the road and to detect areas with denser fog ahead.

3.7 Fixed Road Lighting and Car Lights

Surprising as it may seem, as far as the visibility of objects at certain positions on the road is concerned, the combination of fixed road lighting and vehicle lights is far from optimum. But the former is nevertheless an important positive counter measure for glare from oncoming cars.

3.7.1 Visibility of Objects on the Road

As has been discussed earlier, fixed road lighting aims at making objects visible as dark silhouettes against the bright road surface (in negative contrast). The lower the vertical illuminance on the road and the higher the road-surface luminance, the better the visibility of possible objects. Car headlights do exactly the opposite: they aim at making possible objects visible by having them stand out brightly against a

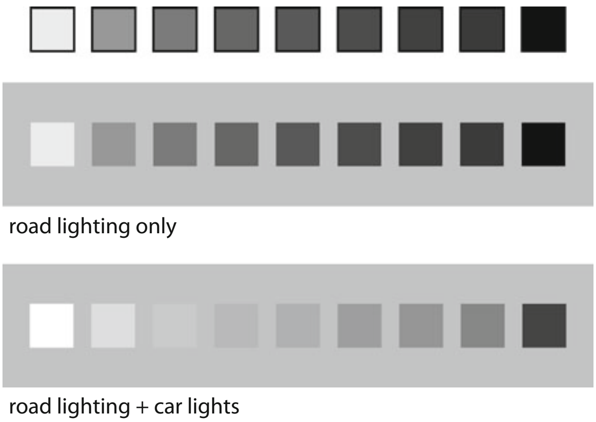


Fig. 3.27 A set of objects typical of pedestrian clothing (*top*), seen with road lighting only (*middle*) and with the combination of road lighting and a driver's car lights that make the objects brighter (*bottom*)

darker background (in positive contrast). Here, the higher the vertical illuminance on the road and the lower the road-surface luminance, the better the visibility of any objects on the road. Fixed road lighting and car headlights thus influence each other negatively. With dipped, or low-beam, halogen car headlights the negative influence is only noticeable up to some 60 m from the car. With low-beam high-intensity discharge car headlights the negative influence may reach as far as some 80 m. With main, or high-beam car lights, however, the negative influence is noticeable much further. The principle of the effect is shown in Fig. 3.27, where the middle part shows the effect of "road lighting only" on the visibility of a set of objects, and the bottom part the effect when the objects all receive the same amount of extra light from the car headlights.

Figure 3.28 shows the reflectance-factor range that is invisible 100 m in front of a car in a situation with only fixed road lighting (car headlights off) and with fixed road lighting and own headlights on. The example is given for a road-lighting installation of 1 cd/m^2 average road-surface luminance. With headlights switched on, the range of invisible objects shifts to those with lower reflectance factors that in practice do in fact occur on the road more often, as also indicated in the figure.

The overall conclusion when comparing the situations with car headlights only and car headlights with fixed road lighting is that the visibility of most objects is improved by introducing road lighting, especially of those objects at greater distances where headlights (dipped-beam or low-beam headlights especially) gradually become less effective.

3.7.2 Glare from Oncoming Cars

On unlighted roads, glare from oncoming cars, especially those with badly-aligned headlights, has a pronounced negative effect on visual performance. Glare is then often experienced, at best, as being very annoying, and at worst as threatening. On

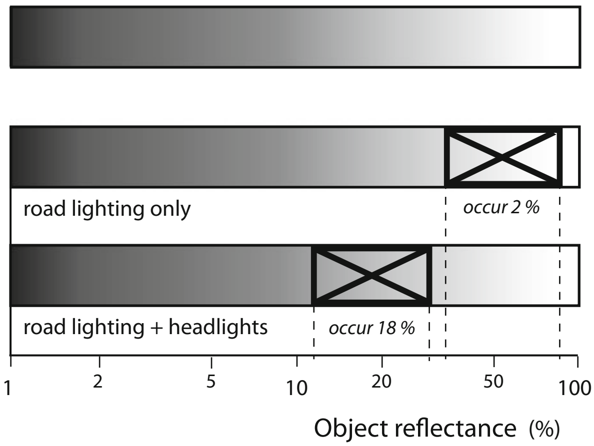


Fig. 3.28 Ranges of reflectance factors that are invisible (big crosses) 100 m in front of a car with and without headlights, together with their percentage of occurrence based on pedestrian cloth-reflectance factors. Fixed road lighting: $L_{av} = 1$ cd/m^2; headlights: E_{vert} at 100 m = 10 lx. Basis: objects subtended an angle of 4 min

an unlighted road, while driving in a car with low-beam high-intensity discharge-lamp headlights, the detection distance of pedestrians decreases to almost half in a situation with one oncoming car with the same type of headlights, compared to the situation where there is no oncoming car (Saraiji et al. 2013). Bullough and Derlosfk (2004) showed that glare from an oncoming car increases the percentage of missed targets on the road as well as increasing the reaction time to targets that are not missed. Dangerous last-minute evasive manoeuvres may be the result. Fixed road lighting minimises the problem because it raises the adaptation level of the drivers. To illustrate how important this positive effect on visibility is, we show the results of a French test covering three different situations (Bacelar 2004): one with dipped-beam lights only, one with dipped-beam lights and an oncoming car with dipped beam, and finally a situation where fixed road lighting of good quality is added in conjunction with dipped beams (Fig. 3.29). From this figure it can be seen that the visibility level in the situation of a car with his dipped beam on (top bar of the figure) decreases considerably when there is an oncoming car (middle bar). The same situation of an oncoming car, but now with road lighting (lower bar) doubles the visibility level.

3.8 Pedestrian Road Crossings

With good road lighting pedestrians on road crossings are visible from a relatively large distance in negative contrast. Closer to the crossing the pedestrians become visible in positive contrast. This is because of the vertical illumination of a car's headlamps. The purpose of additional lighting at a road crossing is specifically to draw the attention of motorists to the presence of the crossing. The presence of extra lighting columns at the crossing may, even during the daytime, in itself help to signal the presence of the crossing. A higher lighting level at the crossing than on

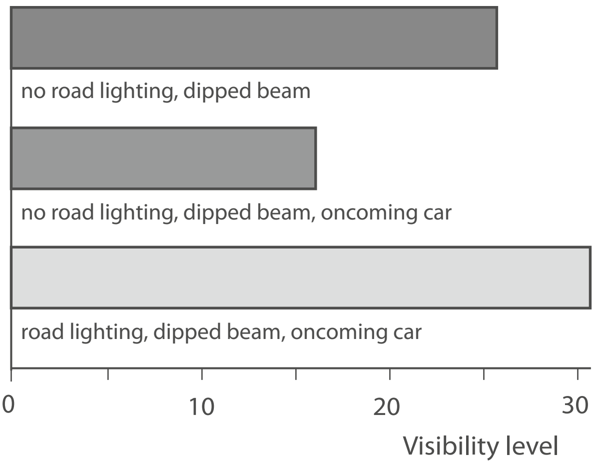


Fig. 3.29 Visibility level of an object (0.20 × 0.20 m and reflectance factor 0.20) 40 m in front of a car with dipped halogen headlight in different situations in the presence of an oncoming car 100 m away (with dipped halogen headlight). Road lighting installation: L_{av} 2.45 cd/m2, U_o 0.6, Ul 0.7 and TI 5 %. (Based on Bacelar 2004)

the adjacent parts of the road may further strengthen the signalling effect. For this to be effective, the light transition should be sharp: that is to say, the extra illumination should be confined to a narrow band around the crossing area. This also helps to encourage pedestrians to cross at the crossing point provided. To ensure that the illuminated crossing stands out against the other road parts, the difference in lighting level should be at least a factor of 2.

The additional lighting also has an influence on the contrast of the pedestrian seen against the road surface behind the crossing, as seen from the motorist's viewpoint.

If the additional lights are placed behind the crossing, as seen from the motorist's viewpoint (Fig. 3.30 top-left and top horizontal bar), the contrast changes into a larger negative contrast (silhouette vision). However, when the motorist comes closer than some 80 m to the crossing there comes a point where, because of his own car lights, the contrast changes polarity. Around the point of polarity change there is a short stretch where the pedestrian may be invisible. To avoid this change of polarity so close to the crossing, the additional lighting is best placed before the crossing so that the extra light is not only radiated towards the horizontal surface of the crossing but also illuminates the side of the pedestrians seen from the approaching driver (Fig. 3.30 top-right and bottom horizontal bar). In this way the contrast is shifted over the whole approach towards a more positive contrast. If the effect in the latter case is only weak, the pedestrians may still become invisible. It is therefore important in this situation to take care that the vertical (or semi-cylindrical) illuminance is significantly higher than the horizontal illuminance.

In a field test, Gibbons (Gibbons and Hankey 2006; Gibbons 2007; FHWA 2008) studied the detectability of pedestrians wearing black, denim or white clothing at a pedestrian crossing. The crossing was on a major road with fixed road lighting and additional crossing lighting delivering an extra vertical illuminance of 5 lx, 20 lx, 40 lx or 60 lx. The tests were performed by 16 elderly persons (average age 69.5 years) seated in a stationery car with low beam headlights from a distance of 83 m from the

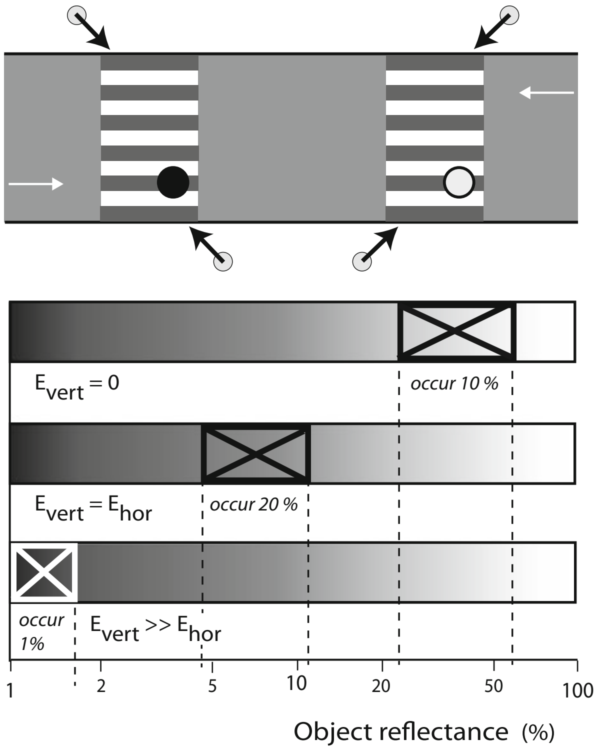


Fig. 3.30 *Top left*: pedestrian-crossing lighting from behind the crossing increases negative-contrast seeing. *Top right*: lighting from in front of the crossing increases positive contrast seeing. Examples of invisible reflectance factor ranges (according to the vertical illuminance obtained from the additional crossing lighting) are given for three different situations by the large crosses. The corresponding occurrence of pedestrian's clothing becoming invisible is given as well

crossing and with an oncoming car 60 m away, also with low beam headlights. By analysing the number of missed and incorrect detections and the response time to correct detections, it was found that 20 lx additional vertical illuminance was required for satisfactory results. This value was confirmed in a dynamic test with a similar group of elderly persons (Edwards and Gibbons 2008). Of course, the additional vertical illuminance is more effective if the installation supplying it is such that an increase of horizontal lighting level is limited as much as possible. In situations with higher background brightness due to a higher level of road lighting, or other lighting in the surroundings, higher vertical illuminance levels are required.

3.9 Optic Flow

More than 60 years ago Gibson (1950) wondered how animals controlled their locomotion (movement) through their environment. Locomotion here concerns both keeping direction and avoiding obstacles. Of course, this is also the task that motorists, cyclists or pedestrians have to carry out continuously while following their chosen path. Gibson supposed that the changing pattern of images across the retina as a result of movement through the environment is one of the key elements in the

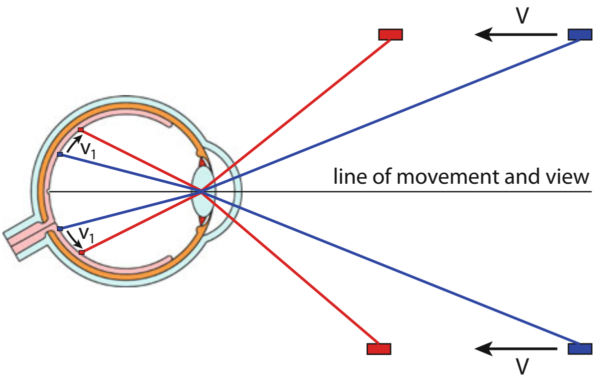


Fig. 3.31 Optic flow: the changing pattern moving across the retina caused by the images of objects as a result of the environment moving towards an observer with speed V. The speed of change across the retina is v_1. Drawing not to scale

perception of movement. This changing pattern of images across the retina has since been called "optic flow". Figure 3.31 illustrates the changing pattern on the retina for two visible objects moving towards a static observer. This situation is equivalent to the situation where a dynamic observer moves towards stationary objects, but the first situation is easier to illustrate. The objects can, for example, be obstacles on a road or small parts of the white lines bordering a carriageway or traffic lane. The speed, V, of the moving environment moving towards the observer (or, identically, the speed of the moving observer through the environment) determines the speed, v_1, of the radial outward movement of the images on the retina.

The optic flow therefore contains the information about the changing distance of objects in the environment for a constant speed of movement. At non-constant speeds of the observer, the rate of change of the optic flow is the perception tool that enables advance determination of time-to-contact with the object (Lee 1980). It seems that a specialized region in the brain analyses the optic flow (Wurtz 1998). The brain performs the required computations so rapidly that indeed the optic flow enables the control of steering and braking at high speeds. In fact the perception tool's mechanism is even more complicated. Firstly, motorists, cyclists and pedestrian "meet" not only with stationary objects but with moving objects as well (such as other vehicles, cyclists and pedestrians). The information from all these movements is contained in the optic flow. Secondly, the eye and the head are always slightly in motion. The retinal flow caused by this motion is superimposed over the optic flow caused by the movement in space.

Since the early investigations into the mechanism of perception of motion and action, many other researchers have confirmed and extended our knowledge on the subject (Blake and Sekuler 2006; Vaina et al. 2004). In the previous sections of this chapter some visual-performance tests have been discussed where the observer or observers were actually moving, as in the tests concerning visibility in the road's surrounds (Sect. 3.4) and on traffic flow (Sect. 3.5). Fundamental research on motion processing as a function of light level is only rarely carried out (Billino et al. 2008a). Various studies have shown age-related deficits in motion perception (Billino et al. 2008b). The author of this book is not acquainted with research specifically devoted

Fig. 3.32 Driving simulator used by Muzet (2003) allowing EEGs to be recorded during simulated (night) drives. Photograph CI2N

to road lighting and optic flow. Effects of, for example, the influence of lighting level and spectrum of light source on the basic mechanism of motion perception are therefore not known, but could be important.

3.10 Lighting, Brain Activity and Alertness

There exists a negative relationship between driver fatigue and road safety. Both the performance and vigilance, or alertness, of the fatigued motorist decrease. Sleepiness or drowsiness may lead to micro sleeps of from less than a second to some tens of seconds. The risk of this occurring is especially great during long, monotonous night drives. A test, carried out by the university of Paris, with night-time motorists equipped with instrumentation to measure their EEG so as to determine the duration of each individual micro sleep whilst driving, has shown alarming results (Mollard 2003). On a 415 km stretch of unlit motorway, those night drivers that did not take a rest before the beginning of their night drive showed a cumulative micro-sleep time of 6 min and 12 s. No extensive tests have yet been carried out on equally-long stretches of lighted motorways. Tests in a simulator in which EEGs have been recorded (Fig. 3.32) have shown that the sleepiness during the first hour of a nighttime motorway drive is less on a lighted road than on an unlighted road (Muzet 2003; Remande 2009). During the subsequent three driving hours of the test there is no difference in sleepiness on the lighted and unlighted road. The same study showed that after a 1-h drive in the middle of the night on an unlit motorway, the resulting sleepiness decreases rapidly (on a 5-point sleepiness scale from 4.5 to 3.1) while subsequently driving on a lighted stretch of motorway. The lower level of sleepiness was measured during the whole 10 km drive on the lighted stretch. Sleepiness started rising again after a subsequent unlighted stretch.

It seems that neurophysiologic studies indeed can help to identify which road conditions, result in the greatest risk of sleepiness and drowsiness (Brown et al. 2013). Such studies aimed at lighting conditions could possibly lead to specific lighting scenarios for long motorways.

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Chapter 4
Visual Comfort for Motorists

Abstract Visual comfort is a subjective aspect related to road-lighting quality. If the degree of visual comfort is not good enough, a motorist's level of fatigue will increase and as a consequence, his visual performance and alertness will decrease. So both visual comfort and visual performance are important for road safety. Subjective appraisal studies have shown that the lighting level, the uniformity of the road-surface luminance pattern and glare have an influence on visual comfort. The same type of studies have been the basis for definitions of visual comfort metrics such as longitudinal uniformity, luminance gradient and discomfort glare marks. The spectrum of the light source used has an influence on the last mentioned. LEDs may sometimes have a special influence on visual comfort because they are available in a much wider range of spectra than are the conventional light sources. Their small light-emitting surfaces enable more pronounced beams to be produced, that in turn may influence visual comfort or discomfort. Most LED luminaires consist of a multiple array of small LEDs resulting in a non-uniform luminance distribution of the light-emitting surface, which may have an influence on their discomfort glare aspect.

For a high level of visual performance to be maintained over a longer time, the road user must feel comfortable in his visual environment. If he has the feeling that it is tiring to get the visual information he needs for safe driving, he will feel uncomfortable. As a consequence his level of fatigue will quickly increase. This in turn has a negative effect on both his visual performance and his alertness. Visual comfort is a subjective aspect of road lighting as it has to do with the road user himself. Aspects of road lighting known to influence visual comfort are the lighting level, the uniformity of the lighting pattern, and glare.

4.1 Lighting Level

It goes without saying that the degree of visual comfort experienced by a road user is very much dependent upon the value of the average road-surface luminance to which he is adapted. The higher this luminance, the more comfortable he will feel in the performance of his driving task. In order to gain a quantitative insight into the effect of the lighting level, the subjective appraisal technique is often used, either

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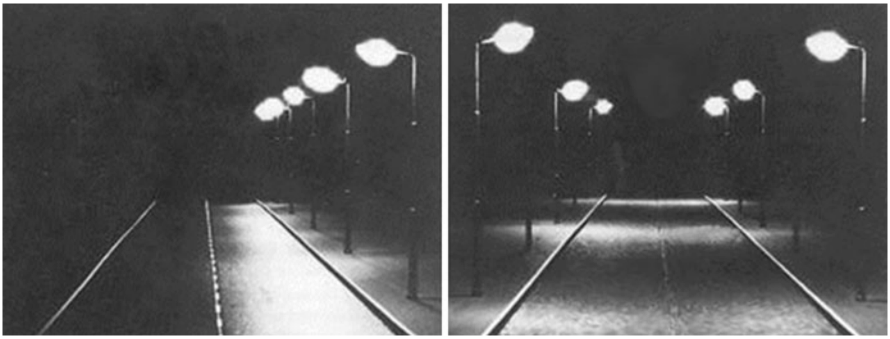

Fig. 4.1 Photographs, taken in a road-lighting model, illustrating bad uniformity from a visual performance point of view (*left*: very low U_o and high U_l value) and from a discomfort point of view (*right*: moderate U_o and very low U_l value)

in static, but especially also in dynamic driving experiments. The most extensive experiments were carried out in the seventies and eighties of the last century and have been reported in some detail by Van Bommel and de Boer (1980). The appraisal for lighting level appears to be particularly dependent upon the type of road considered—the appraisal differing for main roads (including motorways) and secondary roads. An appraisal 'good' is obtained for secondary roads at an average road-surface luminance of slightly greater than 1 cd/m^2, whereas for main roads an average road-surface luminance level of at least 2 cd/m^2 is required for the same appraisal.

4.2 Uniformity

4.2.1 Longitudinal Uniformity

An important comfort aspect of road lighting is the lengthwise uniformity of the luminance pattern of the road in front of a motorist. A continuously-alternating sequence of bright and dark strips on the road disappearing under the vehicle while driving may or may not have a negative effect on visual performance, but is always experienced as being uncomfortable if the brightness difference between bright and dark areas is too great. Figure 4.1 illustrates this with two photographs taken in a road-lighting model.

The photograph on the left shows an installation with a very low value of overall uniformity U_o, which is the ratio of minimum luminance, L_{min} (seen in this example on the left-hand side of the road), to the average luminance, L_{av}. From a visual-performance point of view this is really-bad road lighting: objects on the left side of the road will be invisible. However, from the visual comfort point of view the installation is not so bad. This is because the lengthwise, or longitudinal, uniformity U_l is very good. The installation shown in the photograph on the right is slightly better

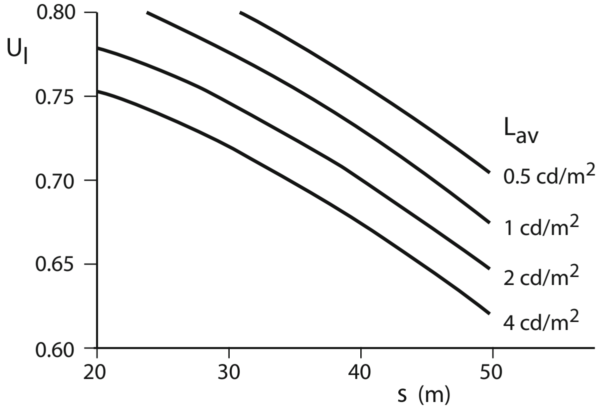

Fig. 4.2 Just acceptable longitudinal uniformity, U_l, as a function of luminaire spacing, s, for different values of average road-surface luminance, L_{av}. Based on a driving speed of 50 km/h in a semi-dynamic road-lighting simulator. (Walthert 1975)

from a visual performance point of view because the ratio of minimum luminance to average luminance (viz. U_o) is somewhat better. However, this installation is very bad from a visual comfort point of view. The problem is the sequence of bright and dark areas on the road ahead of the motorist, viz. the so-called "zebra effect". The longitudinal uniformity U_l, defined as the ratio of minimum to maximum luminance on the line parallel to the road axis, is very poor. As it is important that both visual performance and visual comfort are good, road-lighting installations should be designed so that both overall and longitudinal uniformity are acceptable.

The appraisal for longitudinal uniformity is dependent on both the average road-surface luminance level and the spacing of the luminaires. Figure 4.2 shows that the higher the average road-surface luminance and the longer the luminaire spacing, the lower the longitudinal uniformity can be for the same "just acceptable" appraisal for that longitudinal uniformity.

4.2.2 Luminance Gradient

The road-surface luminance gradient, viz. the rate of change of luminance with distance covered, also has an influence on visual comfort. If, for the same longitudinal uniformity value the minimum and maximum values are located close together, the discomfort effect will be greater than when those locations are farther apart from each other. With conventional luminaires it is difficult, if not impossible, to produce such pronounced beams that the luminance gradient becomes a problem in practice. Since with LED luminaires much more pronounced beams can be produced, an old and seldom-used concept, introduced by De Boer and Knudsen (1963) could become useful for today's circumstances. They defined as a metric for the discomfort aspect of the luminance gradient the so-called relative maximum luminance slope, S_{max}. It is defined as the maximum luminance variation found over any 3 m along or 1 m across the road, expressed as a percentage of the average road-surface luminance.

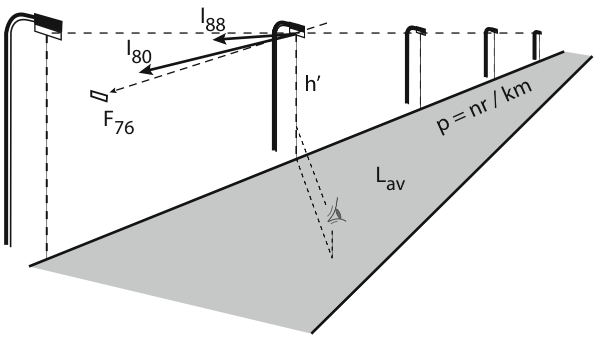

Fig. 4.3 Luminaire and installation characteristics influencing discomfort glare

4.3 Glare

4.3.1 Discomfort Glare

It has already been shown that glare can have a distinct negative, disturbing effect on visual performance. But this is not all: it may also have a distinct discomfort effect. To distinguish between these two effects we speak of disability glare (already dealt with in Sect. 3.1.3.1) and discomfort glare, respectively. These two effects may be caused by partly different mechanisms in the eyes, nerves and brain. It has been hypothesized that discomfort glare effects coincide with and can be studied through uncomfortable contractions of the iris (changing the pupil size), eye lens and muscles surrounding the eyes (Berman et al. 1994; Murray et al. 2002; Stone 2009; Zhu et al. 2013a). Discomfort glare may divert the attention of the motorist away from the scene to be surveyed towards the bright glare source, thereby reducing safety. This seems to be especially a problem for beginning drivers.

Many investigations have been carried out, again especially in the seventies and eighties of last century, in which observers were asked to appraise the degree of discomfort glare experienced under both static and dynamic driving conditions, using both model and actual installations. These are discussed in some detail in Van Bommel and de Boer (1980). From these investigations it was found that the degree of discomfort glare is influenced by the following luminaire and installation characteristics (see also Fig. 4.3):

- Luminaire characteristics

I_{80}: absolute luminous intensity (cd) at an angle of 80° to the downward vertical in the vertical plane parallel to the road axis (the smaller this intensity the better),

I_{80}/I_{88}: run back ratio of the luminous intensities at 80° and 88° to the downward vertical in the vertical plane parallel to the road axis (the larger the run-back ratio the better),

F apparent flashed (light-emitting) area of the luminaires (m^2) as seen at an angle of 76° to the downward vertical (the larger the area the better);

Table 4.1 The De Boer nine-point appraisal scale for glare

Glare mark	Glare appraisal
9	Unnoticeable
7	Satisfactory
5	Just admissible
3	Disturbing
1	Unbearable

- Installation characteristics

L_{av}: average road-surface luminance (cd/m^2) (the larger the better),
h': the vertical distance between eye level and the luminaires (the larger the better),
p: number of luminaires per kilometre (the smaller the better).

The interrelationship between these characteristics can be described with one figure: the so-called glare control mark G. This glare control mark is based on a nine-point scale of assessment introduced by de Boer et al. (1959) often used for subjective appraisal studies and shown in Table 4.1.

The interrelationship between glare control mark G and the luminaire and installation characteristics as standardized by CIE (1976) is:

$$G = 13.84 - 3.31 \log I_{80} + 1.3(\log I_{80}/I_{88})^{0.5} - 0.08 \log I_{80}/I_{88}$$
$$+1.29 \log F_{76} + 0.97 \log L_{av} + 4.41 \log h' - 1.46 \log p$$

In the 1980s Bennett, supported by the Illuminating Engineering Society of North America, carried out discomfort-glare experiments in a driving simulator in which the simulated road-lighting luminaires changed in size and luminance according to the simulated speed (Bennett et al. 1985; Liu and Konz 1991). Test persons were asked to indicate the border between comfort and discomfort (BCD). The experiments resulted in a discomfort glare metric called the tolerable cumulative brightness effect, CBE_{tol}. It is dependent on the luminances of the glaring luminaires, L_g, the solid angle, ω, under which the luminaires are seen, the angle between the line of vision and the glare source, θ, the road-surface luminance, L_r, and the number of luminaires, n:

$$CBE_{tol} = \frac{3.22 * 10^4}{L_r^{0.5}} * \sum_{i=1}^{n} \frac{L_{g,i}^{1.67} * \omega_i}{\theta_i^2 + 153}$$

This is the formula as converted from non-metric foot-lamberts into cd/m^2. Adrian (1991) showed from a mathematical comparison that CIE's glare control mark G-formula and Bennett's cumulative brightness effect CBE_{tol}-formula, have the same characteristics and give comparable results.

In the design practice of road lighting it is often only the disability glare that is restricted, the idea being that excessive discomfort glare will then be avoided as well. It is not sure that this works out well enough for all types of LED luminaires (see Sect. 4.3.4 further in this chapter).

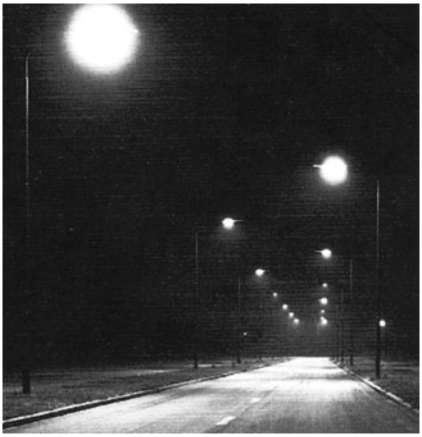

Fig. 4.4 The photograph of a lighted road which was employed by De Boer when making assessments of discomfort glare. The holes at the position of the luminaires was filled completely and homogeneously with the light of various types of light sources

4.3.2 Spectrum and Discomfort Glare

As has been mentioned in Chap. 3 there is no or only a very marginal effect of the spectrum on disability glare. The discomfort glare sensation, however, is clearly influenced by the spectrum of the light source used. De Boer (1955, 1974) carried out early investigations with observers appraising discomfort glare on a model with low-pressure sodium, high-pressure sodium and high-pressure mercury light (Fig. 4.4).

On the basis of these investigations it was concluded that the 1976 CIE formula of the discomfort glare control mark should incorporate a correction factor of + 0.4 to + 0.8 in the case of low-pressure sodium lamps and + 0.3 to + 0.6 for high-pressure sodium lamps (Van Bommel and de Boer 1980). This is because these lamps result in lower discomfort glare than lamps with a cooler light colour (higher colour temperature).

With the introduction of LED light sources that are available in a great variety of spectra, the effect of the spectrum on discomfort glare has received renewed interest. Recent research shows that the spectral sensitivity for discomfort glare is not solely determined by the photopic or by a combination of the photopic and scotopic spectral eye sensitivity. Especially also the short-wavelength type of cone cells (so called “S” or “blue sensitive” cones) play a role (Bullough 2009; Fekete et al. 2010; Bodrogi et al. 2012; Akashi et al. 2013; Niedling et al. 2013). This explains why light sources with a relatively large amount of short wavelengths (blue light) result in higher discomfort glare effects than do long-wavelength spectra (yellowish light).

So far, much of this research has been carried out with narrow-wavelength light sources (quasi monochromatic). Preliminary tests with conventional light sources (high-pressure sodium, fluorescent and metal halide lamps) and broad-wavelength white light LED sources indicate that in the colour temperature range of 2200–6000 K the difference in glare control mark varies from some 0.5–2 point in the nine-point de Boer scale to the advantage of the lower-colour-temperature versions (Niedling et al. 2013; Zhu et al. 2013a; Lin et al. 2014). Ongoing research will hopefully result

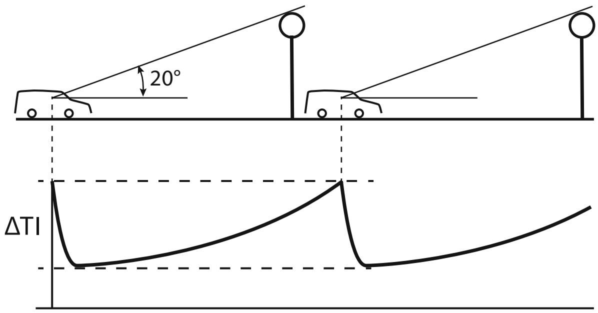

Fig. 4.5 Variation in glare during drive causing discomfort

in clear guidelines as to what correction factors should be applied for discomfort glare for different spectra.

4.3.3 Discomfort from Glare Variation

The amount of glare experienced by a road user varies continuously with his forward movement along the lighted road. This variation in glare, sometimes called pulsating glare sensation, can itself give rise to a feeling of discomfort. The maximum discomfort sensation will occur just before the nearest luminaire is shielded by the roof of the car, while the minimum sensation will occur immediately after the car has passed this point (Fig. 4.5). The car shielding angle has been standardized by CIE for the purpose of glare evaluations at 20° above the horizontal.

Bennett's work in the USA with a driving simulator, already mentioned in Sect. 4.3.1, in fact was especially aimed at finding a predictive metric for the disturbing dynamic pulsating glare effect (Bennett et al. 1985; Liu and Konz 1991). Unfortunately, at the time of his death, the work was not yet finalised (Keck 1991).

Perhaps the variation in the bright veil caused by the glare sources on the retina of the eye whilst driving is the source of the discomforting pulsating effect. A straightforward simple measure for the pulsating effect could then be expressed as the veiling luminance ratio:

$$\frac{L_{v,min}}{L_{v,max}}$$

It is probable that the frequency of the glare pulses also play a role. This frequency depends on driving speed and luminaire spacing. Liu and Konz (1991) concluded from their driving simulator experiments that for speeds between 65 and 95 km/h, speed has no influence for their simulated spacing of 64 m (single-sided arrangement, mounting height 9 m). More research into this aspect is needed.

In principle, the beam shape of a road-lighting luminaire can be designed to not only restrict the maximum amount of glare but also to limit the discomfort effect caused by the variation in glare during driving. With the small light-emitting surface

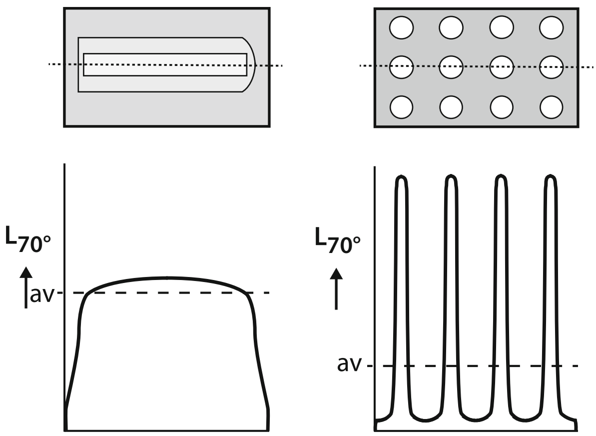

Fig. 4.6 Typical example of a relatively uniform luminaire luminance distribution as obtained with conventional light sources as compared with the non-uniform luminance distribution with an array of LEDs

of LED light sources these possibilities are much greater than with conventional light sources with their larger light-emitting surfaces. It is therefore not surprising that where in the past this subject hardly received attention, the first investigations have now started (Zhu et al. 2013b).

4.3.4 LEDs and Discomfort Glare

The effect of the different spectra of LEDs on discomfort glare has already been discussed in the Sect. 4.3.2.

LED luminaires make use of a multiple array of small LEDs because each individual LED, although efficient, does not have a sufficiently high luminous flux. This means that the luminance distribution of the light-emitting surface of those luminaires is much more non-uniform than that of luminaires using conventional light sources (Fig. 4.6).

The spatial arrangement of the LEDs together with the luminance of the individual LEDs determine the degree of non-uniformity. In the past the effect of non-uniform luminance distributions on discomfort glare has hardly been investigated, either for indoor lighting or for road-lighting applications. Recent studies with LED luminaires, for both indoor and road-lighting applications, show that the luminance distribution does indeed have a pronounced effect. The more non-uniform the luminance distribution of the light-emitting surface of the luminaires, the higher the discomfort glare sensation is, even if the average luminance is the same (Lee et al. 2007; Ayama et al. 2013; Higashi et al. 2013; Tashiro et al. 2014). Further studies into these aspects, so typical for LED luminaires, are thus clearly needed. They must also clarify whether the often-applied practice in road lighting design of only restricting disability glare will not, with some LED luminaires, result in excessive discomfort glare.

For new studies it is interesting to note that Vos (2003) has shown that there are large qualitative and quantitative similarities between the discomfort glare concept used for indoor lighting (unified glare ratio UGR) and that employed for road lighting (glare control mark G). This notwithstanding the fact that the formulas on first sight look completely different and research for the two application fields have been carried out totally independent from each other. Perhaps this should be a reason for developing more common glare evaluation methods over the borders of the different lighting application fields. The application field of automobile lighting should, of course, be included here as well. The most widely used system of discomfort glare prediction for automobile lighting is, already for a long time, that developed by Schmidt-Clausen and Bindels (1974). It uses the illuminance at the eye caused by a glare source, together with the background luminance (road surface luminance) and the angle from the line of sight to the glare source to calculate discomfort glare in terms of the nine-point de Boer scale.

A completely new approach towards studying glare has been proposed in which neural activity in the brain caused by glare is mapped by means of functional magnetic resonance imaging, or fMRI (Raynham et al. 2007). Perhaps such an approach may lead in the future to an objective model for discomfort glare.

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Chapter 5
Visual Performance, Comfort and Pleasantness for Pedestrians, Cyclists and Residents

Abstract It is important that the lighting of residential roads promotes the safety, security and visual guidance of pedestrians, cyclists and moped riders, in addition to that afforded to motorised traffic.

The real problem as far as the safety of the former group is concerned lies with possible hazardous irregularities in the pavement, such as holes, cracks, bumps, and protruding kerb stones. A suitable horizontal illuminance is required to make these clearly visible. Also, many pedestrians feel scared after dark. Sufficiently high brightnesses in the street and its surroundings will enable them to see at a glance the whole area, thus contributing to a feeling of security (both actual and perceived). The brightness needed is dependent not only on the illuminance level but also on the spectrum of the light source employed.

Apart from getting an overview of the whole area, it is also important that the pedestrian should receive sufficient visual information regarding other persons in that area. Facial recognition or identification possibilities improve with increase of semi-cylindrical illuminance. Visual orientation in complete darkness is impossible, as is therefore the ability to find our way. Good visual orientation implies the ability to identify houses and other buildings and features of the environment. A suitable measure for this to be possible is the illuminance on the surrounding facades.

From the point of view of comfort and pleasantness, the aspects of spatial brightness and colour quality of the light sources again play an important role, as do the restriction of discomfort glare and the visual impact of the installation during the daytime.

As was explained in Chap. 2 “Basic lighting parameters”, the lighting parameter for this category of users is in most cases illuminance.

5.1 Visual Performance

5.1.1 Safety

It is important for pedestrians and cyclists to be able to see approaching vehicles so that they can judge their distance, speed and direction of travel. Thanks to the vehicle lights, this is not a difficult visual task. Pedestrians and cyclists should also be able to see obstacles and any irregularities lying in their path in time to avoid tripping

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or falling. Potential hazards, such as parked or discarded bicycles, bicycle racks, construction barriers and street furniture are mostly relatively large. The real problem lies with hazardous irregularities in the pavement or road surface, such as holes, cracks, bumps, and protruding kerb stones, which are usually much smaller in size and therefore, more difficult to see. Given the relatively slow speeds of pedestrians and cyclists, detection of these potential obstacles is only needed from relatively short viewing distances. An investigation in which 15 subjects walked along three routes at night with an eye-tracker built into a light-weight helmet, showed that slightly more than 40 % of the time the subjects were looking at the pavement immediately in front of them (Davoudian and Raynham 2012). Another eye-tracking experiment confirms this tendency to concentrate at the near path: an area less than approximately 4 m ahead (Fotios et al. 2014a, b). In a laboratory setup, Fotios and Cheal (2009, 2013) studied the detection of obstacles representing an irregular pavement surface that had to be seen in time by pedestrians to avoid the risk of tripping. They conclude, for a glare-free situation and the use of high pressure sodium lamps, that for a real life obstacle height of 25 mm to be detected from a distance of 6 m, a local minimum horizontal illuminance of 1.8 lx is required, provided that the pedestrian is adapted to this low lighting level. Below this level there is a steep decrease in detection possibility, while up to some 5.5 lx the detection of smaller obstacles still increases considerably. If the adaptation level of the pedestrian is higher than that determined by the lighting level on his path, higher lighting levels are needed. Since the safety of motorised traffic calls for relatively high road-lighting values, the minimum horizontal illuminance needed for the safety of pedestrians and cyclists has to be proportionally increased on footpaths and cycle paths immediately adjacent to roads carrying motorized traffic. Special attention should be given to the lighting so as to make the boundaries between the cycle or pedestrian path and the flanking areas clearly visible. Here an appropriate choice of the surface material can help considerably.

5.1.2 Security

Many pedestrians feel scared after dark, and are indeed more vulnerable to threats or even attacks than they are during daytime, especially in unsafe areas. For some people this is a reason for not going out after dark, and this can lead to social isolation, especially for women and the elderly (Banister and Bowling 2004; Blöbaum and Henecke 2005; Johansson et al. 2011). Consequently, lighting in built-up areas has a twofold security function to perform: it should provide a feeling of security (perceived security), and it should provide actual security itself. The former will encourage people to venture outdoors, while the latter will help to ensure their safety.

The brightness of the street and its surroundings, or in other words the spatial brightness, if high enough, enables us to see at a glance the whole area, so contributing to a feeling of security. A feeling of insecurity is more likely to arise when an easy escape possibility is not available or seems not to be available. It is therefore essential that the road lighting is harmonised with a proper design of the outdoor environment,

Fig. 5.1 A brightly-lit street with a reasonably good overview, and yet with a person a short distance away who nevertheless cannot be recognized

so as to make escape possibilities clearly visible during the hours of darkness. A field study carried out on 24 open-air car parks (Boyce et al. 2000) showed that the feeling of security increases with increase in the average lighting level up to some 30 lx. In the illuminance range up to 10 lx, a small increase in illuminance results in a large increase in perceived security. In the case of an outdoor environment designed for optimized security, lower lighting levels than those resulting from the car park tests, say 3–5 lx, may be sufficient for a good feeling of security. At the same time, such an environment and lighting will help to deter those with hostile intentions because they realize that they are easily visible and recognizable. A mock-up study has been carried out in a large hall, where the façade of a single house with a 3-m-long front garden, was assessed from the roadside by test persons from different backgrounds, including police officers (Van Bommel and Van Dijk 1985). It showed that under street-lighting conditions with an average horizontal road-surface illuminance of up to 5 lx, a facade illuminance as low as 1.5 lx helps to create a psychological barrier to burglars. In higher-brightness surroundings the lighting levels have to be proportionally higher because the eyes adapt to these higher brightnesses, making the darker parts to appear darker. Quite a few investigations have shown that the spectrum of a light source influences the subjective impression of brightness and thus the feeling of security and the actual security (Morante 2008; Rea et al. 2009; Knight 2010; Schäfer et al. 2010; Fotios and Cheal 2011). Light sources of a higher colour temperature result in a higher subjective impression of brightness than do those of a lower colour temperature. Details will be discussed in Chap. 6 “Mesopic Vision”.

Apart from getting an overview of the whole area, it is also important that the pedestrian should receive sufficient visual information from other persons in the street to judge whether or not they represent a possible threat. For this, visibility of the body and recognition of emotional body posture or body language is important (Meeren et al. 2005; Davoudian and Raynham 2012; Fotios and Yang 2013). Identification of the face and the facial expression is essential in the final judgment process.

Figure 5.1 shows that even in a brightly-lit street with a good-enough overview, identification of a person in the street can be totally impossible. In order to provide

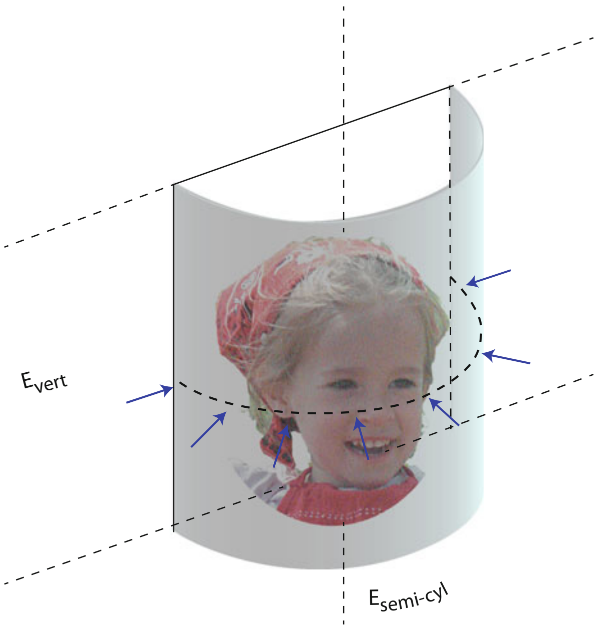

Fig. 5.2 The concept of vertical versus semi-cylindrical illuminance

proper identification of faces, the lighting at face height at all locations in the street should be sufficient. Sometimes the vertical illuminance at face height is used as the basic lighting parameter for providing this information. However, the semi-cylindrical illuminance at face height is a somewhat better basic parameter for this purpose This is because the human face is not simply a flat vertical plane: light incident on the sides of the face contributes to its visibility (Fig. 5.2).

Figure 5.3 shows the results of identification tests of faces under road-lighting conditions (Van Bommel and Caminada 1982). As a basis for the lighting-level requirement, an identification distance of 4 m is sometimes proposed (Van Bommel and Caminada 1982; CIE 2000). At this distance an alert person can still take an evasive or defensive action. From Fig. 5.3 it follows that a semi-cylindrical illuminance value of slightly less than 1 lx, fulfils this requirement. The anthropologist Hall (1969/1990) recognized, on the basis of worldwide research of the human use of space, that human beings like to keep a certain distance from each other, the actual distance being dependent on the type of social contact.

Hall defines four different so-called "proximity zones" (Fig. 5.4):

- the intimate zone,
- the personal zone (family members),
- the social-consultative zone (business contacts),
- and finally the public zone (people who do not know each other).

The public zone begins at a distance of some 4 m. Urban lighting that enables the identification of persons at this distance thus promotes a "natural" feeling of comfort

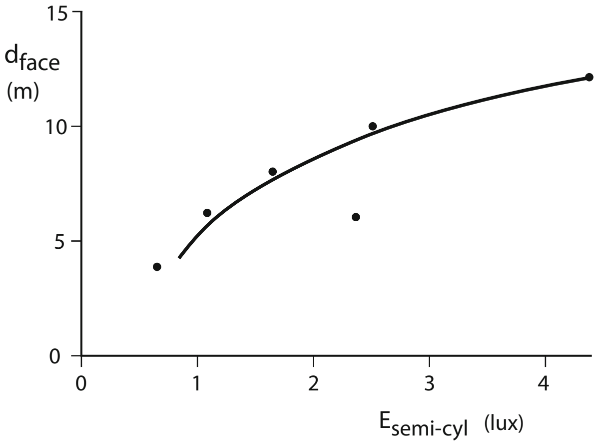

Fig. 5.3 Facial identification distance versus semi-cylindrical illuminance at face height (light source used: white high-pressure mercury light); TI between 8 and 15 %. (Van Bommel and Caminada 1982)

for people in the street who do not know each other. From Fig. 5.3 we can see that for this a minimum semi-cylindrical illuminance of about 1 lx is required. Later studies on proximity zones show that interpersonal distances vary with lighting level, indoor or outdoor environment, and especially with the experimental procedures employed (Fotios and Yang 2013).

Since the first investigation on facial recognition under road-lighting conditions, many more investigations have been carried out by different researchers. One of the aspects investigated is whether or not the spectrum of the light has an influence on facial recognition. The results of these studies are conflicting. Many show an effect of the spectrum in that light sources with better colour rendering facilitate facial recognition (Raynham and Saksvikrønnin 2003; Knight et al. 2007; Qi Yao et al. 2009). However, another, extensive, study does not show any effect of the spectrum on facial recognition (Alferdinck and Hogervorst 2013). The same holds for a study by Rea et al. (2009). Lin and Fotios (2013) have investigated what the reasons can be for these conflicting results. A probable cause is differences in task difficulty. When the task is relatively easy in terms of large visual size (i.e. short observation distance) and long observation time, the spectrum has no influence. However, in the case of small tasks (i.e. larger observation distances) and shorter observation times, the spectrum does have a significant influence. They also conclude that in the case of difficult tasks, where the spectrum does have an influence, that influence cannot be directly related to one of the familiar spectrum characteristics, such as colour rendering index (Ra), colour temperature (T_k) or S/P ratio. Further analysis is needed to establish a spectrum metric that relates to facial recognition.

Again other studies concentrate not so much on facial recognition but on the possibility to determine the emotion expressed by the face (Montel and Menar 1989; Fotios and Yang 2013). A Japanese study (Kohko et al. 2008) has determined in some detail the influence of glare (expressed by the value of the threshold increment TI) on facial recognition. Some of these studies are not expressed in terms of semi-cylindrical illuminance but in terms of facial luminance, which makes the studies

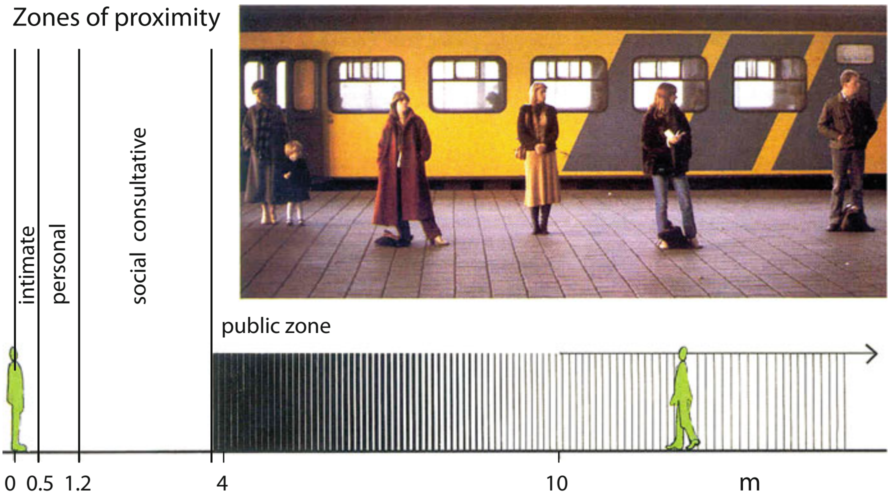

Fig. 5.4 Zones of proximity according to the nature of the social contact

more applicable to different skin colours. For a recognition distance of 4 m these studies show that facial luminances of 0.1 cd/m^2 (TI = 0) (Fotios and Yang 2013) to 0.18 cd/m^2 (TI = 15 %) (Kohko et al. 2008) are required. For a face reflectance of 0.4 this corresponds to 0.8 lx and 1.5 lx semi-cylindrical illuminance, respectively.

Most of the studies described here involved continuous observation of the target person during the approach. In reality, a person will not look at another person continuously while approaching that person in the street. Fotios et al. (2014a, b) investigated at what distance and for how long do test persons fixate their direction of view on other pedestrians in the street. For this purpose the test persons were equipped with an eye-tracker. On the basis of the results of their study, the authors propose that 15 m as the distance and 0.5 s as the observation time should be employed when investigating the effects of lighting on interpersonal judgments.

5.1.3 Visual Orientation and Guidance

Visual orientation in complete darkness is impossible. Without light, we do not know where we are or which way to go. Orientation is a complex process involving parameters such as expectation, experience and visual memory. A resident familiar with his environment needs less lighting for orientation purposes than do those less familiar with the environment in question. Good visual orientation implies the ability to identify houses and other buildings and features of the environment, including road junctions. The eye-tracker investigation mentioned earlier showed that the test persons walking along a route looked at houses, roads (not the pavement on which they walk) and trees for slightly more than 50 % of the time (Davoudian and Raynham 2012). Street signs and house numbers should, of course, be legible as well.

Fig. 5.5 For visual orientation, lighting of facades and features of the environment is needed

For all this to be possible the lighting should light not only the horizontal surfaces within the area but also vertical surfaces such as the facades (Fig. 5.5). In fact this requirement for visual orientation coincides with that of providing a quick overview of the surroundings and making escape possibilities visible as needed from a point of view of security, as was discussed earlier. However, special attention should be given to avoiding "overlighting" of the facades in order not to visually disturb residents in their homes (see Part 2 "Light pollution"). The mockup study mentioned earlier (Van Bommel and Van Dijk 1985) made clear that facade illuminances as low as some 1.5 lx can serve for visual orientation purposes under street lighting conditions with a lighting level of 5 lx average horizontal illuminance.

5.2 Visual Comfort and Pleasantness

For comfort and pleasantness, the following aspects play an important role:

- brightness of the space,
- colour quality of the light sources,
- restriction of discomfort glare,
- visual impact during daytime.

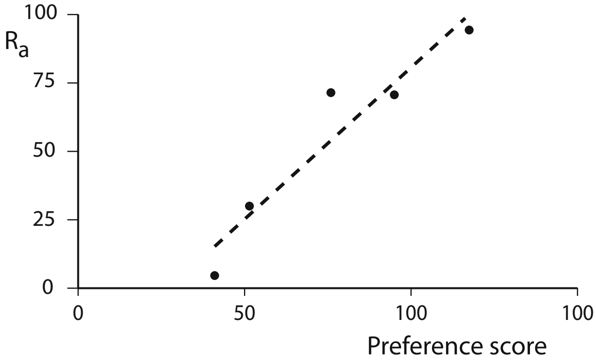

Fig. 5.6 Preference scores in relation to colour rendering index R_a. (Fotios and Cheal 2011)

5.2.1 Spatial Brightness

A street environment that is subjectively judged as not being secure and safe will never be experienced as comfortable or pleasant. The considerations given in Sect. 5.1 regarding safety, security and orientation are therefore relevant here as well. A bright-enough street with bright-enough surroundings that permit of a quick overview of the whole area and what is, or is not, contained in it, is thus a first requisite for pleasantness. Pleasantness tests show that at lighting levels lower than some 3–5 lx the perceived brightness of the street environment becomes the sole determining factor in perceived pleasantness. At lighting levels higher than some 3–5 lx it is the spectrum of the light source that has a more important influence on perceived pleasantness (Nikunen et al. 2012).

5.2.2 Colour Quality of Light

Knight (2010) carried out an extensive appraisal study of street lighting installations involving residents in the Netherlands, Spain and the United Kingdom, before and after changing the light source, while keeping lighting level, uniformity and glare comparable. The perception of comfort in most situations increased when going from yellowish-white high-pressure sodium light (colour temperature 2000 K and colour rendering index of 25) to white metal halide light (with colour temperatures of 2800 and 4200 K) and a colour rendering index of around 80). Tests in a laboratory under mesopic lighting conditions showed that the colour rendering index is the more important aspect of the spectrum as far as preference is concerned (Fotios and Cheal 2011). Figure 5.6 shows the relationship between the preference score of these tests and the colour rendering index.

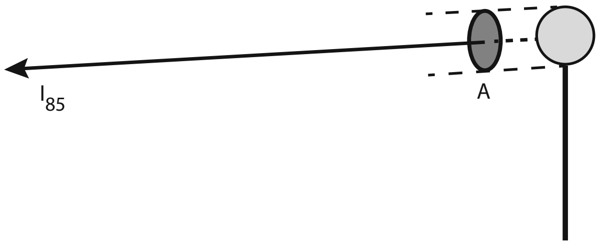

Fig. 5.7 Luminaire glare index

5.2.3 *Discomfort Glare*

Excessive glare because of too-bright luminaires has, of course, a negative effect on the comfort and pleasantness experienced by residents and pedestrians. While motorists have their main direction of view towards the road in front of them, and therefore seldom look straight into a bright luminaire, pedestrians and residents have a more random direction of view, including that directly into bright luminaires. Since the discomfort-glare sensation for residents and pedestrians will be caused by individual bright luminaires appearing near to the direct line of sight, it is sensible to limit the intensity of individual luminaires for critical angles of light emission. The smaller the light-emitting size of the luminaire, the higher the glare sensation and consequently the lower the permissible light intensity of the luminaire. A lighting quality parameter that takes into account both the luminous intensity and bright-area effect is the luminaire glare index (Fig. 5.7):

$$Luminaire\ Glare\ Index = \frac{I_{85}}{A^{0.5}}$$

where:

I_{85} = Maximum intensity at an elevation angle of 85° around the vertical (in cd)
A = Apparent bright area of the luminaire seen under 85° (in m^2).

The required limitation becomes less severe with increasing mounting height. This, of course, is because with increase of mounting height the luminaires move farther away from the more common directions of view. For mounting heights greater than 6 m, CIE recommends luminaire glare index values up to 7000, while for more critical mounting heights lower than some 4 m only values of only 4000 are acceptable.

5.2.4 *Impact During Daytime*

Especially during the daytime, the luminaires and columns can have an important impact on the visual scene. Sometimes, for this reason, decoratively-shaped luminaires are chosen, and sometimes luminaires that are as neutral and discrete as possible.

In the latter case, luminaires and columns are treated as visual obstructions. Larger spacings reduce the number of luminaires required, but demand higher mounting heights. Higher mounting heights increase the possibility of the lighting columns becoming clearly visible as dark silhouettes against the high luminance of the sky. This silhouette effect can be avoided for most directions of view by limiting the column height to half the height of the surrounding houses. It should also be taken into account that in residential roads the scale should be “human”. This means that objects in the street should relate to one’s own height (Caminada and van Bommel 1980). Taking all these, sometimes conflicting, aspects into account leads to the conclusion that the mounting height should be as high as possible but lower than half the height of the facades of the houses.

5.3 Lighting Level, Uniformity and Glare Restriction

From what has been said above about safety, security and visual orientation, certain conclusions regarding the minimum-required lighting quality needed to fulfil the requirements for pedestrians and other slow-moving traffic can be drawn.

As it is both the minimum horizontal illuminance and the adaptation level that determine the required lighting for safety, the quality is usually specified in terms of the average horizontal illuminance, $E_{hor,\,av}$, (which determines the adaptation state) together with an uniformity ratio, usually the minimum over average horizontal illuminance, $E_{hor,\,min}/E_{hor,\,av}$[1]. An average horizontal illuminance of 2 lx is the absolute minimum required. With surroundings that are brighter than that of the path of the pedestrian or cyclist, proportionally higher average horizontal illuminances are required. For security and for visual guidance purposes, the total space should receive some light: a measure for this can be the façade illuminance which should have a value of some 1.5 lx. Here too, brighter surrounds require proportionally higher values. It has been shown that spacial brightness is also dependent on the spectrum of the light source used. Higher colour temperature light sources (cooler tinted light) require lower lighting levels. For the identification of the faces and bodies of persons in the street a minimum semi-cylindrical illuminance of about 1 lx is required at all positions on the path of the pedestrian. The curved surface of the semi-cylinder should be directed towards the person who has to identify the approaching pedestrian. In practice this often means parallel to the line of the pavement, in both directions.

Of course a too-high degree of disability glare will diminish the visual performance of all users of the road or path. While motorists have their main direction of view towards the road in front of them, and therefore seldom look straight into a

[1] The Danes recommend hemispherical illuminance instead of the horizontal illuminance, as the measure for seeing small obstacles in the path of pedestrians. It is suggested that it takes better account of the three-dimensional aspect of obstacles. However this is doubtful because the effect of lighting on the rear side of the hemisphere (and of an obstacle) cannot be seen by the approaching pedestrian.

bright luminaire, cyclists and especially pedestrians have a more random direction of view, including that directly into bright luminaires. The TI glare concept used for the limitation of glare for motorised traffic does not take into account viewing directions directly into luminaires. A separate glare restriction system is therefore needed for cyclists and pedestrians. The luminaire glare index as defined in the previous section is a measure used to restrict discomfort glare for pedestrians and residents.

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Chapter 6
Mesopic Vision

Abstract There are three categories of vision: scotopic, mesopic and photopic. The activity of the two types of light-sensitive cells in the eye, the cones and the rods, is different in each category. At very low adaptation levels only rods are active and vision is scotopic. With rising adaptation levels, from 0.005 cd/m^2, the cones become gradually active and the rods less active. Vision is then mesopic. At adaptation levels higher than 5 cd/m^2 only the cones are active and vision is photopic. Most road lighting installations have lighting levels corresponding to mesopic vision. The cones and rods have differing spectral sensitivities: the rods are more sensitive to short wavelengths while the cones have their maximum sensitivity in the middle of the visible spectrum. Cones are concentrated mainly at that part of the retina of the eye that is used for on-line vision while the rods are located only at locations used for peripheral vision. As a consequence of the above, in mesopic vision, peripheral task performance becomes better with light sources that have a relatively large short wavelength component. The same holds true for the subjective impression of brightness. At lower adaptation levels more rods become active and therefore these advantages become greater at lower lighting levels. Since all photometric units are based on photopic vision, these advantages are not apparent from these units. Correction factors have therefore been determined according to the spectrum of the light source, characterized by its S/P ratio, and of the lighting level obtained from the road lighting installation.

6.1 Spectral Eye Sensitivity

In the mechanism of vision, two different types of light-sensitive cells in the retina of the eye play a role: the cones and the rods. The type of cell that is active is dependent on the lighting level to which the eyes are adapted, which in turn is dependent on the luminance level of the scene that is observed. At high adaptation levels (viz. larger than some 5 cd/m^2) it is the cones that are active. We then talk of photopic vision. Colour vision is possible because we have red, green and blue-sensitive cones. The spectral sensitivity with photopic vision is characterized by the V(λ) curve and reaches its maximum sensitivity at a wavelength of around 555 nm, corresponding to a green-yellow colour (Fig. 6.1). All photometric units (luminous flux, luminous intensity, illuminance, luminance, etc.) are based on the V(λ) function. At very low

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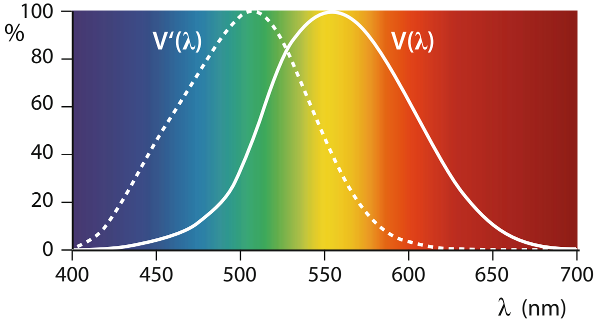


Fig. 6.1 Spectral eye sensitivity curves (also called luminous efficiency curves) for photopic vision V(λ) (CIE 1926) and scotopic vision V′(λ) (CIE 1951)

adaptation levels, lower than some 0.005 cd/m^2 (popularly referred to as being "pitch dark") only the rods are active and we speak of scotopic vision.[1]

The rods have a higher sensitivity to light than do the cones. With scotopic or rod vision, colour vision is impossible. The spectral sensitivity with scotopic vision is characterised by the V′(λ) curve. It reaches its maximum sensitivity at a wavelength of around 505 nm, corresponding to the colours blue-green: relative to the V(λ) curve there is a clear shift towards the blue end of the spectrum (Fig. 6.1). At adaptation levels between approximately 5 and 0.005 cd/m^2 both the cones and the rods are active. We then speak of mesopic vision. In the mesopic vision range, the activity of the rods becomes more important from high to low adaptation levels. As a result, the spectral sensitivity gradually shifts into the direction of small wavelengths—that is to say in the direction of blue.[2] Fig. 6.2 shows this shift. The sensitivity scale here is not relative as is commonly the case (see Fig. 6.1), but in terms of absolute spectral luminous efficacy values, so that the effect of the larger sensitivity of rods, as mentioned above, also becomes apparent.

Because of the shift towards the green-blue end of the spectrum, it can be claimed that under road-lighting conditions, where we are mostly in the mesopic vision range, light sources containing more green-blue light (cool-white light) than yellow-red light (warm-white light) are more efficient for vision. Claims are sometimes exaggerated and sometimes made when they are not valid at all (van Bommel 2009). As will be explained in the next section, such claims are valid for peripheral vision but not for on-line vision.

[1] On an asphalt road surface full moon results in an average of 0.02–0.03 cd/m^2, which is clearly too "bright" for scotopic vision. Dimly-lit residential streets have an average luminance of some 0.2 cd/m^2 to 0.5 cd/ m^2, which is far too bright for scotopic vision.

[2] Because of this shift, our perception of colour is changed somewhat towards blue. This colour-change effect is called the "Purkinje effect".

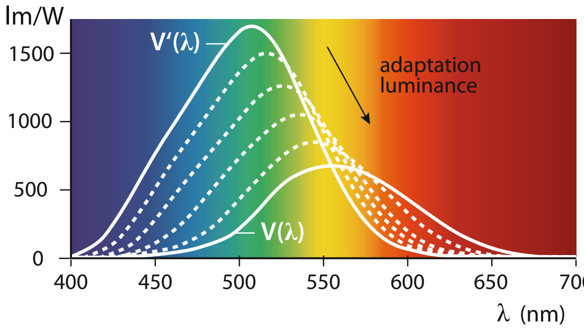


Fig. 6.2 Spectral luminous efficacy curves for scotopic, V′(λ), photopic, V(λ) and mesopic vision Vmes(λ) (broken lines). Maximum of V(λ) is 683 lm/W, of V′(λ) is 1700 lm/W

6.2 On-Line and Off-Line Vision

Cones are concentrated on the part of the retina called the fovea. It is the area of the retina on which a sharp image is formed of the scene contained in a small 2° cone centred around the line of vision. The fovea contains no rods. Outside the fovea the number of cones diminishes very rapidly to a low and more-or-less constant number (Fig. 6.3).

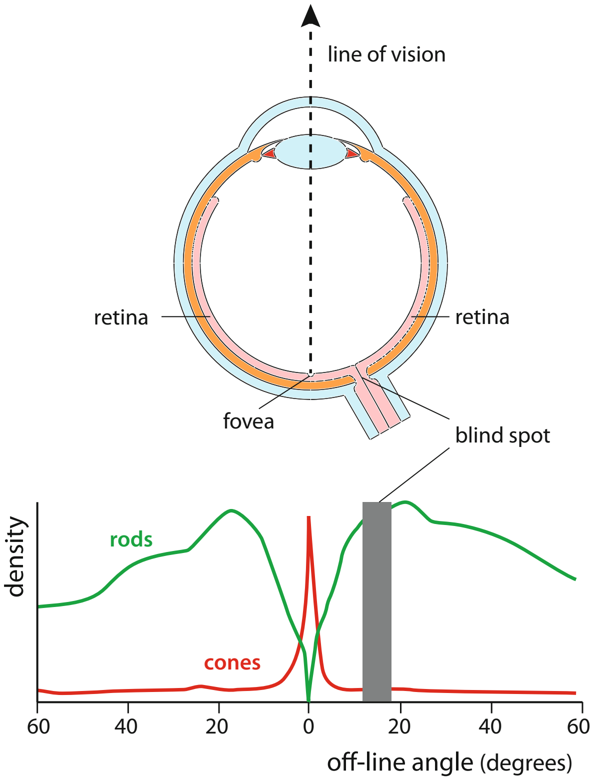
So, for "central" or "on-line" vision (also-called foveal vision), only cones are used. The V(λ) curve provides the prediction of on-line performance, and for this aspect of vision the normal photopic light units should be used, also for mesopic lighting levels (CIE 2010).[3]

The field of view of foveal vision is small, only 2°. Nevertheless, we experience a sharp image, in colour, of a much larger area. This is because our eyes, subconsciously, shift their gaze continuously towards different fixation points in the scene. Part of these fixation-point changes, called saccades, are stepwise and take a very short time: between 0.04 and 0.2 s. The duration of a fixation subsequently takes around 0.25 s. During each saccadic movement, image forming is suppressed so that, contrary to the case of a fast moving camera, no blurred or smeared image is obtained. Through these eye movements many different sharp foveal images are composed by the brain into one sharp picture of a larger area than the 2° field (Fig. 6.4).

The concentration of rods increases on the outer (peripheral) area of the retina, while the concentration of the cones decreases. The maximum concentration of rods is at about 15° from the direction of view (Fig. 6.3). Rods are thus important for "off-line" or "peripheral" vision. Cones at the fovea all have individual nerve connections into the brain so that sharp images are formed (Fig. 6.5). Most rods, however, are

[3] Visual performance tests under foveal mesopic viewing conditions give conflicting results. Some show a positive effect for cool-white light (Fotios et al. 2005; Fotios and Cheal 2007; Szabó et al. 2010), while some others show a positive effect for warm-white light (Bisketzis et al. 2009; Fotios and Cheal 2011). Others show no specific spectral effect (Kebomaki et al. 2003; Alferdinck and Hogervorst 2013). It may be expected that there exists some interaction between rods and the three different types of cones that influences foveal mesopic vision (Ripamonti et al. 2009).

Fig. 6.3 Density of cones and rods on the retina of the eye



interconnected so that the brain signal loses information as from where the signal originates and consequently the peripheral image formed is not sharp but blurred.[4]

6.3 S/P Ratio of Light Sources

In order to quantify the effect of the spectrum of a light source on peripheral vision in the mesopic luminance range, we have to characterise the proportions of the spectrum of the light source in the $V(\lambda)$ and $V'(\lambda)$ areas respectively. The so-called S/P ratio has shown to be a suitable measure for this. It is the ratio between the scotopic-weighted spectrum, according to $V'(\lambda)$, and the photopic-weighted spectrum, according to $V(\lambda)$. The S/P ratio can easily be calculated from the spectrum of the light source. As an example, let us take a theoretical monochromatic light source with wavelength of 500 nm. From Fig. 6.1 we see that the relative scotopic $V'(\lambda)$ value for this

[4] The eye has 126 million rods and cones but only 1 million nerve fibres. In the far periphery of the retina some hundreds of rods are connected to a single nerve fibre (Tovée 1996).

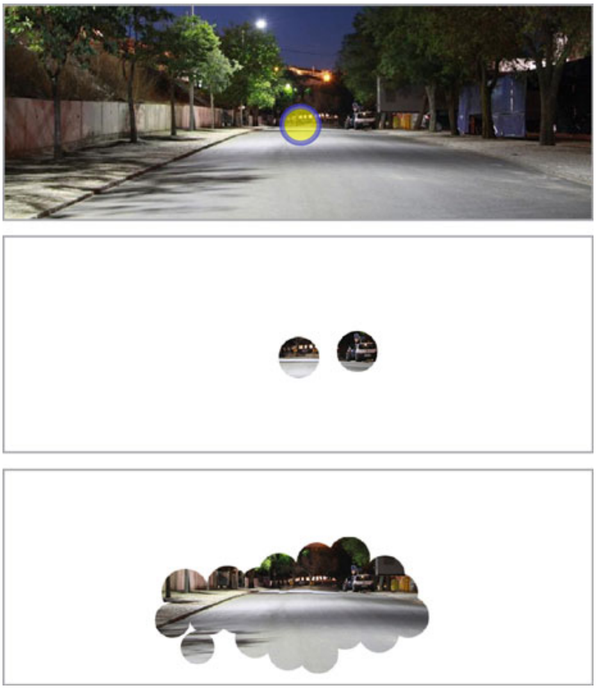


Fig. 6.4 Sharp 2° field of view superimposed on a road-lighting scene and composition of a larger, sharp image obtained by scanning different foveal images through subconscious saccadic eye movements. Note in the middle picture that during a saccadic movement, image forming is suppressed so that no blurred image is formed

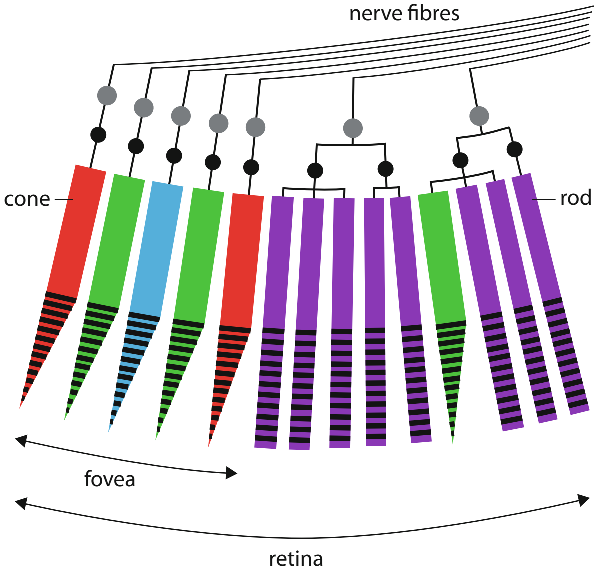


Fig. 6.5 Schematic illustration of nerve-fibre connections between the brain and cones at the fovea and rods at the peripheral part of the retina

Table 6.1 Approximate S/P ratios for different light sources

Light source	S/P ratio
Yellow low pressure sodium	0.25
Yellow-white high pressure sodium	0.65
Warm-white metal halide	1.25
Warm-white LED	1.3
Cool-white metal halide	1.8
Blue-rich white LED	2.15

wavelength is 0.99 and that the relative photopic V(λ) value is 0.30. To convert these relative values into absolute values they have to be multiplied by the maximum eye sensitivity of scotopic (1700) and photopic (683) vision, respectively. Thus, in this example the S/P value equals:

$$(0.99 * 1700)\big/(0.30 * 683) = 8.2.$$

For non-monochromatic light this procedure has to be followed for all wavelengths contained by the light source in question. Many lamp manufacturers give the S/P ratio of their lamps as part of the lamp data. Table 6.1 gives typical S/P values for different light sources used in road lighting. As can be seen, warm-white light sources have relatively low S/P ratio values and blue-white light sources have high values.

6.4 Adaptation Luminance

Under road-lighting conditions the luminance in the field of view is not uniform. For reasons of simplicity, the average road-surface luminance is often, wrongly, taken as the adaptation luminance. Many other, often high-value, luminances in the visual field play a role. Think of the bright road-lighting luminaires, the headlamps of on-coming cars, luminous signs and light reflected off various surfaces. All these will increase the adaptation luminance to a value higher than the average road-surface luminance. The shift of the spectrum towards small wavelengths is therefore smaller than would be concluded from the average road-surface luminance alone. How exactly the adaptation luminance has to be determined is the subject of investigations. In particular eye-tracking instrumentation is used to study eye viewing directions and fixation points. The purpose is to determine where the adaptation field is centred, what shape it has and what size it has. A Technical Committee of CIE (CIE JTC-1 “Implementation of CIE 191 mesopic photometry in outdoor lighting”) is co-ordinating this work. Once the adaptation field is known the next step is to determine how the different luminances in that field have to be weighted. The effect of glare sources in the adaptation field can be roughly estimated by their veiling luminance (Uchida and Ohno 2013). We calculated on this basis the percentages to be added

Table 6.2 Percentages of the average road surface luminance, L_{av}, to be added to the adaptation luminance for different glare situations characterized by TI

TI (%)	$L_{av} = 0.1$ cd/m^2	$L_{av} = 0.5$ cd/m^2	$L_{av} = 1$ cd/m^2
10	24 (%)	18 (%)	15 (%)
15	37 (%)	26 (%)	23 (%)

to the value of the average road surface luminance for different glare situations. The results are given in Table 6.2. From this it is clear that for most road lighting situations at least some 25 % of the average road surface luminance has to be added to the actual average road surface luminance when estimating the adaptation luminance.

6.5 Correction Factors for Photometric Quantities

From the above it is clear that under mesopic vision conditions the photometric quantities for lighting level, luminance and illuminance, need to be corrected, as far as their effect on peripheral vision is concerned, in dependence of the actual adaptation state of the observer. Vision, however, is a complex phenomenon in which rods and three types of cones, a short-wavelength-sensitive cone (S-cone with maximum sensitivity in blue), a medium-wavelength-sensitive cone (M-cone with maximum in green) and a long-wavelength-sensitive cone (L-cone with maximum in red) play a role. Even the light sensitive retinal ganglion cell, discovered in 2002 (Berson et al. 2002), that plays an important role in non-visual biological effects of lighting, influences vision as well: for example in changing the pupil size. Which cells combine and how, is amongst other things dependent on the visual task being carried out and of environmental conditions. As a fundamental consequence, mesopic correction of photometric quantities is different for different tasks and different conditions. As has been shown in previous sections, for road lighting especially task performance and perceived brightness is important.

6.5.1 Peripheral Task Performance

6.5.1.1 CIE Correction Factors

CIE (2010) defined a mesopic photometry system based on peripheral task performance. What has been done to develop this system is to determine the effect of different spectra on the performance of peripheral tasks that need to be carried out under various road-lighting conditions. A huge amount of this type of research has been carried out at many different institutions in the USA (Rea and Bullough 2007), Europe (Goodman et al. 2007) and Asia (Sagawa and Takeichi 1992). This has led to two systems: the so-called American USP (Unified System of Photometry) and the

Table 6.3 Correction factors. CF_{mes}, for photopic luminance for peripheral mesopic vision for different light sources as characterised by their S/P ratio. Basis: task performance, task eccentricity 10° from the viewing line. L_{adapt} in cd/m^2. (CIE 2010)

CF_{mes}			
S/P ratio	$L_{adapt} = 0.03$	$L_{adapt} = 0.3$	$L_{adapt} = 3$
0.65	0.80	0.92	0.99
1	1.00	1.00	1.00
1.45	1.22	1.09	1.01
2.25	1.57	1.24	1.04

European MOVE (Mesopic Optimisation of Visual Efficiency) systems. The USP system is based on the measurement of reaction time to the presence of objects at different peripheral positions (He et al. 1997, 1998). The MOVE system is based on three peripheral subtasks: can a peripheral object be detected (Freiding et al. 2007), how quickly can it be detected (Walkey et al. 2007) and can it be identified (Várady et al. 2007). On the basis of these investigations and in collaboration with representatives from both research groups, the International Lighting Commission, CIE, has published a "recommended system for mesopic photometry based on visual performance" (CIE 2010). This system defines spectral efficiency functions, $V_{mes}(\lambda)$ that allow the curves of Fig. 6.2 to be calculated. The functions are of the form:

$$V_{mes}(\lambda) = m * V(\lambda) + (1 - m) * V'(\lambda)$$

where:

m = a function of the adaptation luminance and of the actual spectrum in terms of S/P ratio. For $L_{adapt} \geq 5$ cd/m^2 $m = 1$ and for $L_{adapt} \leq 0.005$ cd/m^2 $m = 0$.

The CIE report gives in its Appendix the value of m as a function of adaptation luminance and S/P ratio so that $V_{mes}(\lambda)$ can be calculated. This in turn permits, the calculation of the correction factors to be applied (for peripheral vision) to the actual road-surface luminance or illuminance for a given light-source spectrum. Luckily, there is no need to calculate $V_{mes}(\lambda)$ for each different situation, because the same CIE Publication gives the correction factors for a wide range of S/P ratio values and adaptation luminances. Table 6.3, which is a summary of the corresponding CIE Table, gives these correction factors for three different values of adaptation luminance.

For example, for peripheral vision at an adaptation luminance of 0.3 cd/m^2, light sources with an S/P ratio of 1.45 (such as metal halide lamps) are more effective than are light sources with an S/P ratio of 0.65 (such as high-pressure sodium lamps): in fact, the effectivity is a factor $1.09/0.92 = 1.18$ higher. For blue-rich white light with an S/P ratio of 2.25 (such as bluish white LEDs) the effectivity is $1.24/0.92 = 1.35$ higher. It can also be seen that at higher adaptation levels the correction becomes more or less negligible: for the same S/P examples at 3 cd/m^2, only $1.01/0.99 = 1.02$

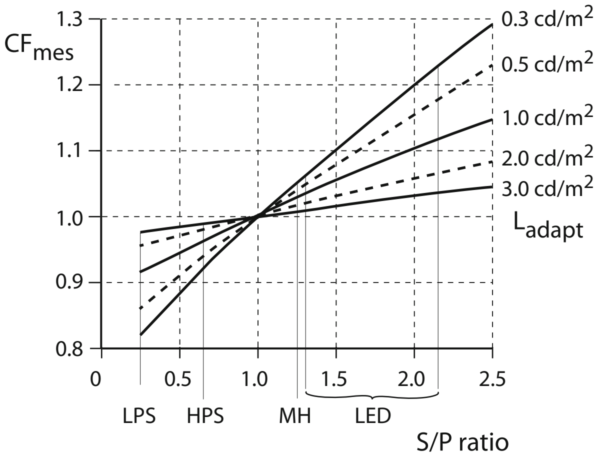


Fig. 6.6 Mesopic correction factor, CF_{mes}, for peripheral task performance in dependence of S/P ratio and adaptation luminance. Based on (CIE 2010). *LPS* low pressure sodium, *HPS* high pressure sodium, *MH* metal halide lamp

and 1.04//99 = 1.05 respectively[5]. The graphical representation of the CIE Table, as given in Fig. 6.6 gives a quick total overview of the correction factors for the range of adaptation luminances encountered in road lighting.

6.5.1.2 Consequences for Road Lighting Practice

In order to be able to put this knowledge of mesopic vision into practice, the question always has to be answered as to whether or not peripheral or foveal on-line vision is the more relevant in the actual application. Where peripheral vision is less important and foveal, on-line vision is the key aspect of the relevant visual tasks, no correction should be applied. A clear example of such an application is motorway lighting for roads with level-free crossings and safety barriers on both sides of the carriageway. For those exterior lighting installations where peripheral vision constitutes an important part of the relevant visual tasks, the correction factor for the relevant adaptation luminance as given in Table 6.3, can be applied for the actual light source spectrum used as characterized by its S/P ratio. As far as peripheral vision is concerned the lighting level can be decreased by this factor. It should be realized, however, that, as a consequence foveal on-line tasks can then be less well performed. This negative by-effect is more severe for older people. The studies that formed the basis for the CIE correction table were carried out with subjects in the age range 20–35 years.

[5] Sometimes we see that the S/P ratio itself is used as correction factor. In this example this would lead to correction factors of 1.45/0.65 and 2.25/0.65 = 3.46 and 2.23 respectively. This is misleading and wrong: the correction factors are, as shown, only 1.18 and 1.35 respectively for an adaptation luminance of 0.3 cd/m^2. That already at an adaptation luminance of 3 cd/m^2 the correction factors are more or less neglectable, illustrates how wrong it is to claim corrections for light sources used in high light level applications as for example outdoor sports lighting.

The human crystalline lens in the eye turns yellowish with age, which means that blue light is largely absorbed in the lens (see Chap. 7 "Age effects"). This implies that the mesopic advantages of blue-rich light, as described above, are smaller for older drivers.

The method for determining the actual adaptation luminance in a non-uniform environment has not yet been defined and standardized. As has been discussed in Sect. 6.4 it is recommended that at least 25 % of the average road-surface luminance be added to the actual average road-surface luminance when estimating the adaptation luminance.

6.5.2 *Brightness*

6.5.2.1 Models for Brightness Prediction

It has been mentioned in Chap. 5 that quite a few investigations have shown that the spectrum of a light source also influences the subjective impression of brightness (Morante 2008; Rea et al. 2009; Knight 2010; Schäfer et al 2010; Fotios and Cheal 2011). This is not a specific property of mesopic vision, but holds true for both mesopic and photopic vision. In the mesopic vision range, light sources with a relatively large proportion of light emission at short wavelengths viz. with high colour temperatures and S/P ratios, produce higher brightnesses for the same illuminance. CIE (2011) developed a "supplementary photometric system" with which light sources or lighted objects can be evaluated in terms of comparative brightness[6]. Other models based on the possible interactions of the different types of light sensitive cells are being discussed (Fotios and Cheal 2011; Rea et al. 2011; Bullough et al. 2014). Fotios and Cheal (2011) tested the brightness prediction of different models against brightness assessments made for those lamps, typically used in road lighting. The lamps were compared in two side-by-side booths. The reference luminance was 0.25 cd/m^2. Not surprisingly, the CIE supplementary system for brightness evaluation showed a good prediction (correlation coefficient $R^2 = 0.89$). Interestingly enough, also the CIE system described in the previous section, developed for mesopic task performance, was also tested. It showed a good prediction with a only slightly lower correlation coefficient of $R^2 = 0.86$.

6.5.2.2 Consequences for Road Lighting Practice

For practical reasons of having to use only one system for road lighting, the proposal is that the same CIE system be used for both peripheral task performance and brightness

[6] The photopic and scotopic luminance together with the chromaticity coordinates x and y (as also used to position lights in the colour triangle) are the quantities used.

prediction: namely the recommended system of mesopic photometry based on task performance (Fotios and Cheal 2011; Fotios and Goodman 2012; CIE 2014). Further testing at reference luminances higher than 0.25 cd/m^2 would serve to strengthen this recommendation. In practice, the recommendation means that the correction factors, given in the CIE 2010 Publication, and summarized in Table 6.3 and Fig. 6.6 can be applied for both peripheral task performance and brightness prediction.

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Chapter 7
Age Effects

Abstract Several-age related changes occur in the optics of the eye, which in turn deteriorate vision. Neurological age-related changes in the efficiency of converting light into neural signals and in their transport towards the visual cortex in the brain also have a deteriorating effect on vision. The neurological changes only have negative effects after the age of about 60. The optical changes, however, have already negative consequences much earlier. The maximum pupil diameter decreases with age, so reducing the total amount of light reaching the retina. Yellowing of the eye lens, which already starts before the age of 20, especially reduces the blue part of the light reaching the retina. The combined effect of pupil size reduction and lens yellowing may reduce the light reaching the retina of a 65-year-old person to less than 30 %. The effect of these age-related changes are demonstrated with the aid of revealing power values obtained with 30, 50 and 65-year-old motorists.

7.1 Age and the Visual Mechanism

Most of the investigations on road lighting, including those described in this book, are carried out with relatively young test persons (often in the age group 20–30 years). With increasing age, vision deteriorates. Here we will go deeper into the causes of this deterioration.

With increasing age, changes occur in the optics of the eye, in the conversion efficiency of the cones and rods, and in the neurological pathway into the brain. The last two factors, especially, have negative consequences after the age of 60 years. The optical changes in the eye have clear negative consequences even before reaching the age of 60. The reduction with age of eye-lens transparency, eyeball transparency (clouding), lens yellowing and smaller pupil size variation due to loss of elasticity, all have negative consequences for the amount of light reaching the retina. For example, Table 7.1 gives the maximum size of the pupil, at mesopic light levels, of 50 and 65-year-old persons relative to the pupil size of a 25-year-old person. The effect is also illustrated in Fig. 7.1 with photographs of the eye of a 24-year-old person (left) and of a 66 year old under the same lighting conditions. The gradual reduction of pupil size stabilizes after 60 years (Nakamura et al. 2009).

The crystalline eye lens gradually loses elasticity and yellows with age and its curvature may change. The loss of elasticity and change of curvature makes focussing

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Table 7.1 Relative maximum pupil size. (Nakamura et al. 2009; Weale 1992)

Age	Pupil size (%)
25	100
50	65
65	55

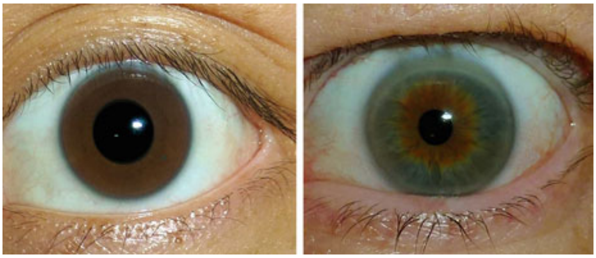

Fig. 7.1 The eye of a 24-year-old (*left*) and of a 66-year-old person showing the great difference in pupil size. (Photographs taken under the same lighting conditions)

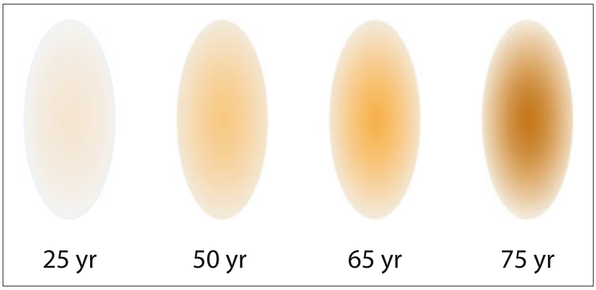

Fig. 7.2 Illustration of the yellowing of the crystalline eye lens with age

on nearby objects more difficult (presbyopia). It can be compensated for by the use of reading glasses or lenses. Bifocal or multifocal spectacles can also be employed. Normally, presbyopia does not result in real problems for motorists in carrying out their visual tasks. However, the gradual yellowing of the eye lens illustrated in Fig. 7.2 reduces its transmittance and so reduces the amount of light reaching the retina. The figure shows that the yellowing process has already started in the 25-year old lens.

Most of the yellow, green and red light can pass through a yellow lens, but blue light (which in the spectrum is farthest away from yellow) is largely absorbed. Figure 7.3, which gives the transmittance of the lens according to wavelength, shows that the yellowing of the lens indeed reduces the transmittance, especially in the blue part of the spectrum. This effect of the yellowing of the eye lens is called the “blue light loss effect”.

Light sources with a relatively large part of their output in the blue region of the spectrum (cool-white light sources) are less effective for older people. This is because only a small part of the blue light reaches their retina. Table 7.2 gives the transmittance, calculated from the curves of Fig. 7.3, for a typical warm-white phosphor LED of 2700 K and of a cooler-white phosphor LED of 4000 K for 50 and 65 year old persons relative to that for a 25 year old.

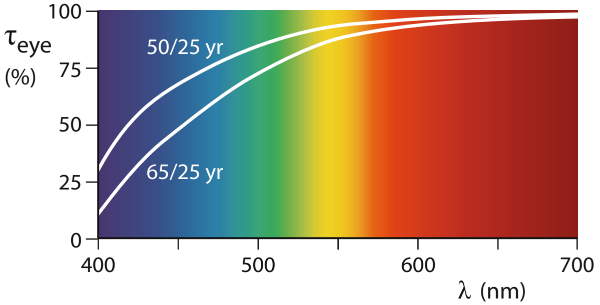

Fig. 7.3 Transmission of the human eye, τ_{eye}, for a 50 and 65-year old relative to that for a 25-year-old. (Based on Van De Kraats and Van Norren 2007; CIE 2012)

The combined effect of reduced pupil size and reduced transmittance of the eye is given in Table 7.3. The light on the retina for 50–65 year-old persons is reduced to 43–28 %. As a comparison: normal sun glasses fall in the transmittance range of 30–45 %.

The effects are illustrated in Fig. 7.4 where the same view is shown as "seen" through the eyes of a 25 and a 65-year old person.

Eventually, the mechanisms causing lens yellowing usually lead to cataract (as, for example, the lens of the 75-year old in Fig. 7.2). With relatively simple surgery, the crystalline lens can then be replaced by an artificial one, a so-called intraocular lens (IOL). There is a great debate going on as to whether that artificial lens should be chosen such that it transmits all visible light equally or that it should absorb some part of the blue light by the use of a so-called blue-block lens (Henderson and Grimes 2010). Blue-block lenses have spectral transmittances similar to the crystalline lens of a person of around 50-years, meaning that full transmittance does not return. The dispute relates on the one side to the, as yet, unproved hypothesis that retinal damage due to life-long exposure to blue light increases the risk of age-related macular degeneration (AMD), leading to loss of vision in the centre of the visual field. The yellowing of the crystalline lens is by the supporters of this theory seen as a natural protection of the retina against prolonged energy-rich blue light. On the other side, some scientists not supporting this hypothesis point to the benefits of a clear lens for visual and especially for non-visual biological effects of light via the ipRGC light-sensitive cells in the retina These cells, discovered only recently (Berson et al. 2002) have a high sensitivity for short-wavelength light viz. blue light. They are important as regards circadian and neuro-behavioral regulation (Lucas et al. 2013).

Table 7.2 Transmission of warm-white and cool-white LED light through eye lenses of 50 and 65-year-old persons relative to that of a 25-year old lens

	Transmission relative to 25 year old (%)	
Age	Warm-white LED 2700 K S/P ratio: 1.28	Cool-white LED 4000 K S/P ratio: 1.47
50	66	55
65	62	51

Table 7.3 Combined effect of reduced pupil size and reduced eye transmission on light reaching the retina

	Transmission relative to 25 year old (%)	
Age	Warm-white LED 2700 K S/P ratio: 1.28	Cool-white LED 4000 K S/P ratio: 1.47
50	43	36
65	34	28

Fig. 7.4 The same photograph shown with different filters applied according to the transmittance of the eye for a 25 and a 65 year-old observer

If one wants to compensate for the deterioration effects of vision for the elderly by providing more light, one has to bear in mind that because of lens clouding, the elderly are more sensitive to glare. The scattering of light in the eye lens and eyeball, which is to a great extent responsible for disturbing glare, can be expressed in terms

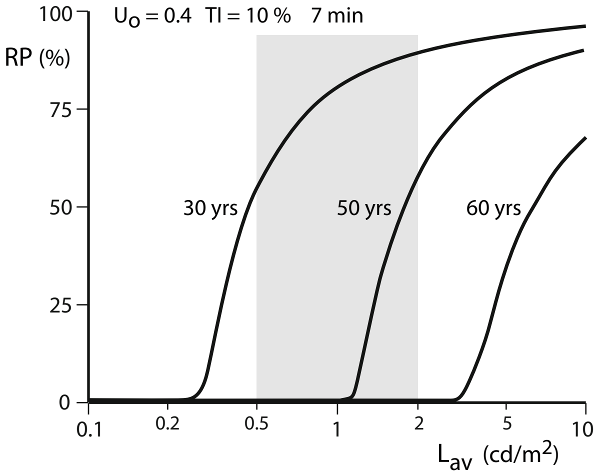

Fig. 7.5 Revealing power (*RP*) of cloth targets at the darkest location on the road as a function of the average road-surface luminance (L_{av}) for $U_o = 0.4$ and $TI = 10\,\%$. Visual angle 7′ (20 × 20 cm at 100 m, the safe stopping distance at a speed of 100–120 km/h). Age 30, 50 and 60 year

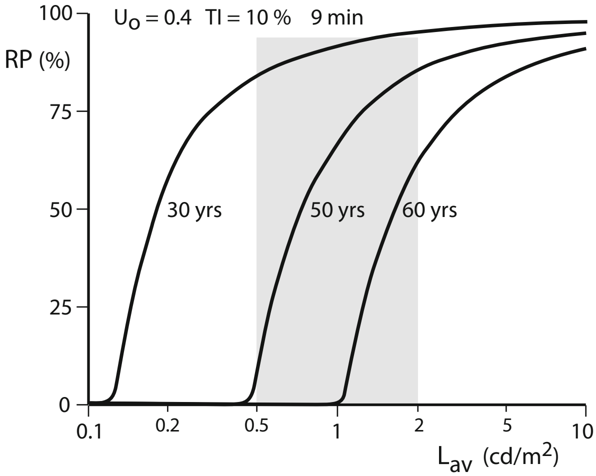

Fig. 7.6 Revealing power (*RP*) of cloth targets at the darkest location on the road as a function of the average road-surface luminance (L_{av}) for $U_o = 0.4$ and $TI = 10\,\%$. Visual angle 9′ (20 × 20 cm at 75 m, the safe stopping distance at a speed of 80–90 km/h). Age 30, 50 and 60 year

of the veiling luminance. Under the same lighting conditions, the veiling luminance of a 50-year-old is a factor 1.3 times higher than that of a 23-year-old. For 60-year-old the factor is 1.6 and for 70-year-old 2.2 (Fisher and Christie 1965; CIE 2000). So, from all this, it is evident that it is important that special attention be paid to proper glare restriction for the elderly.

A general remark has to be made: ageing effects of the visual system vary considerably between individuals. For example, some people have to undergo a cataract surgery in their early 50s, while some others do need it until much later, when they sometimes are still even able to read without spectacles.

7.2 Age and Visual Performance

In Chap. 3, Sect. 3.2.1 revealing power has been used to show the influence of the lighting parameters average road-surface luminance, L_{av}, uniformity, U_o and glare restriction, TI, on visual performance for 30-year-old motorists (7 minute object). The dramatic effect of age becomes clear from Fig. 7.5 where the revealing-power curve, for good uniformity and glare restriction, of a 30-year-old person is given together with the curves obtained for a 50 and 60-year old person. The age effects are calculated from Adrian's model discussed in Chap. 3 (Adrian 1989). At 1 cd/m^2 for both the 50 and 60 years age groups the revealing power value is zero—which advocates that motorists in these age groups should slow down.

At lower driving speeds, the safe stopping distance is shorter. From that shorter distance a same object is seen at a larger visual angle, thus increasing visibility. To illustrate this effect, Fig. 7.6 gives the revealing power results, again for good uniformity and glare restriction, for an object seen under an angle of 9 minute. This corresponds to a 20 $\times$ 20 cm object seen from a distance of 75 m (safe car stopping distance at a driving speed of 80–90 km/h). At a lighting level of 1 cd/m^2 both the age groups of 30 and 50 years get a high enough revealing power value. However, the age group of 60 years requires a lighting level of 2 cd/m^2 for an only moderate revealing power value.

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Chapter 8
Lighting Quality Parameters

Abstract The quality of a road-lighting installation is expressed in terms of photometric criteria that influence both visual performance and visual comfort. There are two different categories of quality parameters: parameters using solely photometric units and parameters using performance metrics. Examples of the latter category are revealing power, visibility level, small-target visibility and facial identification. A short discussion regarding which category is most suitable for use in road-lighting specification and design is given in this chapter. The exact photometric parameters used in specifying, designing and measuring road-lighting installations will be defined. For lighting installations designed mainly to suit the needs of motorized traffic, these parameters are: average road-surface luminance, overall and longitudinal uniformity, surround ratio, and threshold increment. For the needs of pedestrians, cyclists and residents the parameters are: average horizontal and minimum illuminance together with a maximum value of horizontal illuminance, semi-cylindrical and average facade illuminance. Lighting parameters for the specification of the spectrum of light sources, so far as they are relevant to road lighting, will be defined in the last section of this chapter.

For specification and design purposes, the quality of a lighting installation needs to be expressed in terms of values for quality parameters. There are two fundamentally different categories of quality parameters:

- parameters based solely on photometric units, such as lighting level, uniformity and glare restriction,
- parameters based on task-performance metrics, such as revealing power, visibility index, small-target visibility and facial identification.

The first category depends only on lighting-installation aspects. The road surface is here considered as part of the lighting installation. The second category, however, depends on a combination of lighting-installation and non-lighting-installation aspects such as type of target (size, shape, reflectance etc.), type of maneuver to be supported (keeping distance, reacting to position changes of other cars, cycles and pedestrians etc.). A performance metric can only serve one or a limited number of visual-task aspects and therefore ignores the others. Performance metrics also ignore the importance of visual-comfort aspects. This may lead to wrong conclusions as far as the overall quality of the road-lighting installation is concerned. Road lighting

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providing good quality for one aspect may result in bad quality for another. Performance metrics, of course, cannot be a basis for measurement after completion of a lighting installation, for commissioning, or for maintenance reasons. Bremond (2007) proposes four separate levels in developing quality indexes for road-lighting installations: a functional one (e.g. road safety or personal security), a task one (e.g. small-target detection or facial recognition), a modelling one (relating the relevant task to vision science data) and an operational one (method to define actual quality indexes that can be measured). From a fundamental point of view this makes sense, but it is not practical to repeat this process for each new situation encountered in daily practice.

We consider it best and most practical to base the quality of road-lighting installations on pure photometric units. Careful consideration of the influence of different values of these photometric parameters on the relevant performance metrics for a given situation, should then be the basis for defining specifications. The findings of investigations discussed in the earlier chapters of this book may form a guidance for this.

There are often different solutions fulfilling the same specifications. The final choice of solution may then be determined by cost and environmental (including energy consumption) considerations. In such situation, a clearly-relevant performance metric for that situation may be used as an additional consideration for choosing the final solution.

In the following sections of this chapter, the photometric parameters used in specifying, designing and measuring road-lighting installations will be defined for both motorized traffic and for pedestrians, cyclists and residents. The CIE Recommendations are here taken as the basis (CIE 2010). Some national or regional standards deviate slightly from these basic criteria. Where relevant, such deviations will be dealt with in Chap. 9: “Standards and Recommendations”.

8.1 Motorized Traffic

8.1.1 Lighting Level

The lighting quality parameter employed for lighting level is the average luminance of the road surface between 60 and 160 m in front of the driver. The area of road up to some 160 m is the background area against which objects must be detected for most driving speeds. The area between 0 and 60 m is not so much the “responsibility” of the fixed road lighting, since it is easily covered by the vehicle’s own headlights. The area between some 60 and 160 m also determines to a great extent the adaptation state of the motorist’s eyes.

The lateral position of the driver for determining the average road-surface luminance is typically taken at one quarter of the carriageway width from the near-side kerb. The symbol used for average road-surface luminance is L_{av}.

8.1.2 Uniformity

In the case of a luminance pattern on the road in which there is a large difference between the luminance value of the darkest part and the value of the average road-surface luminance, it may become difficult to detect objects against that darkest part because the eye adapts itself to the higher average luminance. It is for this reason that the concept of overall luminance uniformity has been introduced. This is defined as the ratio of the minimum to the average road-surface luminance, L_{min}/L_{av}. It is immaterial where on the road the minimum luminance is located, because a motorist needs to be able to see objects at all possible points all over the road. The symbol used for overall uniformity is U_o. For the determination of U_o, the lateral position of the driver is mostly taken as being one quarter of the carriageway width from the near-side kerb.

A continuous sequence of bright and dark spots on the road in front of a driver can be extremely discomforting. This discomfort aspect of a road-lighting installation can be limited by specifying a minimum value for the longitudinal uniformity. This is defined as the ratio of the minimum to the maximum road-surface luminance on a lengthwise line parallel to the road axis $(L_{min}/L_{max})_{length}$. The symbol used is U_l. Apart from the actual luminance difference, it is also the rate of change of this difference that plays a role. The slower this rate, the less is the problem with the non-uniformity. With greater luminaire spacings the rate of change is lower, which means that somewhat lower values of U_l can be tolerated.

8.1.3 Lighting of the Surrounds

We have seen that concentrating all the light on the road surface alone and keeping the surrounds in the dark, makes it difficult to see objects at the side of the road or on the pavement. Moreover, the visibility of the surrounds is important in being able to judge the course of the road ahead. In order to ensure that the cut-off of light at the kerbside is not too sharp, the lighting quality parameter of surround ratio (SR) has been introduced. This is defined as the ratio of the average horizontal illuminance on 5 m strips adjacent to the left and right-hand sides of the road to the average illuminance on 5 m strips on the left and right-hand sides of the road itself (Fig. 8.1):

$$SR = \frac{E_{surround\ (right+left)}}{E_{road\ (right+left)}}$$

In this definition the illuminances on the left and right-hand adjacent strips together make up the average. In cases where one of these two strips has a high lighting level and the other one a really-low level, the average can be relatively high. Consequently, the SR value will be high as well, although visibility against the darker adjacent strip is not good. Therefore, in the European Standard for road lighting, a different parameter is used (CEN 2013). This is called the edge-illuminance ratio (EIR). It is defined separately for the left and for the right hand site of the road. Each of the

Fig. 8.1 Principle of surround ratio (SR) and edge illuminance ratio (EIR). For illustrative reasons, the right-hand side only is shown

separate values must satisfy this requirement. In EIR the width of the strips is not the standard 5 m but is equal to the width of one driving lane.

$$EIR_{right} = \frac{E_{surround\ (right)}}{E_{road\ (right)}}$$

$$EIR_{left} = \frac{E_{surround\ (left)}}{E_{road\ (left)}}$$

8.1.4 Glare Restriction

As we have seen, glare can take either of two forms: disability glare or discomfort glare. In most standards and recommendations for road lighting only a requirement for the limitation of disability glare is given. It is considered that with good restriction of disability glare, discomfort glare will usually be acceptable as well. As has been shown in Sect. 3.1.3.1, the final disability effect is dependent on the combination of equivalent veiling luminance and average road-surface luminance. The overall measure for the degree of disability glare, called threshold increment (TI, in per cent) is given by the relationship:

$$TI = 65 * \frac{L_{veil}}{L_{av}^{0.8}}$$

8.1.5 Summary

Table 8.1 lists the lighting quality parameters for road lighting for motorized traffic.

Table 8.1 Lighting quality parameters for road lighting for motorized traffic

Aspect	Lighting quality parameter	Abbreviation
Lighting level	Average road-surface luminance	L_{av}
Uniformity	Overall uniformity Longitudinal uniformity	U_o U_l
Surround lighting	Surround ratio	SR or EIR
Glare restriction	Threshold increment	TI

8.2 Pedestrians, Cyclists and Residents

8.2.1 Lighting Level

For lighting level , the average horizontal illuminance $E_{hor,av}$ is used in conjunction with the value of the local minimum horizontal illuminance $E_{hor,min}$. The requirement of average horizontal illuminance should guarantee a sufficiently high adaptation level, and consequently sufficient sensitivity for contrast seeing. The local minimum horizontal illuminance should ensure safe movement by providing good visibility of obstacles at all locations in the path of the pedestrians (and cyclists).[1]

For areas where the lighting should also deter crime, the minimum semi-cylindrical illuminance, $E_{semi\text{-}cyl,\ min}$, at face height (standardized as 1.5 m) is added as an extra quality criterion.[2] Sometimes, the minimum vertical illuminance at face height is used as an alternative for the semi-cylindrical illuminance.

8.2.2 Uniformity

For lighting level both the average and the minimum horizontal illuminance are used. But a separate requirement for uniformity is needed as well. A high level of average horizontal illuminance combined with a low value of local minimum illuminance, just fulfilling its requirement, could result in a situation where objects in the dark zone become invisible. This because the eyes adapt to the very high lighting level given by the high average horizontal illuminance. The criterion usually used to provide for uniformity is a maximum value for the average horizontal illuminance.

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[1] In some countries the hemispherical illuminance at ground level, explained in Chap. 2, "Basic lighting parameters", is used as an alternative for the horizontal illuminance.

[2] Using the average semi-cylindrical illuminance as a lighting quality parameter, as is sometimes wrongly done, has no sense at all. This is because the fact that at one area of the street the recognition is very good does not help recognition at areas where recognition is very poor. The only correct parameter for guaranteeing recognition at all positions in the street is therefore indeed the absolute minimum semi-cylindrical illuminance.

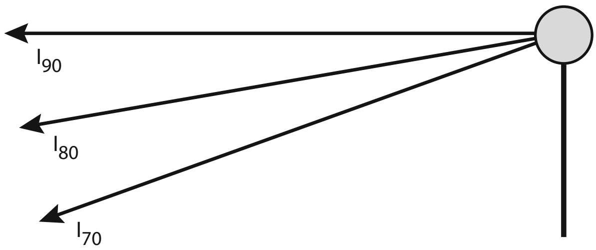

Fig. 8.2 Basis for the G classification system for the glare restriction of luminaires employed in residential areas

8.2.3 Lighting of the Surrounds

For lighting of the surrounds, the lighting quality parameter is the vertical illuminance at the positions of those planes that need to be sufficiently bright. These are usually the facades of houses near to the path of the pedestrian or cyclist. Sometimes, the average vertical plane illuminance, $E_{plane,av}$ (or $E_{facade,av}$), is used as the lighting quality parameter, and sometimes the absolute minimum plane illuminance, $E_{plane,min}$ (or $E_{facade,min}$).

8.2.4 Glare Restriction

The concept of threshold increment (TI) used for the restriction of glare for motorized traffic can also be used for the same purpose for cyclists and pedestrians in those situations where they can be expected to have defined viewing directions along the street and/or along the pavement. Where viewing directions are more random (e.g. directly into bright luminaires), a different concept is needed. A limitation of the luminous intensities of the luminaires in critical directions can limit discomfort glare under these conditions. As a criterion, the maximum luminous intensities at angles of elevation of 70°, 80° and 90° is therefore sometimes used (Fig. 8.2):

$$I_{\max\ at\ 70^\circ} \text{ and } I_{\max\ at\ 80^\circ} \text{ and } I_{\max\ at\ 90^\circ}$$

CIE defined so-called luminaire "luminous intensity classes" (G1 to G6) on the basis of these intensities. The exact classes are given in Chap. 11, Table 11.2.

The discomfort effect of a road-lighting luminaire is in fact not only dependent on its luminous intensities but also on the light-emitting area of the luminaire. A lighting quality parameter that takes into account both the luminous intensity and the bright-area effect is the luminaire glare index. This has already been defined in Sect. 5.2.3 as:

$$luminaire\ glare\ index = \frac{I_{85}}{A^{0.5}}$$

Table 8.2 Lighting quality parameters for road lighting for pedestrians, cyclists and residents

Aspect	Lighting quality parameter	Abbreviation
Lighting level	Average horizontal illuminance And Minimum horizontal illuminance for crime deterrence: Minimum semi-cylindrical illuminance	$E_{hor,av}$ $E_{hor,min}$ $E_{semi\text{-}cyl,min}$
Uniformity	Average horizontal illuminance (maximum value)	$E_{hor,av}$,
Surround lighting	Average or minimum plane of façade illuminance	$E_{plane,min}$ or $E_{plane,av}$
Glare restriction	Threshold increment And/or Luminous intensity restriction at 70°, 80° and 90° Or Luminaire glare index	TI $I_{max,70}$, $I_{max,80}$, $I_{max,90}$ $I_{85}/A^{0.5}$

Table 8.3 Parameters for the colour aspects of light sources used for road lighting

Aspect	Parameter	Abbreviation
Colour appearance	Correlated colour temperature	T_k
Colour rendering	Colour rendering index	R_a
Mesopic vision	Scotopic-photopic ratio	S/P ratio

8.2.5 Summary

Table 8.2 lists the lighting quality parameters for road lighting for pedestrians, cyclists and residents.

8.3 Spectrum of Light

Three different aspects of the spectrum of light have to be distinguished in the context of road lighting: the colour appearance of the light, the colour rendering properties of the light, and the effects of the light spectrum on mesopic vision. Table 8.3 lists these aspects together with the relevant parameters. Some studies suggests that other characteristics for the light spectrum than T_k, R_a and S/P ratio are needed to better predict the effect of the spectrum on the different aspects of vision (Fotios and Cheal 2007, 2011; Lin et al. 2014) .

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Chapter 9
Standards and Recommendations

Abstract Many of the findings of the investigations described in the previous Chapters are seen reflected in standards and recommendations for road lighting. In this Chapter, first the recommendations of the international lighting commission, CIE, will be summarized. They concern lighting of motorized-traffic routes, lighting of traffic conflict areas, lighting for pedestrians and low-speed traffic, the spectrum of light, and lighting that adapts itself to different circumstances. The CIE recommendations form the basis for many national or regional standards for road lighting in many parts of the world. As an example of one of the latter, the European Standard for Road lighting produced by the European Committee for Standardization (CEN) will be described. In North America the primary standard is produced by the Illuminating Society of North America, IESNA, and approved by the American National Standard Institute, ANSI. Where in the past this standard was, on some points, clearly different from the CIE approach, we see today that it is moving much in the same direction, as will be described in the last part of this Chapter.

All values specified in the Standards and Recommendations dealt with in this Chapter concern maintained values. These are lighting values that need to be met during the entire life of an installation. The design value of the new installation needs to be determined by taking into account an appropriate maintenance factor to allow for depreciation of lamp and luminaire (see Sect. 13.5 "Maintenance").

The focus in this Chapter is on the methods that the various standards and recommendations use for specifying road lighting. For copyright reasons, Tables of these Standards and Recommendations are reproduced only in part.

9.1 CIE Recommendation

This recommendation was published in 2010 as CIE Publication 115:2010 "Lighting of roads for motor and pedestrian traffic". For motorized traffic it adapts the luminance approach of road lighting and uses the lighting quality parameters already listed in Table 8.1 of the previous Chapter. For the lighting for pedestrians and low-speed traffic, the parameters listed in Table 8.2 of that same Chapter are used.

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Table 9.1 CIE lighting classes for motorized traffic and corresponding (maintained) values of the various lighting criteria (CIE 2010)

	L_{av}(cd/m^2)	U_o	U_l	TI (%)	SR
M1	2.0	0.40	0.70	10	0.5
M3	1.0	0.40	0.60	15	0.5
M6	0.30	0.35	0.40	20	0.5

9.1.1 Lighting of Motorized-Traffic Routes

The basis of the recommendation is formed by six lighting classes: M1 to M6 ("M" stands for motorized traffic). For each lighting class, values for the criteria: lighting level, L_{av} uniformity, U_o and U_l, glare restriction, TI, and surround ratio, SR, are specified. Table 9.1 gives the specified values for the highest, an intermediate and the lowest class, M1, M3 and M6 respectively. As can be seen from the Table, the lower the class number the higher the lighting quality required. The lighting levels range from 2.0 to 0.3 cd/m^2 from class M1 to M6.

Which lighting class is applicable in a certain situation is dependent on the following factors:

- difficulty of the geometry of the road in terms of separation of carriageways and of intersection density,
- traffic characteristics in terms of speed, traffic volume, traffic composition, possibility of parked vehicles,
- average brightness of the area (ambient luminance),
- quality of visual guidance and traffic-control signaling.

To determine the lighting class applicable according to these factors, CIE gives different weighting values, V_w, for all of these factors. Table 9.2 shows some of these values. The sum of all weighting values, V_{ws}, determines the number of lighting class M according to:

$$M = 6 - V_{ws}$$

Example Consider, for example, a main road with high-speed traffic ($V_w = 0.5$) and a high traffic volume ($V_w = 0.5$) of mixed traffic only ($V_w = 1$) with non-separated carriageways ($V_w = 1$) and a high intersection density ($V_w = 1$), no parked vehicles on the road allowed ($V_w = 0$), a dark environment, viz. low ambient luminance ($V_w = -1$) and good visual guidance/traffic control ($V_w = 0$). The sum of all weighting values, V_{ws}, is: $0.5 + 0.5 + 1 + 1 + 1 + 0 - 1 + 0 = 3.0$. The lighting class for this example is therefore $M = 6 - 3 =$ M3. Table 9.1 specifies the required lighting values for this class. For example, the lighting level has to be 1 cd/m^2. If, again as an example, only motorized traffic instead of mixed traffic were to be permitted on this main road, the weighting value for traffic composition would be 0 instead of 1. Consequently, the resulting class would be M4 instead of M3, with a required lighting level of 0.75 instead of 1 cd/m^2. This, indeed, is in accordance with the less difficult visual task of the new situation.

Table 9.2 Example of parameters determining the M lighting class with their weighting value. (CIE 2010)

Parameter	Options	Weighting value V_w
Speed	High	0.5
	Moderate	0
Traffic volume	High	0.5
	Very low	– 1
Traffic composition	Mixed with high % of non-motorized	2
	Mixed	1
	Motorized only	0
Separation of carriageways	No	1
	Yes	0
Intersection density	High	1
	Moderate	0
Parked vehicles	Present	0.5
	Not present	0
Ambient luminance	High	1
	Low	– 1
Visual guidance/traffic control	Poor	0.5
	Moderate or good	0

9.1.2 Lighting of Conflict Areas

The same CIE recommendation also specifies lighting for so-called conflict areas that may occur on traffic routes where different vehicle streams intersect, where there is a change in road geometry (e.g. reduced number of lanes), or where the same road network is used by a mixture of motorized traffic and other types of traffic (pedestrians, cyclists, etc.). Again, weighting values, now specific for conflict areas, are given to determine the lighting class of the conflict area (C0 to C5). The corresponding lighting required for each conflict lighting class, C, is specified in terms of the familiar lighting criteria for level, uniformity, glare restriction and surround lighting.

For pedestrian crossings, the CIE Guide to the Lighting of Urban Areas (CIE, 2000), specifies the horizontal illuminance values of Table 9.3.

9.1.3 Lighting for Pedestrians and Low-Speed Traffic

The method of specifying lighting for these categories of road users is the same as that for the motorized traffic category dealt with in the previous Section. However,

Table 9.3 Lighting requirements for pedestrian crossings (maintained values). (CIE 2000)

	Lighting criterion	
Type of area	$E_{hor,av}$ (lux)	$E_{hor,min}$ (lux)
Commercial and industrial	30	15
Residential	20	6

The average horizontal illuminance should never be less than 1.5 times the average illuminance of the roadway on each side of the crossing

the lighting criteria and values specified are, of course, different. The basis of the recommendation is formed by six lighting classes: P1 to P6 ("P" stands for pedestrian). For each lighting class, values for the criteria: lighting level, $E_{hor,av}$ and $E_{hor,min}$, uniformity (maximum average horizontal illuminance), $E_{hor,av,max}$, and where crime deterrent is relevant $E_{vert,min}$ and $E_{semi-cyl,min}$ at face height, are specified. As an example of this, Table 9.4 gives these values for classes P1, P3 and P6. The lighting levels range from 15 to 2 lx for the average horizontal illuminance from class P1 to P6.

CIE states the requirement for uniformity as: "the actual value of the maintained average illuminance may not exceed 1.5 times the value indicated for the class". Where facial recognition is considered to be important from a crime-deterrent point of view, the minimum vertical or minimum semi-cylindrical illuminance should be used as an additional criterion to the horizontal illuminance.

Which lighting class is applicable in a certain situation is dependent on the following factors:

- the slow-speed traffic characteristics in terms of speed, traffic volume, traffic composition, possibility of parked vehicles,
- the average brightness of the area (ambient luminance).

To determine the lighting class applicable according to these factors, CIE provides different weighting values, V_w, for all of these factors. Table 9.5 shows part of them. The sum of all weighting values, V_{ws}, determines the number of lighting class P according to:

$$P = 6 - V_{ws}$$

For glare restriction, CIE Publication "Lighting of roads for motor and pedestrian traffic" (CIE 2010) refers to a number of methods in use on a national basis. The European method (amongst others mentioned there) will be given in one of the next Sections. The "CIE Guide to the lighting of urban areas" (CIE 2000), which is also still valid, uses the luminaire glare index method described in Sect. 8.2.4 for restricting discomfort glare for pedestrians, in which both the luminous intensity of the luminaires under an elevation angle of 85° and the size of the bright part of the luminaire are used (see also Fig 5.7). Table 9.6 gives the limiting values for different mounting heights.

Table 9.4 CIE lighting classes for pedestrians and low-speed traffic and corresponding (maintained) values of the various lighting criteria. (CIE 2010)

Lighting class	Lighting criteria				
	$E_{hor,av}$	$E_{hor,min}$	$E_{hor,av,max}$	$E_{vert,min}$ face height	$E_{semi-cyl,min}$ face height
	(lux)	(lux)	(lux)	(lux)	(lux)
P1	15	3.0	22.5	5.0	3.0
P3	7.5	1.5	11.2	2.5	1.5
P6	2.0	0.4	3.0	0.6	0.4

Table 9.5 Example of parameters determining the P lighting class with their relative importance given by their weighting value. (CIE 2010)

Parameter	Options	Weighting value V_w
Speed	Low	1
	Very low (walking speed)	0
Traffic volume	Very high	1
	Very low	− 1
Traffic composition	Pedestrians, cyclists and motorized traffic	2
	Pedestrians and cyclists only	1
	Pedestrians only	0
Parked vehicles	Present	0.5
	Not present	0
Ambient luminance	High	1
	Low	− 1

Table 9.6 Restriction of luminaire glare index values to restrict discomfort glare for pedestrians. (CIE 2010)

Mounting height	Luminaire glare index $I_{85}/A^{0,5}$
< 4.5 m	< 4000
> 6 m	< 7000

9.1.4 Spectrum of Light

CIE published a Technical Report on the effect of the light spectrum on the lighting of urban and pedestrian areas (CIE 2014). It allows lower lighting levels for spectra with higher S/P ratios, based on the mesopic correction factors already given in Chap. 6 “Mesopic Lighting” (Table 6.3). However, the same publication states that these lower levels are only permitted on the condition that the light source used has a colour rendering index R_a of at least 60. If high-pressure sodium lamps (S/P ratio of 0.6) are taken as the basis for which the uncorrected values apply, all lamps with higher S/P ratios (thus cooler colours) can have lower, average horizontal illuminances for all P1 to P6 classes. As an example of this, Table 9.7 gives these lower values for classes P1, P3 and P6.

Table 9.7 Values of the average horizontal illuminance (maintained) after applying mesopic correction factors of Table 6.3 in dependence of S/P ratio. Corrected values only permitted when Ra ≥ 60. Basis: high-pressure sodium lamps (S/P ratio = 0.6)

	$E_{hor,av}$ (lux)			
	S/P = 0.6	S/P = 1.0	S/P = 1.4	S/P = 2.2
Class P1	15	14.4	13.8	12.8
Class P3	7.5	7.1	6.6	5.9
Class P6	2.0	1.8	1.6	1.3

9.1.5 Adaptive Lighting

The traffic characteristics that determine the lighting quality required, as defined by the weighting values of Tables 9.2 and 9.5, may vary during the course of the evening and night, allowing for periods with reduced lighting level. The CIE recommendation explicitly mentions adaptive lighting that adapts itself to temporarily-changing circumstances such as traffic, weather and ambient lighting conditions as a possibility to significantly reduce energy consumption. If the lighting installation is designed such that the lighting level can, indeed, be adapted (dimmed), important reductions are possible. It is important to note that under such circumstances only the lighting level should be lowered, not the uniformity. Switching off individual luminaires is therefore not a possibility.

9.2 European Standard

The first European Standard for road lighting published by the European Committee for Standardization (CEN) was published in 2003. In 2014 or 2015 a completely revised version will be published. In this Section we will consider the draft version for public comment, prEN 2013, of this revised standard (CEN 2013a, b). It is based largely on the CIE system described above. Therefore only the main points of the European standard will be described here.

9.2.1 Lighting for Motorized Traffic Routes

The European system uses the same six lighting classes (M1–M6) as used by the CIE. The lighting values for each of these classes are specified in draft Standard EN 13201-2 "Road Lighting—Part 2: Performance requirements" (CEN b). The required values for the criteria L_{av}, U_o, U_l and TI are exactly the same as those required by CIE as already given in Table 9.1, but with just one exception (U_l for M6). So, the lighting level range is from 2.0 to 0.3 cd/m^2 from class M1 to M6.

For the lighting of the immediate surrounds of the carriageway the European standard uses the parameter EIR instead of SR (as already defined in Sect. 8.1.3.). The EIR range is from 0.35 to 0.30.

Which lighting class is applicable in a given situation is specified in draft CEN/TR 13201–1 "Road Lighting—Part 1: Guidelines on selection of lighting classes" (CEN 2013a). Here, too, the European system follows the system of the CIE described in the Section above. Which lighting class is applicable in a certain situation is dependent on the following factors:

- the difficulty of the geometry of the road in terms of whether there is separation of carriageways and intersection density,
- the traffic characteristics in terms of speed, traffic volume, traffic composition, possibility of there being parked vehicles,
- the average brightness of the area (ambient luminance),
- the difficulty of the navigational task.

To determine the lighting class applicable according to these factors, different weighting values, V_w, are given—just as in the CIE Publication. The factors used are largely the same as those used by CIE (see Table 9.2). Again, as in CIE, the sum of all weighting values, VWS, determines the number of lighting class M according to:

$$M = 6 - VWS.$$

9.2.2 *Lighting of Conflict Areas*

For the lighting of conflict areas on traffic routes, where different vehicle streams intersect, where there is a change in road geometry (e.g. reduced number of lanes), or where the same road network is used by a mixture of motorized traffic and other types of traffic (pedestrians, cyclists, etc.), the draft European Standard (again as in CIE) uses weighting values to determine the lighting class of the conflict area (C0–C5) (CEN 2013a). The corresponding lighting required for each conflict lighting class, C, is specified in terms of the familiar lighting criteria for level, uniformity, glare restriction and surround lighting (CEN b).

For pedestrian crossings a quantitative specification is not given. It is stated that the intention of specific pedestrian-crossing lighting is to illuminate the pedestrians themselves and to draw the attention of motorists to the presence of the crossing. The draft states that illuminance on a vertical plane should therefore be significantly higher than the horizontal illuminance at the crossing. Zones at either end of the crossing, where pedestrians wait to enter the crossing, should receive adequate illumination.

9.2.3 Lighting for Pedestrians and Low-Speed Traffic

The method of specifying lighting for these categories of road users is the same as that used for the motorized traffic category dealt with in the previous Section. But, needless to say, the criteria and lighting values specified are different. Just as for motorized traffic, the lighting classes for pedestrians and cyclists, called P1–P7, are obtained from a weighting-value table. The factors used in this table are largely the same as those used by CIE, viz.:

- travel speed (ranging from low to walking speed),
- intensity of use (ranging from busy to quiet),
- traffic composition (from a combination of pedestrians, cyclists and motorized traffic together to cyclists only),
- the presence, or otherwise, of parked vehicles,
- the ambient luminosity (from high to low),
- the need, or otherwise, for facial recognition.

The weighting values themselves differ slightly from those of CIE. Again, as in CIE, the sum of all weighting values, VWS, determines the number of the lighting class P according to:

$$P = 6 - VWS.$$

The values specified for the average and minimum illuminance for the various P classes are exactly the same as those specified by CIE (see Table 9.4).

An additional set of classes is defined to supplement the P classes for those cases where the purpose of the lighting is to also reduce crime and suppress feelings of insecurity. These additional classes are called SC classes, where SC stands for semi-cylindrical, the illuminance measure used as the criterion for these classes. The lighting values required for the SC classes range from 10 to 0.5 lx for the semi-cylindrical illuminance. Another set of additional classes is defined for situations where vertical surfaces need to be seen, as for example at street crossings. These types of additional classes are called EV classes, where EV stands for vertical illuminance. The SC and EV classes require considerably higher semi-cylindrical and vertical illuminance values, respectively, than do the corresponding classes of CIE. The range of minimum semi-cylindrical illuminance for the European SC classes goes from 50 to 0.5 lx (CIE from 3 to 0.4 lx) and for vertical illuminance from 50 to 0.5 lx (CIE from 5 to 0.6 lx). The European Standard does not give guidelines for the selection of SC or EV classes. The Standard leaves this to national level for the individual countries.

The European standard uses two different luminaire classification systems for glare restriction, namely the luminous intensity "G" classification system and the luminaire glare index "D" system (the latter taking the size of the bright area of the luminaire into account, in addition to the luminous intensity). Both systems are defined in Sect. 8.2.4. The lower the class number the higher the risk of glare or obtrusive light. Such "low-class" luminaires can only be used where the surroundings are bright and/or where a relatively large amount of glare can be tolerated.

Table 9.8 Example of adaptive lighting classes for different time periods. Based on different weighting values V_w for the parameter "traffic volume"

Parameter	Options	Description	V_w	V_w selected			
		% of maximum capacity		17:00 20:00	20:00 23:00	23:00 05:30	05:30 09:00
Traffic volume	Very high	> 45	1	1			1
	Moderate	15–45	0		0		
	Very low	< 15	− 1			− 1	
VWS sum of other parameters				3	3	3	3
VWS total sum				4	3	2	4
M = 6 − VWS				M2	M3	M4	M2

9.2.4 *Spectrum of Light*

The draft European Standard contains no specifications for the light spectrum, colour temperature or the colour rendering index of the light sources used. All lighting-level specifications of the Standard are independent of the spectrum.

9.2.5 *Adaptive Lighting*

The EN standard explicitly mentions adaptive lighting. The traffic characteristics that determine the lighting quality required, as defined by the weighting values, may vary during the course of the evening and night. This may permit of periods with reduced lighting level. The standard stresses the importance of using the weighting tables for this purpose. An illustration of this is given in Table 9.8. It is for a two lane traffic route that corresponds to an M2 lighting class, where the traffic volume is pronouncedly different at different time intervals in the evening and night. The table shows the part of the weighting table of the European standard that corresponds to the parameter "traffic volume".

The sum of the weighting values for the M2 class is 4 and is, in this example, relevant for the time intervals 17:00–20:00°h and 05:30–09:00 h. Because of the lower traffic volumes for the time intervals from 20:00 to 23:00°h (weighting factor: 0) and from 23:00 to 05:30°h (weighting factor: − 1) the M class changes for the corresponding time intervals from M2 to M3 and M4 and back to M2. According to the European standard, M2 requires a lighting level of 1.5 cd/m^2, M3 of 1.0 cd/m^2 and M4 of 0.75 cd/m^2. So if indeed the lighting installation can be switched or dimmed to these lower levels, considerable savings are possible with such an adaptable lighting system. Care should be taken that while adapting the lighting level, the uniformity values are not affected.

9.3 North American Standard

9.3.1 Lighting for Roads with Motorized Traffic

The American National Standard Practice for Roadway and Street Lighting has been revised by the Illuminating Engineering Society of North America (IESNA) and is accepted by the American National Standards Institute (ANSI) in 2014 and is published as RP-8-14 (ANSI/IES 2014). The Standard recommends the luminance design method for straight roadways and streets, and the horizontal illuminance design method for intersections and interchanges. For pedestrian areas, horizontal and vertical illuminances are the recommended design parameters. As far as small-target visibility (STV) is concerned the Standard Practice writes:

> this method is still undergoing evaluation but may be a valuable tool when comparing the expected results of two designs delivering approximately the same luminance and illuminance performance.

The criteria used for luminance and illuminance are largely the same as those of CIE, with a few minor exceptions. For lighting level the criterion is L_{av} as in CIE. For uniformity, as in CIE, two criteria are used: the ratios L_{av}/L_{min} and L_{max}/L_{min}. The ratio L_{av}/L_{min} serves the same purpose as CIE's U_o value, being the reciprocal of $U_0 = L_{min}/L_{av}$. Note that the ratio L_{max}/L_{min} contrary to CIE's U_l value, is not based on a longitudinal line along the road but on the whole road area. For glare restriction, as in the CIE, the combination of veiling luminance, L_v, and average road-surface luminance, L_{av}, are used, but in a slightly different composition. RP-8-14 uses the ratio L_v/L_{av}, which is called the veiling luminance ratio, whereas CIE uses TI, which is $65\, L_v/L_{av}^{0.8}$.

The road-lighting classes are—for roads not intended to have pedestrian or cyclist activity—directly defined in terms of Freeways (class A and B) and Expressways. The street-lighting classes for roads where pedestrians and cyclists are present are termed Major roads, Collector roads and Local roads. Here a differentiation is made between high, medium and low pedestrian activity. Table 9.9 shows, by way of example, the recommended lighting values for Freeway class A, for Major roads and for Local roads. The lighting level ranges from 1.2 to 0.3 cd/m^2. The highest lighting level specified is somewhat lower than the 2.0 cd/m^2 of CIE and EN.

The range of the uniformity ratio L_{av}/L_{min} goes from 3.0 to 6.0, corresponding to CIE's U_o values of 0.33 and 0.16 respectively. Since both CIE and EN require U_o values of 0.35 to 0.40, the American standard clearly specifies lower uniformity values.

For glare, the range of the veiling luminance ratio of 0.3 to 0.4 corresponds to TI values of 30 to 50. So the American standard permits of more glare than do CIE and EN

Table 9.9 Recommended (maintained) lighting values as specified in the American Standard RP-8 for some different classes of roadway. (ANSI/IES 2014)

Road	Lighting criterion				
	Pedestrian activity	L_{av} (cd/m^2)	L_{av}/L_{min}	L_{max}/L_{min}	L_v/L_{av}
Freeway class A		0.6	3.5	6.0	0.3
Major road	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Local road	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

9.3.2 Lighting for Intersections

As can be seen from Table 9.9, the American Standard differentiates between high, medium and low pedestrian presence. For intersections, the Standard adds specific average horizontal illuminance requirements. As an example: for intersections in major roads (34 to 18 lx), in collector roads (24 to 12 lx) and in local roads (18 to 8 lx). The value in the ranges is dependent on the type of pedestrian-conflict area (high, medium and low, respectively).

9.3.3 Lighting for Pedestrian Areas and Bikeways

The Standard addresses the lighting needs of pedestrian and bikeway areas by dividing them into three categories according to the degree of pedestrian conflict: high, medium and low. The type of conflict relates here especially to the vehicle/pedestrian interaction. The Standard states that because the visual environment may often be cluttered and detection of pedestrians is required, both the horizontal and the vertical illuminance should fulfill minimum requirements. Vertical illuminance is here defined at a height of 1.5 m in both directions parallel to the main pedestrian flow. Table 9.10 shows the recommended values for some examples of areas.

The Standard explicitly states that the recommended values do not consider areas where there is increased crime and vandalism.

Glare restriction for pedestrian and bikeway areas is not given in a specific, quantitative way. It is merely stated that glare must be restricted by paying careful attention to luminaire mounting heights, the light output of the lamps, and their photometric distribution.

Table 9.10 Recommended (maintained) lighting values as specified in the American Standard RP-8 for some examples of pedestrian and bikeway areas. (ANSI/IES 2014)

Pedestrian conflict area	Prevailing users	Lighting criterion		
		$E_{hor,av}$ (lux)	$E_{hor,av}/E_{hor,min}$	$E_{vert,av}$ (lux)
high	Vehicles and pedestrians	20	4	10
	Pedestrians	10	4	5
low	Medium density pedestrians	4	4	1
	Rural/semi-rural area	2	10	0.6

9.3.4 Pedestrian Crossings

For pedestrian crossings, lighting reference is made to a study conducted by the Federal Highway Administration (FHWA 2008) that is also described in Chap. 3.8 of this book. The conclusion of this FHWA study is summarized as follows: 20 lx at a height of 1.5 m is needed to allow drivers to detect pedestrians in pedestrian crossings in time, with the comment that where there is a possibility of glare from oncoming vehicles, where the crossing is located in an area with high ambient light levels or where it is located at a lighted intersection, higher lighting levels may be required.

9.3.5 Spectrum of Light

The Standard refers to the CIE 2011 spectral correction factors for peripheral, mesopic vision, as also described in Chap. 6 of this book (Table 6.3 and Fig. 6.6). The standard uses the term mesopic multipliers for these factors. The Standard adds that the Roadway Lighting Committee recommends that these multipliers only be used in applications for street lighting where there is a speed limit of 25 mph (40 km/h) or less and not in situations where bright light sources or surroundings significantly increase adaptation levels.

9.3.6 Adaptive Lighting

The Standard recommends that the lighting level be dimmed when the traffic volume or the expected traffic volume decreases. The Standard gives guidance by referring to CIE report 115 (CIE 2010) (see Sect. 9.1 of this chapter), Great Britain's ILP Report 27 (ILP 2005) and the AASHTO Lighting design Guide (AASHTO 2005).

References

AASHTO (2005) Roadway lighting design guide
ANSI/IES (2014) RP-8-14, American National Standard Practice for Roadway and Street Lighting
CEN (2013a) Pre-Technical Report prCEN/TR 13201-1, Road lighting—Part 1: guidelines on selection of lighting classes
CEN (2013b) Pre-Standard prEN 13201-2, Road lighting—Part 2: performance requirements
CIE (2000) Publication 136:2000 guide to the lighting of urban areas
CIE (2010) Publication 115:2010 lighting of roads for motor and pedestrian traffic
CIE (2014) Publication 206:2014 the effect of spectral power distribution on lighting for urban and pedestrian areas
FHWA (2008) Federal Highway Administration Publication FHWA-HRT-08-053, Informational report on lighting design for midblock crosswalks
ILP (2005) Technical Report 27, code of practice of variable lighting levels for highways

Chapter 10
Equipment: Lamps and Gear

Abstract Since 1932, the low-pressure sodium lamp, the first commercially-used gas-discharge lamp, has bathed many roads in its yellowish light. Within a few years it was joined by the high-pressure mercury lamp providing bluish-white light. The high-pressure sodium lamp, introduced in the late 1960s, with its yellow-white colour and much higher efficacy, then relatively-quickly replaced the high-pressure mercury lamps in a large number of applications. There, where lighting levels were not high and white light was preferred, fluorescent lamps, usually of the compact type, were sometimes also employed.

In the last part of the last century induction lamps with extremely long lifetimes were introduced. Around the same time, metal halide lamps with their high-quality white light became available with lifetimes long enough for them to be employed for road lighting—high lighting-level road lighting with high quality white light of high efficacy had become a possibility.

The beginning of this century marked the commercial introduction of a fundamentally new type of light source, made of solid-state semiconductor material: the light-emitting diode, or LED. Today, LEDs have taken over from many gas-discharge lamps used in road lighting. The principle of operation, the construction and the application possibilities of all these light sources are widely different and will be described in this chapter, as will the auxiliary electrical devices, such as ballasts, igniters and drivers, needed for their proper functioning. Because of their importance today, extra attention is given to LED light sources.

Both gas-discharge lamps and solid-state light sources are used for road lighting for motorized traffic. Figure 10.1 groups the lamps used for this application according to the technology employed.

In the middle of the past century, the high-pressure mercury (HPM) and the low-pressure sodium (LPS) were those that were used for road lighting. HPM was used mainly in built-up areas while LPS was used for motorway lighting[1]. Sometimes, twin or three-lamp tubular-fluorescent (FL) lamps were also used.

After the introduction of the high-pressure sodium (HPS) lamp in the late 1960s of the last century, this lamp type replaced most HPM lamps because it has twice the

[1] In the United Kingdom, low-pressure sodium lamps were also widely used in built-up areas, including residential areas.

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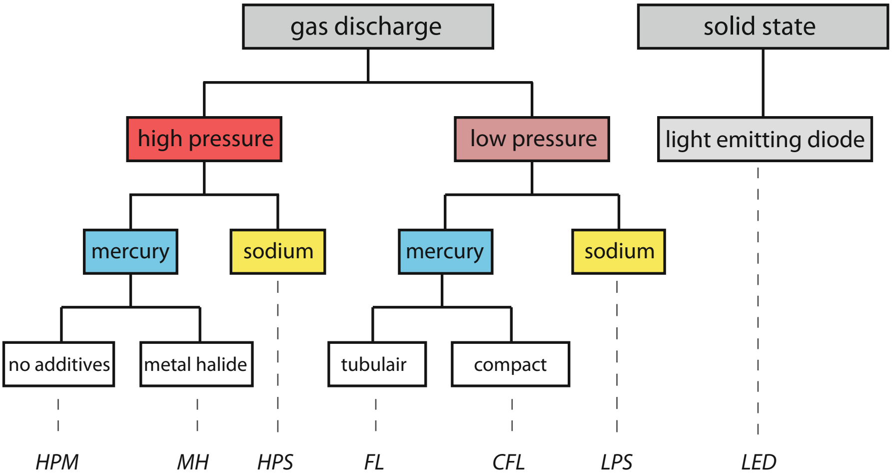

Fig. 10.1 Light sources used in road lighting, grouped according to the technology employed

efficacy of the HPM lamp. The compact fluorescent lamps (CFL), introduced in the late-1980s of the last century, are also sometimes used in built-up areas—especially in residential areas. They have the advantage of emitting white light, compared with the yellow-white light of the high-pressure sodium lamp. Today, white metal-halide gas-discharge (MH) lamps, in versions specifically developed for road lighting, are also employed.

At the beginning of this century the first pilot installations with solid state lighting (SSL) systems for road lighting were installed. New installations are now often equipped with solid-state LED systems. This is for reasons of efficiency (relatively-high lm/W), long lifetime and because more emphasis is now placed on improved colour quality or spectrum of the light. The good efficiency is not only due to the higher luminous efficacy (lm/W) of the LED systems, but also because of their small size and hence their ability to provide better beam control.

Gas discharge and solid-state lamps cannot function properly when they are operated directly from the mains-supply voltage. Certain electrical and/or electronic peripherals have to be built into the lamp circuit. The collective name for these devices is electrical control gear. The devices needed are called igniters, ballasts and dimmers and, in the case of solid-state lamps, drivers. Control gears and drivers will be discussed in Sect. 10.4 of this chapter, after having examined in more detail the different type of lamps and their properties.

Table 10.1 Some of the more important characteristics of lamps

Luminous efficacy (lm/W)	Shape and dimensions
Lumen package (lm)	Run-up time (min)
Lamp price	Re-ignition time (min)
Lifetime (h)	Dimmable yes/no
Correlated colour temperature (T_k)	Burning position
Colour rendering (R_a)	Ambient temperature sensitivity
S/P ratio	Brightness
Lamp-lumen depreciation	Environmentally-unfriendly materials

10.1 Performance Characteristics

10.1.1 Survey of Lamp Properties

There are a great number of different lamp types. The reason for this is that the ideal lamp simply does not exist. A lamp that is suitable for one situation may be totally unsuited for another. Each lighting application calls for a lamp with a specific set of properties. Table 10.1 provides a list of some of the more important lamp properties, which can vary with different lamp types. It is the task of the lighting designer to choose the lamp properties best suited to a particular application.

Table 10.2 gives a survey of the more important characteristics of the different lamps used in road lighting. The values given include the effect of the electrical gear, and are representative for the wattage versions commonly employed in road lighting.

10.1.2 System Efficacy

The measure of energy efficiency as far as lamps is concerned is the luminous efficacy expressed in lumens per watt. Apart from the lamp itself, the electrical gear, in particular the ballast for gas discharge lamps and the driver for solid state lamps also consume energy, so it is important to always include the ballast and driver losses in lm/W figures to give the so-called system lm/W figures. This, of course, has been done in Table 10.2 as will be done everywhere in this book.

From the standardized eye-sensitivity curve, V(λ), as given in Fig. 6.2, it directly follows that the theoretical maximum luminous efficacy of a hypothetical, ideal, lamp that produces electromagnetic radiation without energy losses and with a single wavelength for which the eye has its maximum sensitivity (i.e. 555 nm) is 683 lm/W. This theoretical maximum is valid for monochromatic light. The theoretical maximum efficacy of a lamp producing white light is not as clearly defined, because it is dependent on the quality of the white light being considered. With a hypothetical, ideal light source of reasonable-to-good white colour quality, in which again all

Table 10.2 Survey of characteristics of light sources employed in road lighting for motorized traffic. Luminous efficacy (lm/W), correlated colour temperature T_k, Colour-rendering index R_a, lifetime in hours (based on 20 % mortality), and shape. Basis: wattage versions that are commonly used in road lighting

Lamp type	lm/W	T_k	R_a	Lifetime (h)	Shape
High-pressure mercury HPM	60	4500	40–60	15,000	Compact
Metal halide (MH)	100	4000	60–80	20,000	Very compact
High-pressure sodium HPS High-pressure sodium tubular	120–140	2000	25	20,000	Compact Very compact
Low-pressure sodium LPS	150–190	1700	0	15,000	Long linear
Tubular fluorescent	70–90	4000	80	15–20,000	Long linear
Compact fluorescent CFL	70–75	4000	80	12–20,000	Linear
LED (white)	80–150	3000–6000	60–80	35–100,000	Point source

radiation is produced without any energy losses, a luminous efficacy between 350 and 450 lm/W can be achieved (Ohno 2004). It is interesting to note that today the low pressure sodium gas discharge lamp providing monochromatic light is, with its 190 lm/W, nearest to the theoretical maximum of 683 lm/W. It is not to be expected that low pressure sodium lamps or other type of gas discharge lamps will far exceed the 190 lm/W value. White LEDs, with their ca. 130 lm/W (for high colour rendering versions) are nearest to the theoretical maximum for white light sources. Here considerable further improvements in lm/W values may be expected.

10.1.3 Lifetime and Lumen Depreciation

With the introduction of LEDs with extremely-long lifetimes it becomes important to understand how these lifetimes are defined and estimated in practice. This section therefore goes into more detail on the quality aspects of lifetime and the related lamp-lumen depreciation.

Sensible lifetime definitions have to be based on a large batch of lamps of the same type, taking their statistical variation in end-of-life into account. Figure 10.2 shows as an example a life-survival curve (continuous drawn line). The grey area is an indication of the spread that may be expected. Apart from lamp failure, the lumen depreciation of the still-functioning lamps also determines how long an installation will continue to provide lighting up to specification in an efficient way. The dashed-line curve in Fig. 10.2 shows the lumen depreciation curve. The overall result of

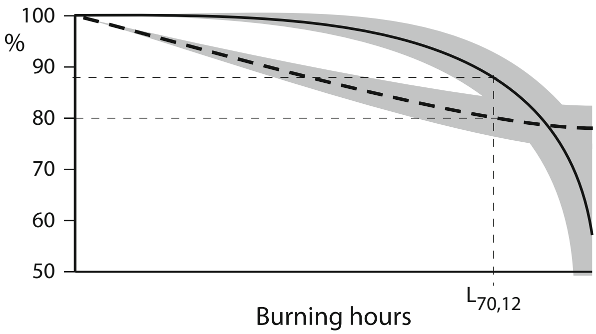

Fig. 10.2 Examples of lamp survival (*continuous line*) and lumen depreciation (*dashed line*) curves

lamp failure and lamp lumen depreciation is a decrease in luminous efficacy and lighting level, which may reach a stage where it is economically more profitable to replace all lamps by new ones, rather than to wait for their ultimate failure. The concept of economic lifetime or rated life has therefore been introduced. It takes both lamp failure and lamp lumen depreciation into account. The economic or rated life of lamps in an installation is defined as: the time after which, due to lamp failure and depreciation of light output of the lamps, the light output of the installation has fallen by a certain percentage. Which percentage is relevant is especially dependent upon the type of application and the actual costs of lamp replacement (including labour cost). For road lighting installations percentages of 20–30 % are often used. The corresponding economic lifetimes are called L_{80} and L_{70} respectively, 80 and 70 standing for the percentage of light that remains. Figure 10.2 gives an example of a rated lifetime according to L_{70}: a survival rate of 88 % and a lumen depreciation of the remaining lamps of 80 % results in a total remaining light output of the installation of $88 \times 80 = 70$ %.

The International Electrotechnical Commission (IEC) recommends that for LED systems (especially those using a multitude of individual LEDs) the rated-life statement should include a statement of the actual "catastrophic" (viz. complete) failures in addition to the remaining percentage of light (IEC/PAS 2011a, b). Rated life is then given in terms of L_x, the remaining light percentage as a result of both gradual lumen depreciation and catastrophic failures, together with "F_y", the actual failure fraction at that rated lifetime. The rated life of the example of Fig. 10.2 thus corresponds to $L_{70}F_{12}$. For a LED module (or LED luminaire) with a multitude of individual LEDs this means that at the stated lifetime the remaining light output of a great number of these modules is 70 %, while at that moment 12 % of the modules or luminaires have to be considered as failures (viz. producing between "less than 80 %" and 0 % of light output).

Given the long lifetime of LEDs it is impossible for manufacturers to actually measure LED failures and lumen depreciation over the total period of the stated life: it would simply takes years to collect the data. Keeping this practical consideration in mind, IES document LM-80 "Measuring lumen maintenance of LED Light Sources" has laid down norms for life testing (IES 2008). It requires testing of LEDs for at

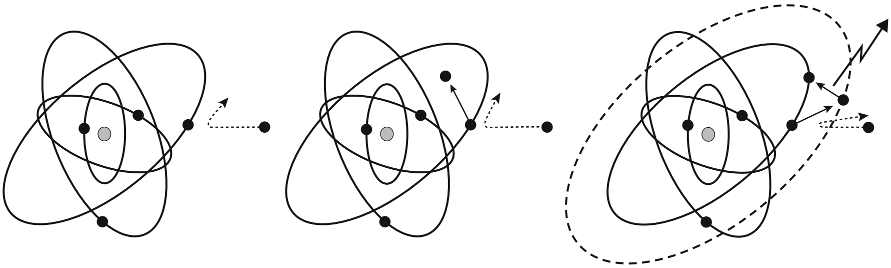

Fig. 10.3 Elastic, ionizing and exciting collision of an electron with a gas or vapour atom resulting in heating of the gas, so increasing the number of free-moving electrons and the emission of electromagnetic radiation respectively. Drawing after (Meyer and Nienhuis 1988)

least 6000 h and recommends 10,000 h. These measurements have to be done at three LED case temperatures (55, 85 °C, and a third temperature to be determined by the manufacturer), so that users or luminaire manufacturers can see the effects of temperature on light output. LM-80 specifies further additional test conditions to ensure consistent and comparable results. Leading LED manufacturers indeed test their products according to the LM-80 i.e. minimum of 6000 or 10,000 h, and then apply extrapolation methodologies as described in IES TM-21 to arrive at L_{90}, L_{70} and L_{50} figures (IES 2011).

10.2 Gas Discharge Lamps

10.2.1 Principle

A gas discharge lamp consists of a tube of transparent or translucent material with, at each of the two ends, a sealed-in metal electrode from metal material. The tube is filled with a gas and/or metal vapour. When a voltage difference is applied between the electrodes, free electrons are emitted (pulled) out of the negatively-charged electrode and move to the positively-charged electrode at the other end of the tube.

During their passage through the discharge tube these electrons may interact or collide with the gas or vapour atoms in three different ways (Fig. 10.3):

- some of the kinetic energy of a low-speed electron is absorbed by the gas or vapour atom heating up the gas (a so called elastic collision),
- the collision of a very high speed electron with an atom completely ejects an electron from the atom that was orbiting around its core (the nucleus) so that an extra free electron is generated (so called ionization); the extra free electron subsequently contributes to the discharge process,
- the collision of a high speed electron with an atom temporarily ejects an electron from the atom into a higher orbit corresponding to a higher energy level (termed excitation); the excited electron very quickly falls back into its original orbit of lower energy and the difference in energy is emitted as electromagnetic radiation.

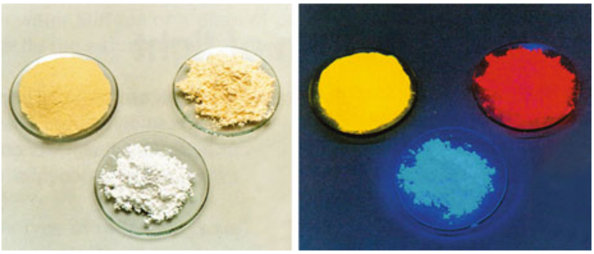

Fig. 10.4 Examples of different types of fluorescent powder as seen under white light (*left*) and under ultraviolet radiation (*right*)

All three types of interactions are essential and need to be controlled in a proper way. Elastic collisions determine the gas temperature, ionization the lamp's current and, of course, excitation the emission of light. The wavelength of the electromagnetic radiation depends on the type of gas or vapour and on the pressure of the gas (Meyer and Nienhuis 1988; Coaton and Marsden 1997). Controlling the temperature sometimes requires a secondary bulb around the discharge tube that acts as a thermal isolator. To avoid an unlimited increase in free-moving electrons and thus in the lamp current, a current-limiting device called a ballast is needed. Most gas discharge lamps need an ignition device that temporarily produces a high peak voltage to help it start viz. emitting electrons from the electrodes when the discharge tube is still cold. Some gas discharges emit a relatively large part of their electromagnetic radiation not in the visible but in the ultraviolet part of the spectrum. In that case fluorescent powder is used to convert the ultraviolet radiation into visible light. Fluorescent powders are commonly referred to as phosphors. The physical phenomenon of converting short-wave electromagnetic radiation into longer-wave visible radiation is called photo-luminescence. High energy short wavelength electromagnetic radiation temporarily excites an electron of a molecule of the fluorescent material, sending it into a larger orbit. When that electron falls back into its original orbit electromagnetic radiation of lower energy and thus longer wavelength is emitted[2]. The fluorescent powders used today most often contain rare-earth metals that belong to a group of 17 elements with properties also widely used in energy technology devices. By mixing different fluorescent powders in different proportions, lamps emitting different tints of white, i.e. with different colour temperatures and colour rendering, can be produced. Figure 10.4 shows three different types of fluorescent powders that under white light all look whitish-yellow, while under ultraviolet radiation the resulting, converted, visible light is yellow, red and blue respectively.

[2] According to Max Planck's quantum theory the energy E of a photon is proportional to the reciprocal of the wavelength: $E = h \times f = h \times c/\lambda$. With h = Planck's constant, f = frequency, c = speed of light and λ = wavelength. Photons with a longer wavelength thus have less energy than photons with a shorter wavelength.

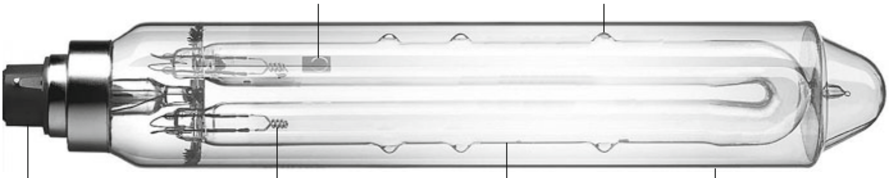

Fig. 10.5 Main parts of a low-pressure sodium lamp

10.2.2 Low-Pressure Sodium Lamps

All low-pressure gas-discharge lamps have in common the fact that they are long, as is the low-pressure sodium lamp. Low-pressure sodium (LPS) lamps belong to the group of High-Intensity Discharge (HID) lamps, because they are available in high-light output (and thus high-luminous-intensity) versions. They are highly-efficient lamps (up to 190 lm/W) with a good lifetime but no colour rendition at all. Their application is therefore restricted to those situations where colour rendering is of no importance, as on motorways. When used on masts positioned along the sides of a road, the light directed across the road cannot be fully controlled because of the length of the lamps. An important part of the lamp's light output, close to 50 %, is therefore radiated towards the adjacent areas of the road instead of onto the road itself. This lowers the efficiency of the installation. The compact high pressure sodium lamp, although having a lower efficacy, in many situations therefore offers a similar or better installation efficiency.

10.2.2.1 Construction

The construction is shown in Fig. 10.5. To reduce the length of the lamp, the discharge tube is bent into a U-shape. Nevertheless, the version with the highest lumen package still requires a lamp length of 1.2 m. The discharge tube contains dimples in which the sodium is deposited. During ignition the discharge starts in a so-called starting gas, where it heats the gas causing some of the sodium to vaporise and take over the discharge. The sodium vapour pressure is then slightly less than 1 Pa (10^{-5} atm). The starting-up process takes about 10 min. At switch-off, the sodium condenses at the coldest spots, these being the dimples. In this way no sodium condenses along the whole length of the inner-tube wall, so avoiding the gradual build-up that would otherwise considerably decrease light transmission. For thermal isolation the U-shaped discharge tube is contained in an evacuated outer-glass tube. To further increase the thermal insulation, this outer bulb is coated on its inner surface with a layer that reflects infrared radiation but transmits visible radiation. During operation

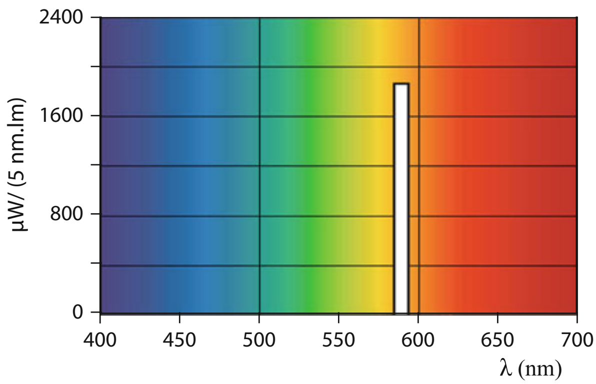

Fig. 10.6 The mono-chromatic line of 589 nm of the low-pressure sodium spectrum

of the lamp, minuscule particles evaporate from the glass and metals in the outer bulb. To absorb these particles, together with traces of air and water that remained after evacuation of the tube, a getter is added. Most gas discharge lamps having an outer bulb make use of a getter in one form or another.

10.2.2.2 Lamp Properties

Spectrum and Colour Properties The low-pressure sodium lamp emits yellowish monochromatic light with a wavelength of 589 nm, which is very close to the wavelength of 555 nm for which the eye has its maximum sensitivity (Fig. 10.6). It is mainly for this reason that the lamp's efficacy is extremely high. It also means, however, that the lamp makes colour rendition impossible, viz. $R_a = 0$. The colour temperature is around 1700 K and the S/P ratio is 0.25.

Lumen Range Low-pressure sodium lamps are available in the range from approximately 2000 to 30,000 lm, corresponding to the wattage range from 18 to 180 W.

System Efficacy The luminous efficacy of the low-pressure sodium system is strongly dependent upon the wattage of the lamp and ranges from 70 lm/W (18 W version) to 190 lm/W (131 W version).

Lifetime The economic life based on L_{80} is up to 15,000 h.

Run-Up and Re-ignition The warming-up process takes about 10 min. Re-ignition is almost immediate, with the exception of the highest wattage versions (131 and 180 W), which re-ignite after 10 min.

Dimming Low-pressure sodium lamps cannot be dimmed.

Burning position Electrodes and lead-in wires coming into contact with condensed sodium can eventually suffer damage. Low-pressure sodium lamps therefore have restrictions as to their burning position: higher wattages horizontal $\pm 20°$ and lower wattages base up $\pm 110°$.

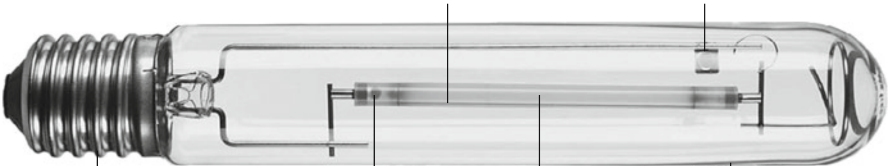

Fig. 10.7 Main parts of a tubular high-pressure sodium lamp

10.2.3 High-Pressure Sodium Lamps

High-pressure sodium (HPS) gas-discharge lamps belong to the group of high intensity discharge HID lamps. HPS lamps, in common with all high-pressure discharge lamps, are relatively compact. By increasing the vapour pressure in a sodium lamp, the spectrum around the typical yellow sodium line broadens. The result is that colour rendering improves and the colour appearance changes from yellow to yellow-white, albeit at the cost of a decrease in efficacy. However, the resulting efficacy is more than double that of a high-pressure mercury lamp. At its introduction in the late 1960s, a very efficient alternative was thus obtained for the many high-pressure mercury lamps employed at that time, and which are still sometimes employed today, in road lighting. Since then, road-lighting installations all over the world very often use high-pressure sodium lamps. LED solutions have now become an alternative.

10.2.3.1 Construction

Figure 10.7 shows the construction of the high-pressure sodium lamp. The discharge tube is made of sintered ceramic material because it is resistant to sodium at very high operating temperatures. In many versions, the sodium is brought into the gas-discharge tube as a sodium-mercury amalgam composition, which partially vaporises when the lamp reaches its operating temperature. At 10 kPa the operating vapour pressure is ca. 10,000 times higher than that of a low-pressure sodium lamp, but still lower than 1 atmosphere (0.1 atm). To thermally insulate the gas discharge tube and to protect its components from oxidation, an outer bulb is employed. Xenon is usually added as a starting gas, which in mercury-free versions, also acts as a buffer gas that regulates the voltage and reduces thermal losses. Increase of the pressure of the xenon gas increases the efficacy of the lamp. In versions making use of this phenomenon, an auxiliary ignition wire or strip, also called an antenna, is required and added very close to the discharge tube to ensure proper ignition. Like most gas discharge lamps, this lamp's outer bulb also contains a getter to maintain the vacuum during the life of the lamp.

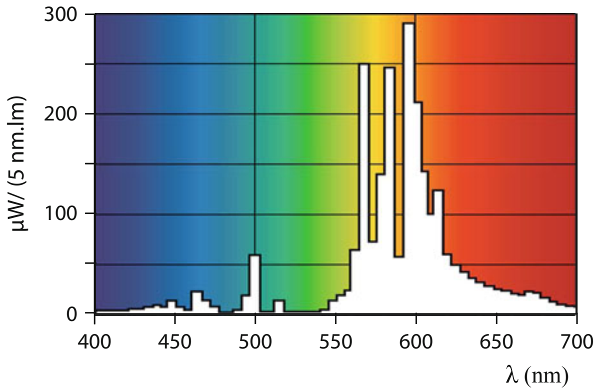

Fig. 10.8 Spectral power distribution of the high-pressure sodium lamp

10.2.3.2 Lamp Properties

Spectrum and Colour Properties As with all gas-discharge lamps, the high-pressure sodium lamp spectrum is discontinuous (Fig. 10.8). The main part of the spectrum is centred around the yellow sodium line. It provides yellow-white light with a colour temperature of around 2000 K and a colour rendering index R_a of 25. The colour rendering for road lighting is quite acceptable, although, for indoor lighting applications it is, of course, far from adequate[3]. Since the spectrum is relatively strong in the red wavelength area, the rendition of human faces is often experienced as being somewhat flattering. The S/P ratio is around 0.65.

Lumen Range High-pressure sodium lamps are produced in the approximate range of 4000 (50 W)–150,000 lm (1000 W).

System Efficacy The efficacy goes from 80 lm/W, for the lower wattages, to 140 lm/W for the higher wattages.

Lifetime High-pressure sodium lamps have a lifetime, based on L_{80}, of up to 20,000 h.

Run-Up and Re-ignition The nominal pressure and full light output is reached after 3–5 min. Re-ignition of the hot lamp requires the lamp to cool down for about 1 min to allow the pressure to decrease far enough for the ignition pulse to again ionise the sodium atoms.

Dimming Lower wattages (100–150 W) can be dimmed to 20 % of light output with special electronic gear. Higher lamp wattages can be switched to some 50 % of

[3] By further increasing the sodium pressure, the colour quality of the light improves so that white light is obtained with a colour rendering index of 80. These lamps are suitable for indoor lighting applications but are seldom used in road lighting because their efficacy decreases to less than 50 lm/W.

light output, by including an extra inductive coil (ballast) in the lamp circuit, Lamp colour remains virtually constant and lifetime is not affected.

Bulb Shape The outer bulb is either tubular (T-shape) or ovoid in shape. The internal wall of the ovoid bulb is usually coated with diffusing powder. As a consequence of this, these versions have a lower luminance at a similar lumen output. They were originally introduced so as to obtain the same light-emitting surface area as high-pressure mercury lamps have (see Fig. 10.12). In this way the coated ovoid high-pressure sodium lamps could be used with the same luminaire optics as those developed for high-pressure mercury lamps.

10.2.4 Tubular-Fluorescent Lamps

Tubular-fluorescent lamps belong to the family of low-pressure mercury lamps. As with all low-pressure gas-discharge lamps, they are long: the tubular ones up to 1.8 m for the higher wattages. Their length makes good optical control in any plane through the lamp axis, which in road lighting is across the road axis, impossible to achieve. Given their moderate lumen output, there where moderate to high lighting levels are required, the luminaire would need to house several lamps in order to achieve that lighting level. So, the length of the tubular versions and their moderate lumen output are decided disadvantages in so far as the use of these lamps in road lighting is concerned. We will therefore not go into detail on these lamps, although some older road-lighting installations do still employ tubular fluorescent lamps.

Compact fluorescent lamps may sometimes offer cost-effective solutions for use in residential and pedestrian areas and are therefore dealt with in the following section.

10.2.5 Compact Fluorescent Lamps

Low-pressure mercury lamps of the compact type, normally referred to as compact fluorescent lamps (CFLs), were originally developed at the beginning of the 1980s for use in those applications where incandescent lamps were traditionally in use. Today, the application of "twin-leg" compact fluorescent lamps has been widened to include those residential streets where relatively low lighting levels suffice. Alternatives are low wattage high pressure sodium, metal halide and to an increasing extent solid-state lamps.

10.2.5.1 Construction

The operating principle of compact fluorescent lamps is exactly the same as that in tubular fluorescent lamps. A tube made out of glass is filled with an inert gas

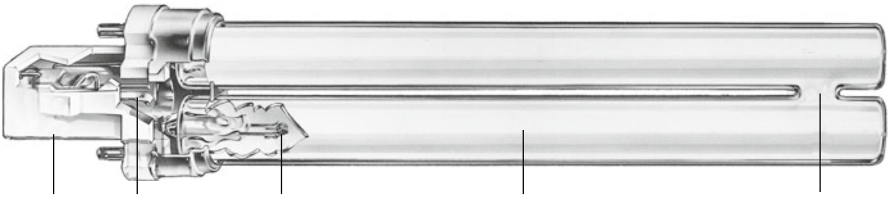

Fig. 10.9 Main parts of a compact fluorescent lamp (welded-bridge version)

and a little mercury. To facilitate starting, the electrodes sealed into each end of the tube are pre-heated prior to ignition by a high-voltage pulse. Once the mercury is completely vaporised, an operating gas pressure of slightly less than 1 Pa ($\pm 10^{-5}$ atm) is reached. The radiation emitted from the low-pressure mercury discharge contains a large amount of ultraviolet radiation and a small amount of blue light. The inside of the tube is therefore coated with a mixture of fluorescent powders that convert the ultraviolet radiation into visible light as it passes through this coating. The final result is white light, the colour properties of which depend on the mix of fluorescent powders employed.

The compactness of these lamps is achieved by reducing their length by folding a longer tube into a U-tube, or by joining together two (or more) parallel tubes by means of a welded bridge so that one open pathway is obtained where free electrons and ions can move from one electrode to the other (Fig. 10.9). A great variety of tube shapes are available. Versions with the electric gear integrated in the lamp itself and with a lamp cap as in normal incandescent lamps are produced as energy-saving retro-fits for incandescent lamps. The compact fluorescent lamps employed in road lighting are normally of the non-integrated type and the gear needs to be installed in the luminaire. They are of the twin-leg or circular versions. The twin leg versions have a length, depending on wattage, of between 100 and 600 mm.

10.2.5.2 Lamp Properties

Spectrum and Colour Properties As has been mentioned, different spectra can be produced by mixing different fluorescent powders. As with all gas discharge lamps the spectrum is always discontinuous. The colour-type designation used for fluorescent lamps has been standardised, with the first digit standing for the colour rendering index Ra, and the last two digits for the colour temperature T_k. A type of compact fluorescent lamp often-used in street lighting is the colour type 840, which has a colour rendering index in the 80s and a colour temperature of around 4000 K (Fig. 10.10). The S/P ratio is approximately 1.5 (for colour type 830 it is about 1.3).

Lumen Range Non-integrated compact fluorescent lamps are available in the range from some 250–6000 lm, corresponding to the wattage range of 5–80 W.

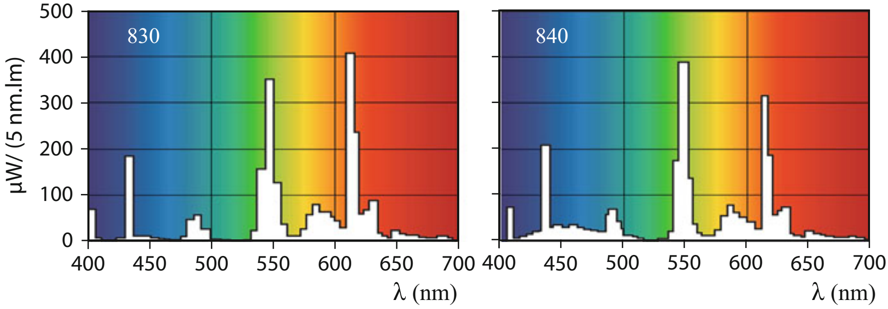

Fig. 10.10 Spectral power distributions of a compact fluorescent lamps with colour types 830 and 840

System Efficacy The higher-wattage versions, which are most suited for street lighting, reach efficacies up to some 70 lm/W.

Lifetime Non-integrated CFLs have lifetimes, based on L_{20} between 7000 and 20,000 h, with the better values for the higher wattages.

Run-Up and Re-ignition Fluorescent lamps operated om present-day electronic gear start within 1.5 s and without flickering. When a hot lamp is switched off, the vapour pressure drops so quickly that re-ignition is instantaneous.

Dimming Non-integrated compact fluorescent lamps with four-pin lamp cap can be dimmed.

Ambient-Temperature Sensitivity The luminous flux of a fluorescent lamp is determined by the mercury vapour pressure during operation. The mercury vapour pressure is in turn determined by the coldest spot in the tube, which, because fluorescent lamps have no outer bulb, is dependent on the ambient temperature. With a compact lamp the coldest spot is also dependent on its tube shape. In all cases the luminous efficacy decreases with temperatures lower than some 20–30 °C ambient temperature. In completely-open luminaires, at −10°, the remaining light output may be lower than 20 % of the nominal value. So, in colder regions, fluorescent lamps should never be used in open luminaires.

10.2.6 Induction Lamps

Induction lamps, like fluorescent lamps, belong to the family of low-pressure mercury gas-discharge lamps. Unlike other discharge lamps they have no electrodes, which is why they are also called "electrodeless lamps". The consequence of having no electrodes is a very long economic life of around 60,000–75,000 h. This long life is also the main feature of induction lamps. They find their application in situations

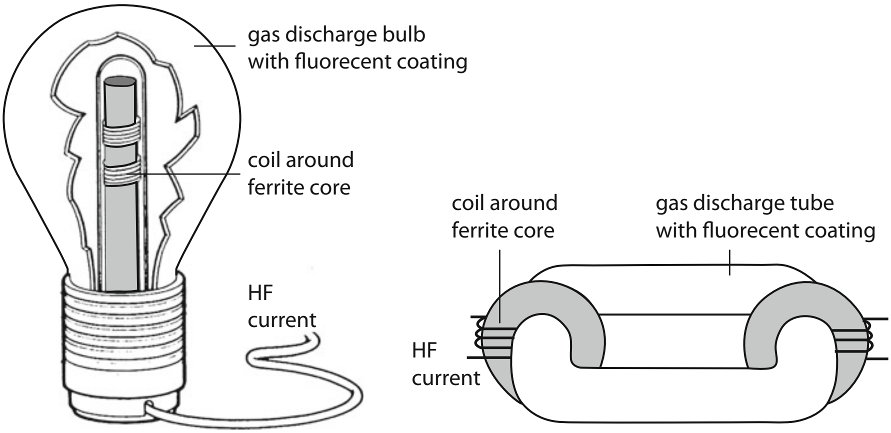

Fig. 10.11 A bulb-shaped induction lamp with coil winded ferrite antenna inside a cylindrical cavity of the lamp and a planar shaped lamp with external coils around ferrite core

where lamp replacement is near- impossible or very expensive. In many cases long-life LED systems are an alternative. Light technical the most important difference is the light emitting surface area: square millimetres with LEDs and something like a square decimetre with induction lamps.

10.2.6.1 Construction

In an induction lamp, the free-running electrons needed for the gas discharge are obtained by winding an induction coil around a ferrite core (called the antenna) placed in or around a discharge vessel (Fig. 10.11). The induction coil is connected to a high-frequency power source and acts like a primary winding in a transformer. In the discharge vessel, the mercury gas surrounding the ferrite core acts as the secondary coil since mercury is a metal. The secondary current initiated in the mercury consists of free-running electrons around the ferrite core. As in a normal fluorescent gas discharge, these free-running electrons ionise and excite other mercury atoms, which results in the emission of the same radiation as in a fluorescent lamp. Since the vessel's interior is coated with the same fluorescent powder as in normal fluorescent lamps, the same light is obtained. The high frequency of 2.65 MHz is generated by an electronic circuit.

10.2.6.2 Lamp Properties

Spectrum and Colour Properties The radiation of the low-pressure mercury discharge and the fluorescent coating compositions are the same as those in normal fluorescent lamps, so the spectrum and colour characteristics are also the same. See Sect. 10.2.5.

Lumen Range Induction lamps are produced in the range from 3000 to 12,000 lm.

System Efficacy The luminous efficacy of induction lamps is smaller than that of normal fluorescent lamps. Depending on the wattage it varies between 65 and 75 lm/W.

Lifetime The lifetime is extremely long, based on L_{20}, between 60,000 and 75,000 h.

Run-Up and Re-ignition A high-voltage ignition pulse produced by the HF generator ignites the lamp within 5 s, after which it emits its full light output within 1 min. Hot re-ignition is immediate.

Dimming Special versions, dimmable to 50 % are available.

10.2.7 High-Pressure Mercury Lamps

High-pressure mercury (HPM) lamps belong to the group of high-intensity discharge HID lamps. High-pressure mercury lamps, like all high-pressure discharge lamps, are compact compared to low-pressure discharge lamps. HPM lamps have a moderate efficacy and moderate colour rendering. With their cool-white light they were extensively used in road lighting, especially in built-up areas. Since the introduction of the more efficient high-pressure sodium lamps in the late 1960s, these high-pressure sodium lamps have in most cases replaced high-pressure mercury lamps.

10.2.7.1 Construction

Figure 10.12 shows the construction of the high-pressure mercury lamp. The discharge tube is made of quartz, which has a higher melting point than that of glass required in view of the high operating temperature of the lamp. An ovoid outer bulb with an inert gas filling isolates the gas discharge tube so that the ambient temperature has no influence on its proper functioning. To aid starting, an auxiliary electrode is placed close to one of the two main electrodes. Because of this, the high-pressure mercury lamp is one of the few gas discharge lamps that does not need an external ignition device. The discharge tube contains a small quantity of mercury which completely evaporates during operation. The operating pressure is 10^6 Pa (10 atm). The radiation of the gas discharge is mainly in the visible part of the spectrum but lacks red. In most high-pressure mercury lamps, therefore, a fluorescent powder coating on the inner surface of the outer bulb is applied. This converts the small ultraviolet component into visible radiation, predominantly in the red. This does little to increase the efficacy, but improves the colour quality of the white light.

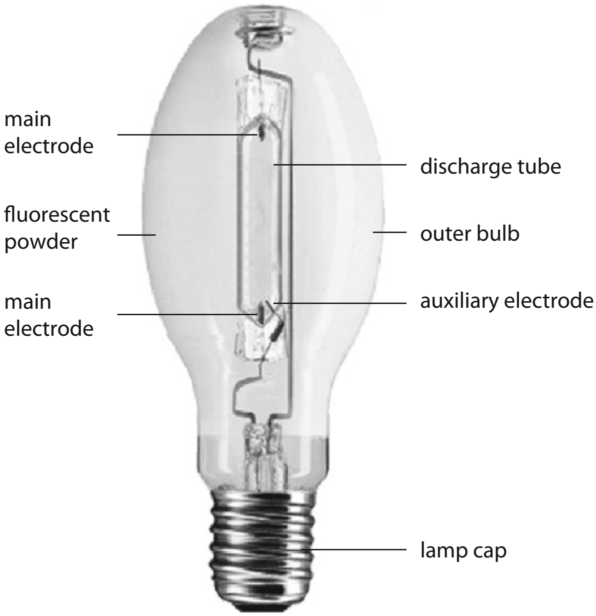

Fig. 10.12 The main parts of a high-pressure mercury lamp. For the purpose of illustration, the fluorescent powder has been partly removed

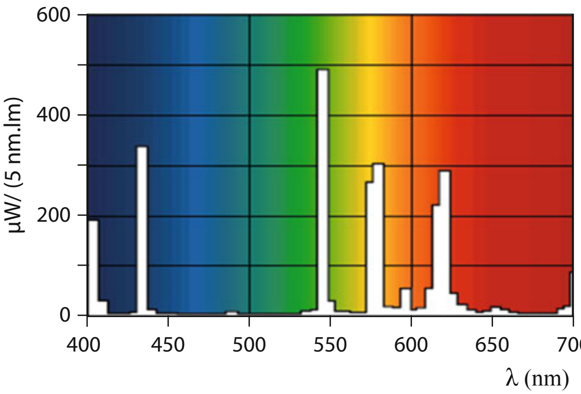

Fig. 10.13 Spectral power distribution of a compact high-pressure mercury lamp with fluorescent coating and colour temperature of 4500 K

10.2.7.2 Lamp Properties

Spectrum and Colour Properties Figure 10.13 shows the typical discontinuous line spectrum resulting in bluish-white light. The two lines in the red are the result of the conversion of ultraviolet radiation by the fluorescent powder. Different compositions and qualities of fluorescent powder are used to produce lamps with colour temperatures between some 3500 and 4500 K, with colour rendering index values of around 60 for high-colour-quality versions and around 40 for ordinary versions. Since the ordinary versions have a higher efficacy, it is those versions that were mostly used in road lighting. S/P ratios vary between approximately 1.1 and 1.4.

Lumen Range High-pressure mercury lamps are available in lumen packages between some 2000 and 60,000 lm, corresponding to wattages between 50 and 1000 W.

System Efficacy Luminous efficacy varies with lamp wattage and with colour quality from some 35 to 60 lm/W.

Lifetime Economic life based on L_{80} varies according to type between 10,000 and 15,000 h.

Run-Up and Re-ignition The run-up time of a high-pressure mercury lamp to its operating temperature and corresponding nominal mercury pressure is some 4 min. The hot lamp will not restart until it has cooled sufficiently to lower the vapour pressure to the point at which re-strike with the mains voltage is possible. The re-ignition time is in the order of 5 min.

Dimming High-pressure mercury lamps cannot be dimmed.

10.2.8 Metal Halide Lamps

Metal halide (MH) lamps are high-pressure mercury lamps that contain metal halides in addition to the mercury. These, too belong to the group of high-intensity discharge lamps. In the heated discharge tube, the metals of the halides take part in the discharge process and radiate their own spectrum. Compared with high-pressure mercury lamps, both colour properties and efficacy are considerably improved. Thanks to the fact that no fluorescent powder is needed, the small gas-discharge tube itself is the light-emitting surface. This small light-emitting surface makes the lamps extremely suitable for use in reflector and floodlight luminaires.

Originally, these lamps were produced in extremely-high lumen packages (up to more than 200,000 lm) for use in sports stadium floodlighting. Their lifetime, at some 6000 h, was short but more than good enough for stadium and sports lighting where the annual burning hours are limited. Today, compact metal halide lamps are available in small lumen packages with much longer lifetimes, which makes them suitable for use in road lighting. In urban and residential areas they offer white light of high quality with efficacies slightly higher than those of high pressure-sodium lamps of comparable lumen output. LED lamps have now become another alternative for these applications.

10.2.8.1 Construction

Figure 10.14 shows the construction of a metal halide lamp. The discharge tube is made of either quartz or a ceramic material. Some metals of the metal-halide compounds have the tendency at high temperatures to migrate slowly through the quartz wall of the tube. With ceramic discharge tubes this is impossible, so that the lifetime improves and the colour quality during life remains constant. All metal

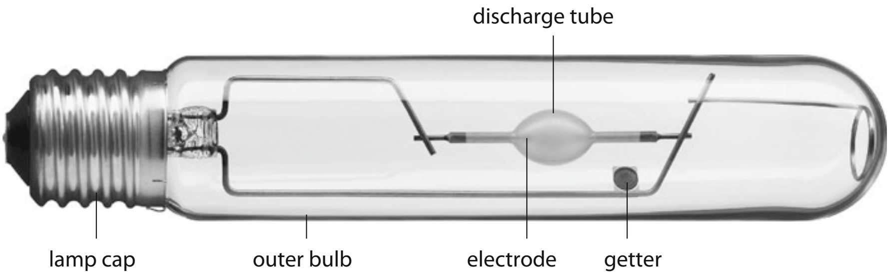

Fig. 10.14 Main parts of a metal halide lamp in this example with a ceramic gas discharge tube

halide lamps used in road lighting have either a vacuum or an inert-gas filled outer bulb for heat insulation of the discharge tube. As with most gas-discharge lamps, the outer bulb contains a getter to maintain the vacuum during the life of the lamp.

Suitable metals that vaporise in the hot discharge tube so as to contribute to the discharge process cannot be added directly to the mercury in the discharge tube. This is because metals suitable for this purpose would attack the wall of the tube. The solution to this problem has been found in adding these metals in the form of their non-aggressive chemical compounds with a halogen (iodine, bromide or chloride): hence their name—metal halide lamps. The solid metal halide starts evaporating at a certain temperature. When this vapour enters the area of the mercury discharge in the centre of the tube, with its very high temperature (around 3000 C), it dissociates into its separate elements: metals and halogen. There the metals in their pure, vaporised state, take part in the discharge process where they are important in determining the efficacy and colour characteristics of the radiation. The aggressive vaporised metal cannot reach the tube wall because at the lower wall temperature (some 1000 C), they recombine again to form the harmless metal halide compound. In fact, so-called rare-earth metals are used that excite more easily than does mercury. This means that mercury in a metal halide lamp does not take part in the generation of light but merely serves to keep the discharge going through a process of heat and voltage regulation (buffer gas).

10.2.8.2 Lamp Properties

Spectrum and Colour Properties The spectrum of a metal halide lamp is to a large extent determined by the mixture of rare-earth metals used. In theory, some fifty different metals are available and different manufacturers have introduced various combinations of these metals that produce different spectra. The same colour designation system that is used for fluorescent lamps is used for metal halide lamps. Figure 10.15 shows the spectra of metal halide lamps used in road lighting with colour designation 728 and 942. Metal halide lamps are produced in versions in the colour temperature range of 2700–4500 K and colour rendering indexes from 60 to 90. The S/P ratio of metal halides is for warm-white versions around 1.25 and for cool-white versions around 1.8.

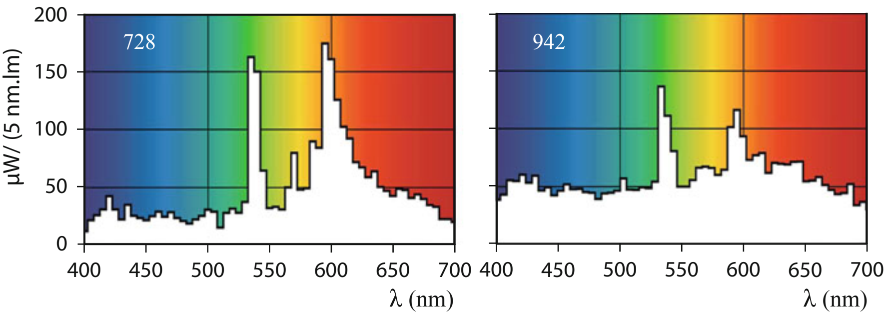

Fig. 10.15 Spectral power distribution of two metal halide lamps with colour designations of 728 ($T_k = 2800$ K and $R_a = 70$) and 942 ($T_k = 4200$ K and $R_a = 90$) respectively

Lumen Range Typical versions of the metal-halide lamps developed for use in road lighting are available in lumen packages from some 5000 to 50,000 lm. The versions for floodlighting range from some 20,000 to more than 200,000 lm.

System Efficacy The road-lighting versions range from 80 to 110 lm/W, and the floodlight versions from 75 to slightly more than 105 lm/W.

Lifetime The ceramic metal halide lamps specifically developed for use in road lighting have lifetimes of up to 20,000 h (basis L_{80}). The floodlight types have shorter lifetimes ranging from 4000 to 10,000 h.

Run-Up and Re-ignition The metal halides in the discharge tube need time to heat up, evaporate and dissociate into metal and halide. During this process, which takes about 2–3 min, the light output and colour gradually change until the final stable condition is reached. If there is an interruption in the power supply, medium and high-wattage lamps will take approximately 10–20 min for the pressure in the lamp to decrease enough for it to re-ignite. Compact ceramic lamps reignite faster: after some 3–10 min.

Dimming Dimming of metal halide is difficult because with the resulting decrease in temperature some of the metal halides may condense, so changing the colour properties of the lamp. Only by employing specially shaped burners can this phenomenon be avoided. Most metal halide lamps specifically developed for road lighting can indeed be dimmed to at least 50 % of their light output. The lamp types used mainly for floodlighting cannot be dimmed.

Bulb Shape Metal halide lamps used for road lighting are produced in different bulb shapes. The most important ones are the tubular shape similar to the shape of the tubular high pressure sodium lamp, an ovoid shape (coated with a diffusing powder) similar to the ovoid high-pressure mercury and sodium lamps and a compact tubular one with a special bi-pin lamp cap to ensure exact positioning of the burner within the optical system of a luminaire.

Burning Position The majority of the metal halide lamps employed in road lighting have a free burning position. Many of the types developed for floodlighting purposes have restrictions as to their burning position.

10.3 Solid-State Light Sources

In 1907, the radio engineer Round reported that light was emitted from a silicon carbide crystal, intended to be used in radio receivers (Round 1907). This was in fact the first solid-state light source (SSL): in this case, a small light emitting diode or LED. It took until 1962 for the first practical light-emitting diode to be demonstrated (Holonyak and Bevacqua 1962). Since then LEDs have been widely used as signal lamps in all kind of electrical appliances. In the 1990s high power LEDs were introduced. When, in 1995, Nakamura also developed a high power blue LED, it became possible to produce white light LEDs, based on such blue LEDs covered with fluorescent powders (Nakamura et al. 1995). It was then clear that solid state lighting would become a possibility for many lighting applications. Today, in most application fields, especially in road lighting, solid-state light sources are often used. With further improvements to be expected, they surely will become the dominant light source of the future.

10.3.1 Principle

10.3.1.1 Light Emission

In solid-state light sources the light is created inside solid-state material consisting of a sandwich of two different kinds of semiconductor material, so-called p and n materials (Schubert 2006; van Driel and Fan 2013). The physical phenomenon of creating light in this way is called electric luminescence. Semiconductors are made of a material that is a poor conductor of electricity. By adding specific impurities (atoms of another material) to the material (a process called doping), the atoms of the material either acquire extra electrons or become deficient in electrons. The doping process makes the material more conductive, hence the name semi-conductor. The material with extra electrons is an n-type of semiconductor (negatively charged) while the material with a deficiency of electrons viz. positively-charged "holes", is a p-type of semiconductor. In the n-type of material the extra electron of an atom moves in an outer orbit with a correspondingly-higher energy level. In the p-type of material the missing electron of an atom was moving in a lower orbit with lower energy level. Connecting the n-type material to a negative charge and the p-type to a positive charge, pushes the n- and p-atoms towards the junction of the p-n sandwich layer (Fig. 10.16).

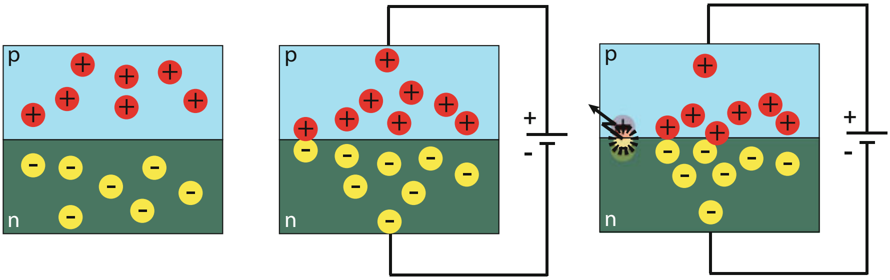

Fig. 10.16 Principle of operation of solid-state light sources: movement of p and n atoms towards the junction of the p-n semiconductor sandwich where successful recombination, resulting in light radiation, occurs

When one of the n-atoms meets with a p-atom at the junction, the electron of the n-atom falls into the orbit of the p-atom with the lower energy level. The energy corresponding to the energy level difference may be radiated as light or may heat up the material. If light is emitted, we speak of a successful recombination. The wavelength of the light is dependent on the energy-level difference between the p and n materials, which in turn depends on the semiconductor material used. Thus, different semiconductor materials emit different wavelengths, and thus different colours of light. The spectrum is always a narrow-band spectrum (quasi-monochromatic light). The process of solid state light emission is very much like the process of excited electrons in a gas discharge falling back to their original orbit with a lower energy level while emitting light. When the voltage difference across the p-n material is reversed, no flow of atoms towards the junction will take place. The electrons in the n-type material will be pulled towards the positive connector, where they are absorbed and the holes in the p-type material will be pulled towards and absorbed by the negative connector: the p-n semiconductor sandwich (also called chip) is in fact a rectifier diode. Solid state light sources are therefore also called Light-Emitting Diodes, or LEDs. The light-emitting surface of an individual LED chip, with an area of some 0.5–5 mm^2, represents the smallest artificial light source currently available. Light emitting diodes made out of organic (carbon containing) material (OLEDs) are flat or planar solid state light sources that offer many interesting application possibilities, but not for most road lighting applications and are therefore not dealt with here.

10.3.1.2 White Light

As has been mentioned, the spectrum of a single LED is always narrow. Consequently, its light is coloured (Fig. 10.17). White LED light can be obtained by combining three (or more) differently-coloured LED chips. A common method is to combine red, green and blue LED chips into a single module to produce white light (RGB LED). However, such systems are not very efficient and are therefore not suitable for use in road lighting.

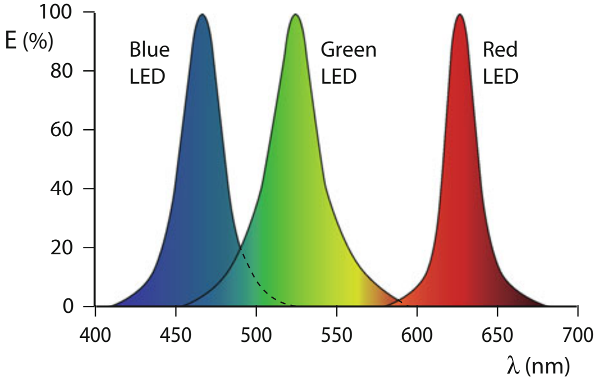

Fig. 10.17 The narrow spectrum of LEDs; example of a *blue*, a *green* and a *red* LED

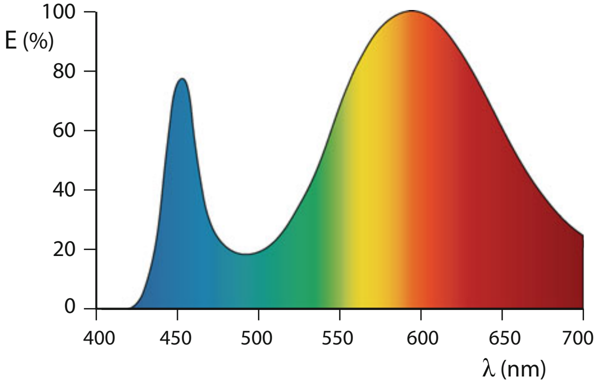

Fig. 10.18 Example of the spectrum of a white phosphor LED, $T_k = 3000$, $R_a = 75$, S/P ratio = 1.28

Good-quality white light suitable for road lighting, is obtained by using a blue LED chip in combination with fluorescent material that converts much of the short wavelength blue light into light of many different longer wavelengths spread over almost the whole visible spectrum (see Fig. 10.18). The blue LED uses so called InGaN material (an indium gallium nitride semiconductor compound). The fluorescent powders used are of rare-earth phosphor material. These types of white LEDs are therefore called white phosphor LEDs.

A relatively novel method of converting the wavelength of blue light (or of ultraviolet radiation), is the use of quantum dots (Anikeeva et al. 2009; Talapin and Steckel 2013). Quantum dots are particles with a size of 2–10 nm made of semiconductor material. Because of their nano size, corresponding to some 50 atoms, they have properties different from those of their corresponding bulk material. Under excitation from short wavelength radiation they emit light of a longer wavelength in a very-narrow wavelength band, smaller than 35 nm. The wavelength emitted depends on the size of the quantum dots (larger size, longer wavelength). So, quantum dots can be precisely produced to emit any wavelength. This, in principle, offers the possibility to fine tune the resulting spectrum of a blue LED on which a mixture of quantum dots are applied. Where for example, traditional rare-earth phosphors also produce some infrared radiation that does not contribute to visible radiation, the emission in infrared can be better controlled with quantum dots. Quantum dots, either used as the sole wavelength conversion method or in combination with phosphors, may in the future also be used in LED systems for road lighting.

Research is also going on to produce single, multi-layer LED chips, each layer producing a specific colour of light so that the combined result is white light.

10.3.2 LEDs

10.3.2.1 Construction

Different steps, or levels, are commonly distinguished in the construction of LED systems, ranging from level 0 to level 3.

- Level 0: LED chip.
- Level 1: LED package. Chip packed with its electrical connection, mechanical connection and protection, heat dissipation device and basic optical components.
- Level 2: LED cluster. Since, for most applications the light output of a single LED is not sufficient, multiple LEDs are assembled on a printed circuit board (PCB).
- Level 3: LED module. A module with LED cluster, heat sink, electrical driver and sometimes an optical device. The LED module functions as a lamp.

Sometimes a level 4 and 5 is used to characterize the LED luminaire and the LED lighting installation respectively.

LED Chip The semiconductor, crystalline, p and n sandwich material, the basis of the LED chip or LED die, is deposited on a substrate of suitable composition in a complex industrial process called epitaxial growth. The sandwich and substrate material together determine the quality of the LED chip. The LED chip resulting from this process is a "photon or light trap": that is to say, much of the light emitted within the chip is internally reflected by its surfaces (borders between the material and air) and ultimately, after multi reflections, absorbed in the material (heating this up). Only light that hits the outer surface more or less perpendicularly (approximately 20°) can leave the material. By giving the chip a specific shape, the so-called light-extraction efficiency can be improved. Figure 10.19 gives an example of such a specifically-shaped chip.

LED package The design of LEDs is progressing rapidly, and construction of LEDs will consequently change. Figure 10.20 which shows the construction of a high power LED package, should be seen as a typical illustrative example. The LED chip is placed in a reflector cup, which because of its shape, helps to direct the light in an upwards direction. Highly reflective metal or ceramic material is used. All high-power LEDs have a heat sink of high-thermal conductivity material to conduct the heat away from the chip. Non-successful recombinations of p and n-atoms at the chip's junction, and

Fig. 10.19 An example of a specifically-shaped LED chip that improves the light-extraction efficiency

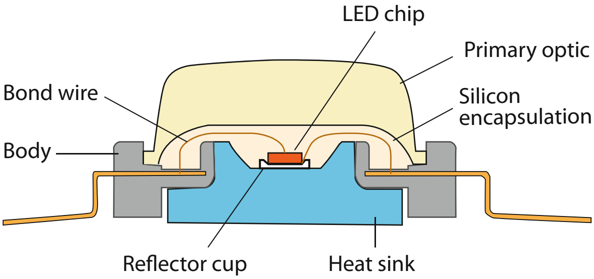

Fig. 10.20 The main components of a high-power LED

light trapped in the chip, heat up the chip, and a higher junction temperature reduces the light output and shortens the lifetime. Effective thermal management is therefore critical for a proper operation of a LED system. This means that LED luminaires, too, must incorporate in their design thermal conduction and convection features. In order to be able to apply power to the chip, the p and n parts of the chip have metal contacts called electrodes. Gold compounds are used for the connecting wires because they form a chemical bond with the surface of the chip. Figure 10.19 shows an electrode with a bond wire. Since the electrodes intercept light leaving the chip, the dimensioning of the electrodes and bond wires, especially on the side of the main light-escape route, is one of the factors that determines the light efficiency of the LED. The top side of the chip, the reflector cup, and the bond wires are encapsulated with silicon for protection. Another important task of the silicon encapsulation is to fill the gap between chip and air. This, together with the primary optics (lens), helps to increase the light extraction from the chip which is essential for a high lumen efficacy of the LED.

In the case of white-light LEDs, phosphors have to be applied over the LED chip. The amount applied is one of the factors that determines efficacy. If too little is applied, the blue radiation can pass partly through it without being converted, if too much is applied the light converted will be absorbed by the phosphors themselves. This also means that the distribution of phosphors over the surface of the LED has to be uniform. The phosphor material may be suspended in the silicon of the encapsulation or sprayed, with a binder, onto the chip surface itself (conformal coating). The latter method results in a more uniform layer (Fig. 10.21) giving a more uniform colour quality of the white light across the whole LED surface.

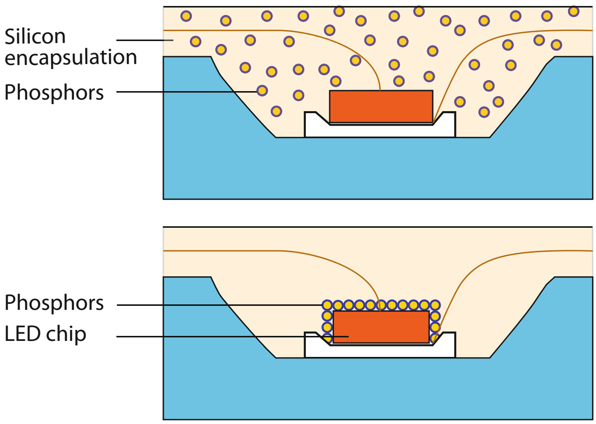

Fig. 10.21 Phosphor suspended in silicon encapsulation (*top*) and conformal phosphor coating (*bottom*)

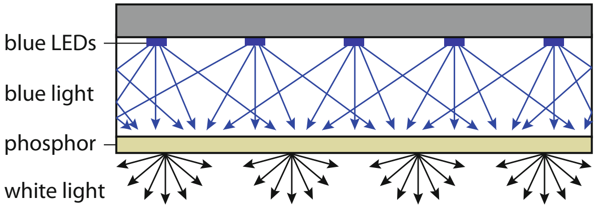

Fig. 10.22 Principle of a remote-phosphor LED module creating *white* light

LED Cluster The luminous flux of one individual LED is quite low compared to that of gas-discharge lamps. Multiple LEDs are therefore often mounted on a printed-circuit board (PCB) to obtain a LED module emitting a high luminous flux. The PCB establishes the electrical connections between all components and the external electrical driver. The PCB must also conduct away the heat from the heat sinks of the individual LEDs to the outside world.

LED Module LED modules integrate the LED cluster with the electric driver, the mechanical connections and with the secondary optics that determine the light distribution of the module.

Some LED modules make use of the so-called remote-phosphor technology (Fig. 10.22). Here, a number of blue LEDs are placed inside a mixing chamber of high and diffuse reflective material. The phosphor layer, positioned remotely from the LEDs on the bottom of the chamber, converts the blue light of the chips into white light. In this way, thanks to the mixing process, small differences in light output and or colour of individual chips are not visible. The risk of disturbing glare is also reduced because the luminance of the large-sized phosphor layer is much lower than the luminances of small, individual LEDs.

For users it can be important to have LED modules (also called LED engines) that, as with most conventional lamps are interchangeable with products from different manufacturers. Interchangeability is achieved by specifications produced by Zhaga, a global industry-wide organisation (Zhaga 2013). The specified interfaces for physical dimensions and for thermal, electrical and photometric properties, are independent of the LED technology used. LED-engine manufacturers can therefore develop and innovate their products completely independently.

10.3.2.2 Lamp Properties

Junction Temperature It has already been mentioned that with increasing temperature of the p-n junction, the performance of LEDs decreases, particularly the light output and lifetime. The performance data are specified for a junction temperature of 25 °C. However, under normal operating conditions, a junction temperature of 60–90 °C is easily obtained. Depending on LED type, the lumen output falls to 60–95 % when the junction temperature increases from 25 to 80 °C. Blue LEDs are least sensitive to changes in junction temperature: at 80 °C the lumen output decreases to 80–95 %. Specification of performance data at a junction temperature of both 25 °C and say, 80 °C would give a much better insight into what may be expected under real-life conditions.

Binning The mass production of LEDs results in LEDs of the same type varying in colour, light output and voltage. In order to ensure that LEDs nevertheless conform to specification, a process called binning is used in the production process. At the end of the manufacturing process, LED properties are measured and LEDs are subsequently sorted into subclasses, or “bins” of defined properties. As the definition of a bin does not change with time, the same quality is also assured from production run to production run. With the advancement of knowledge concerning LED materials and improvements of the mass-production process, we may expect that binning will ultimately no longer be required (“binning-free LEDs”).

Spectrum and Colour Properties By applying different phosphors, white light LEDs within the colour temperature range of 2700 to 10,000 K are produced. Often, the higher-colour-temperature versions have only moderate colour rendering (R_a between 50 and 75). In the lower-colour-temperature versions, LEDs are available with good (R_a greater than 80) to excellent colour rendering (R_a greater than 90 or even 95). The same, three digit, colour-designation system as used for fluorescent and metal halide lamps is also often used for LEDs. Figure 10.23 shows an example of a warm-white (2800 K) and a cooler-white LED spectrum (4000 K). As with all lamps, better colour quality comes at the cost of lower efficacy. The S/P ratio for warm-white versions is around 1.3, for cool-white 1.8 and for blue-rich white 2.2.

Lumen Range Today, high power LEDs exist in lumen packages up to some 1000 lm. In the case of this value, severe screening is called for to restrict glare, because so much light comes from such a small light-emitting surface. As we have seen, by mounting multi LEDs on a printed circuit board, LED modules can be obtained with much larger lumen packages as is required for road lighting.

System Efficacy As with most conventional lamps, the luminous efficacy of LEDs is dependent on the power of the LED and on the colour quality of the light it produces.

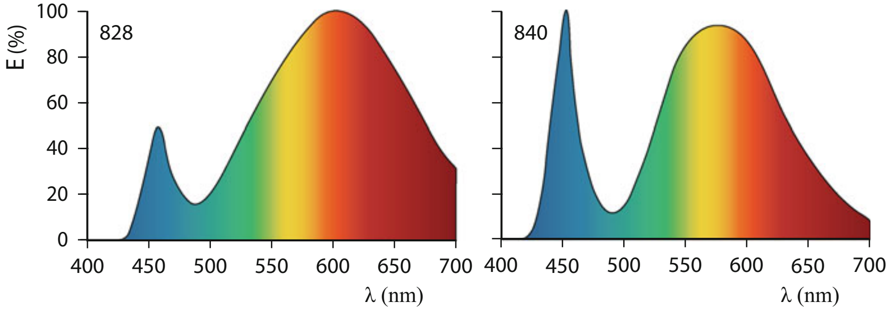

Fig. 10.23 Spectral power distribution of a phosphor LED with colour designation 828 ($T_k = 2800$ K, $R_a = 80$, S/P ratio = 1.2) and 840 ($T_k = 4000$ K, $R_a = 65$, S/P ratio = 1.4) respectively

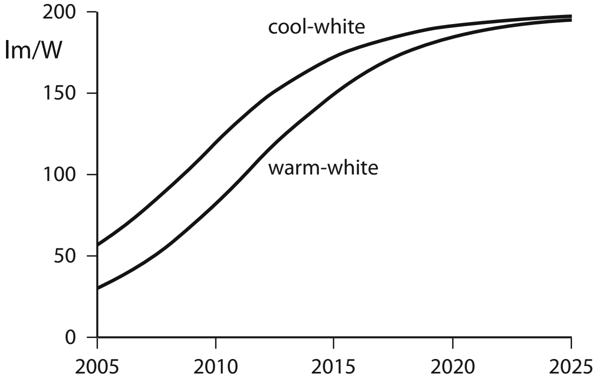

Fig. 10.24 White-light efficacy projections for commercial LED packages. Warm-white: T_k between 2600 and 3700 K with $R_a > 80$; cool to bluish white T_k between 4800 and 7000 K with $R_a > 70$

Higher-power LEDs have higher efficacies, while those with better colour rendering have lower efficacies. Today, cool-white LEDs are commercially available in efficacies of around 150 lm/W, and warm-white LEDs with colour-rendering indices of around 80 with efficacies of around 120 lm/W. These lm/W values include driver losses and do not take into account losses in secondary optics. Further improvements may be expected. The US department of energy (DOE) made future projections through a collaborative effort between industry, academia, research, laboratories and the US government (DOE 2013a). These projections, until the year 2025, are shown in Fig. 10.24 for two groups of phosphor LEDs. The ultimate phosphor LED efficacy according to this projection is about 200 lm/W.

Lifetime LED light sources have a lifetime, based on L_{80}, of between 50,000 and 100,000 h. As has been discussed, the actual lifetime is very much dependent on the chip's junction temperature under operating conditions. Retrofit LED bulbs, with their limited space for heat dissipation, have a lifetime of some 25,000–35,000 h.

Run-Up and Re-ignition LEDs give their full light output immediately after switch-on and after re-ignition.

Dimming LEDs can be dimmed by simple pulse-width modulation down to 5 % of full light output.

Ambient-Temperature Sensitivity Because of the influence of the junction temperature, LEDs perform better at low temperatures (efficacy and lifetime) than at high temperatures. The precise influence of the junction temperature varies for the different types of LEDs and LED luminaires. In high-temperature environments, therefore, relevant information has to be obtained from the manufacturer.

10.4 Control Gear

The control gear needed for operating lamps performs a number of functions: it ensures that the lamp can be started and, once started, can be operated stabely over a longer period of time. Furthermore, if the lamp type permits, it ensures that the lamp can be dimmed. The devices needed for gas discharge lamps are called igniters and ballasts. Instant starting is no problem with solid-state lamps, but the mains supply has to be rectified and transformed to a lower voltage, and measures have to be taken to ensure that the current through the light source is constant. The electrical control gear employed for this purpose with solid-state lamps is usually referred to as the driver. To adjust the lighting level to the actual needs of the moment, many, but not all, of the lamps can be dimmed with proper dimming gear, each different lamp type often requiring a different method of dimming.

10.4.1 Igniters for Gas-Discharge Lamps

Most of the gas-discharge lamps have such a high internal resistance that they require a voltage peak, higher than the normal operating voltage, to initiate the discharge. The igniter is so designed that after the lamp is ignited it stops giving off the high voltage peaks.

In tubular and compact fluorescent lamps, lamp electrodes are preheated for a few seconds before a high voltage peak is applied across the lamp. Preheating facilitates emission of electrons from the electrodes. The voltage peak is either obtained from a traditional glow-switch starter or from an electronic starter. The electronic starter gives a better-controlled voltage peak and always ignites the lamp after one ignition pulse, so eliminating flickering during ignition. Because of the better ignition control, the electrodes suffer less damage, and lamp life therefore increases. Where with conventional ballasts (see next section) the igniter was a separate device in the electrical circuit, while with a modern electronic ballast the ignition function is electronically incorporated in the ballast itself.

Ignition of HID lamps (low-pressure sodium, high pressure sodium and metal halide) is initiated by a high-voltage peak, and there is no pre-heating. Thanks to their built-in, third auxiliary electrode, high-pressure mercury lamps have an ignition voltage lower than the mains voltage and therefore need no igniter. The ignition voltage of most low-pressure sodium lamps is only roughly less than a factor two higher than the 230 V mains and can therefore be obtained with the aid of a transformer that increases the mains voltage sufficiently to ignite the lamp. So-called auto-leak transformers are used that also function as current-limiting ballasts. Low-pressure sodium lamps produced for use on electronic ballasts have an electronic igniter incorporated in the ballast and they are more efficient. Some low-wattage high-pressure sodium lamps have an internal igniter. High-wattage high-pressure sodium lamps (HPS) need an ignition voltage peak of some 3000–5000 volts and metal halide lamps (MH) 600–5000 V. They are normally started using an electronic igniter that generates a series of high-voltage pulses of the required magnitude. The electronic circuit is so designed that these pulses cease after ignition has taken place. Because of differing requirements for ignition voltage, shape of voltage peak and number of voltage pulses within a certain period, each type of HID lamp (and often also each different wattage) needs its own type of igniter.

10.4.2 Ballasts for Gas-Discharge Lamps

The ballast of a gas discharge lamp has two functions to perform. In the section dealing with the operating principle of gas discharge lamps we saw that ionization of the gas results in an ever-increasing flow of free electrons. To avoid an unlimited increase in the lamp current, which would ultimately lead to the lamp's breakdown, a current-limiting device called ballast is needed. The ballast also has to ensure that the lamp continues to operate despite the fact that twice during each frequency cycle of the mains voltage (50 or 60 Hz), the current is zero and the lamp off, and thus has to be re-ignited.

The ever-increasing flow of electrons causes the gas discharge lamp to have a negative-resistance characteristic (Fig. 10.25, left). This means that unless something is done to prevent it, the current will increase uncontrollably (so-called current runaway). The current is stabilized by introducing an external resistor in the lamp circuit (Fig. 10.25, right). The thick-line curve is the result of adding the negative resistance of the ballast (dotted curve) to that of the series resistor (dotted straight line).

Simple resistors can thus be used as current-limiting ballasts for gas discharge lamps, but they dissipate a lot of power and are therefore normally not used. Instead, inductive coils consisting of copper wire wound around an iron core are used. These have the same effect as a resistor, but at much lower power losses in the ballast. These traditional, or conventional, inductive ballasts are called "electromagnetic ballasts" because of the electric and magnetic fields their coils generate. They are sometimes also referred to as "choke ballasts".

An inductive ballast also helps to reduce the time the lamp is "off" during each zero passage of the current—in the ideal case, to zero time off. Figure 10.26 left shows, for the situation where the mains voltage is in phase with the lamp current, that the

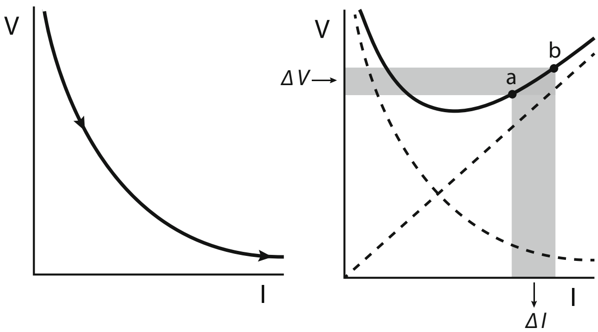

Fig. 10.25 *Left*: negative-resistance device with current run-away. *Right*: with a series resistor in the electrical circuit, the current is stabilized between points *a* and *b*

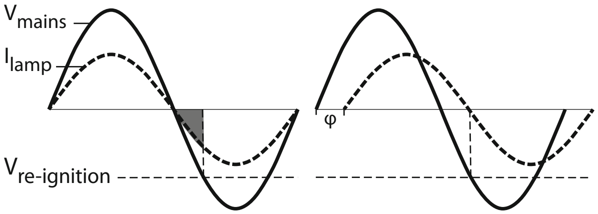

Fig. 10.26 *Left*: lamp circuit without phase shift, shaded area: time interval where the lamp is off. *Right*: Phase shifted inductive lamp circuit, at zero current passage there is sufficient voltage for re-ignition

lamp voltage is after zero passage of the current for a while lower than the required re-ignition voltage. Once the mains voltage is again higher than the re-ignition voltage, the lamp reignites. Figure 10.26 indicates the resulting "off" period of this process by the shaded area. An inductive ballast system helps to reduce the time the lamp is "off" during each zero passage of the current. This is because an inductive system shifts the phase between mains voltage and the lamp current (Fig. 10.26, right): when the current is zero, there is sufficient voltage to immediately reignite the lamp.

Until the 1980s, all ballasts were of the inductive electromagnetic type. Since then, many lamp types can be operated on electronic ballasts supplying the same functions, including the cold-re-ignition function, in a more efficient way. Electronic ballasts for fluorescent lamps were banned from the European market as long ago as 2005 by the European commission because of their low energy efficiency.

Depending on the lamp type, different advantages are obtained with electronic ballasts. With all types, ballast losses are reduced (increasing system luminous efficacy), lamp lifetime is increased, dimming (if possible), is easier and constant light output through life can be obtained (maintained lighting level equal to new lighting level), the ignition function is incorporated, and finally, ballast weight and volume are much smaller.

With fluorescent lamp systems, electronic ballasts also result in an increase of some 10 % in lamp efficacy, so further increasing the system efficacy. Also, remote signaling of lamp failure via the electric network becomes a possibility, enabling tele-management. This is especially important in road lighting with lamps spread over a large area. With fluorescent lamps the electronic ballast transforms the sinusoidal 50 or 60 Hz mains frequency into a square-wave voltage of much higher frequency:

between some 20 and 100 kHz. Hence these ballasts are referred to as HF electronic ballasts. Low-pressure sodium lamps up to some 90 W can be operated on electronic ballasts (in a square-wave frequency range of 45–55 kHz). Those lower-wattage high-pressure sodium and metal halide lamps for which electronic ballasts are available operate in the frequency range of 100–200 Hz. The square-wave operation of electronic ballasts, does of course, ensure direct re-ignition during zero passage of the current, resulting in the ideal zero "lamp-off" situation.

Ballast losses in electromagnetic ballasts vary, according to their quality and lamp type, between some 10 and 30 % of the nominal wattage of the lamp. Electronic ballast losses vary, again according to quality and lamp type, between some 5 and 15 % of the nominal wattage of the lamp. Lamp life increases by 30–50 % in the case of electronic ballasts relative to electromagnetic ballasts.

Electromagnetic ballasts become hot, and too-high temperatures have a drastic negative effect on ballast life. The maximum permitted temperature of the coil windings, T_w, has to be marked on the ballast. Values, dependent on coil insulation, vary from 105 to 150 °C. The ΔT value, which specifies the increase in temperature under standardized ambient temperature conditions, is also given on each ballast housing. The ΔT value varies from 50 to 70 °C. The actual ambient temperature, T_a, at which the ballast can be used is obtained from:

$$T_a = T_w - \Delta T$$

Electronic ballasts produce much less heat than do electromagnetic ones. On the case of the ballast is a test point t_c with an indication of the temperature that should not be exceeded. Luminaire developers should use this point to check that their luminaire satisfies the temperature requirement.

10.4.3 Drivers for LEDs

Like gas discharge lamps, solid-state lamps also fail to function properly when they are operated direct from the mains-supply voltage. The electrical equipment employed for this purpose is referred to as the driver. Solid-state light sources are low-voltage rectifiers that allow current to pass in one direction only. This means that the AC mains supply has to be transformed to low voltage and then rectified into a DC supply. Although a solid-state light source has a positive resistance characteristic, the voltage-current dependency is exponential in the area of operation. Small fluctuations in supply voltage therefore cause large variations in current that can damage the light source (Fig. 10.27 left). A simple series resistor in the electrical circuit stabilizes the current to create, a "constant" current supply (Fig. 10.27, right). In practice only miniature indicator LEDs use such a resistor for stabilizing the current. High-power LEDs use an electronic driver to obtain a similar, constant-current, characteristic.

Power losses in electronic drivers vary, according to their quality, between 10 and 30 % of the nominal wattage of the light source. Losses in poor quality drivers can be

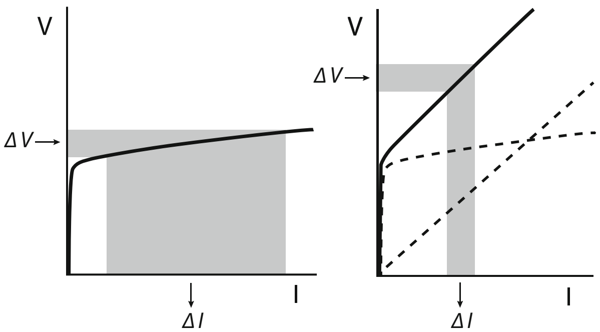

Fig. 10.27 *Left*: voltage-current characteristic of a LED with huge current variation. *Right*: with a series resistor (*dotted line*) the current is stabilized

as high as 50 %. Such drivers may, of course, also easily have an important negative influence on the lifetime of the solid state light source due to too high currents with small voltage variations. The same holds for colour constancy.

In the laboratory, LEDs have been produced where the driver, in the form of a chip, is mounted on the LED chip itself. This just shows just how far miniaturization with LEDs is likely to go.

10.4.4 Dimmers

Dimming is done to adapt the lighting level to the actual lighting needs of the moment in order to optimize power consumption. Low-pressure sodium lamps cannot be dimmed, because their operating temperature would then decrease so much that they would extinguish. High pressure mercury lamps and some of the metal halide lamps cannot be dimmed without producing an unacceptable colour shift.

10.4.4.1 Gas-Discharge Lamps

In the case of fluorescent lamps operated on electromagnetic ballasts, dimming is mostly done by phase-cutting with the aid of a thyristor circuit. This cuts part of the AC current waveform during each half-cycle of the 50 or 60 Hz mains cycle. During the time that the current is cut and the lamp is temporarily off, no power is dissipated, so saving energy while reducing the light output. Fluorescent lamps and high-pressure sodium lamps can also be dimmed by switching a coil, in the form of an extra ballast, in series with the normal ballast. This increases the impedance of the circuit, so decreasing the lamp current and, as a result, the light output of the lamp. In this way the light output can be dimmed by approximately 50 % at 65 % of power. With some high-pressure sodium lamps the twin-ballast system can be combined with an electronic controller that employs phase-cutting. In this way, the light output can be dimmed to 20 % at 35 % power.

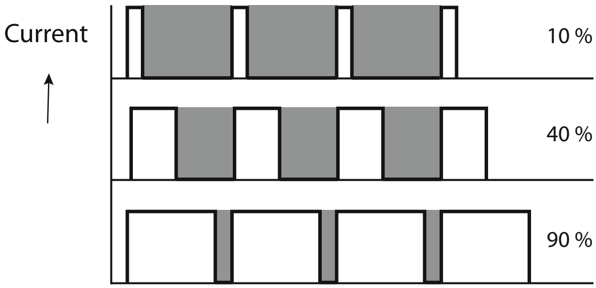

Fig. 10.28 Pulse-width modulation (*PWM*) used for dimming LEDs

Lamps that can be dimmed and that are operated on electronic ballasts use regulation of the frequency of the supply for dimming. Fluorescent lamps can be dimmed to less than 1 % of their nominal light output, provided the electronic ballast provides sufficient heat to keep the electrodes at the proper emission temperature. This means that the two lamp electrodes must be accessible to the dimming circuit, and this is only possible with 4-pin versions. The HID lamps that can be dimmed, can, on electronic dimmers, be dimmed to some 20 % light output at 35 % power. Cold HID lamps cannot be ignited in a dimmed phase. They therefore employ an automatic procedure whereby the lamp is started at full power and dimming is delayed by 3–10 min.

10.4.4.2 Solid-State Light Sources

Most LED drivers with an integrated dimming function use pulse-width modulation (PWM) to regulate the power to the LED. Just as with phase-cutting dimming for incandescent and fluorescent lamps, pulse-width modulation turns the LED on and off rapidly, so reducing the “on-time” so to achieve the desired dimming level. The speed with which this is done (with LEDs: usually between 150 and 400 Hz) is so fast that most people do not notice the flickering of the light. Research on what exactly determines the disturbance felt by a smaller group of people is ongoing (DOE 2013b). The longer the “off” periods are relative to the “on” periods (pulse width), the more the LEDs are dimmed (Fig. 10.28). The smallest pulse width that can be switched by the system determines the lowest dimming level: often approximately 5 %. A relatively simple electronic timer provides the switching off-and-on function. During the “on” pulse, the current is kept at the rated value for which the LED is designed, so that dimming has no negative effects on the operation of the LED, and consequently no negative effects on lifetime.

There is a large quality difference between LED dimmers as regards how much the LED system’s efficacy decreases in the dimmed situation.

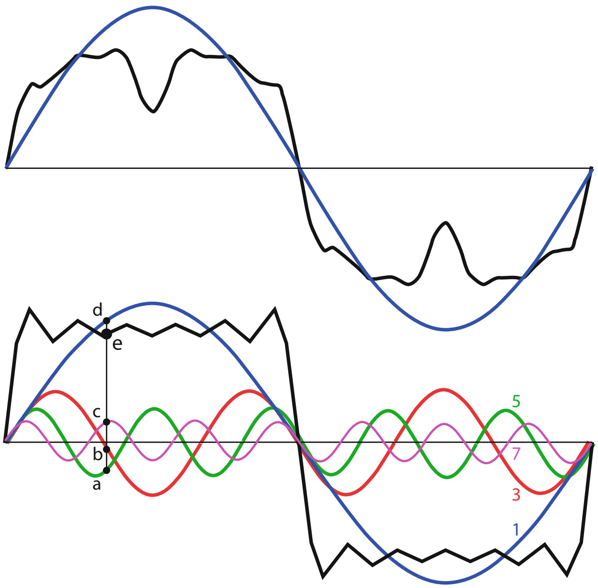

Fig. 10.29 *Top*: an ideal sinusoidal and a distorted current waveform. *Bottom*: the different sinusoidal waves (harmonics) that together add up to the distorted waveform

10.4.5 Power Quality

10.4.5.1 Harmonic Distortion

In gas discharge lamps and in solid-state light sources the mains-current waveform becomes distorted, viz. it is no longer purely sinusoidal (Fig. 10.29, top). Some of the reasons for this are: the ignition peaks during starting of the lamp and re-ignition peaks during zero passage of the current, the use of phase-cutting dimming systems and, with LEDs, the need to provide voltage transformation from AC mains to DC low voltage. The distortion of the waveform is called harmonic distortion. The term harmonic distortion comes from the fact that the distorted current consists of a great number of lower-amplitude sinusoidal waves, called harmonics, of frequencies higher than that of the mains frequency. The higher harmonics are multiples of the fundamental frequency of the mains (50 or 60 Hz) and are numbered sequentially. Figure 10.29 bottom, shows the harmonics, that add up to the distorted square wave (as illustrated by the dots on the thin vertical line: $d + c - b - a = e$). The higher harmonics all result in a different impedance from coils and capacitors in the electrical lamp-gear system. This can lead to an extra energy load. Some current harmonics can flow back into the electricity network where they can subsequently have a disturbing influence on other devices connected to that network. The so called triplen harmonics (3rd, 9th,15th etc.), in particular, have a negative effect because they flow with high currents through the neutral wire of the electricity net with the danger of creating fire hazards. To protect the network, the total harmonic distortion caused by a lamp circuit has to be limited. The first step is the use of high quality lamp, igniter, ballast,

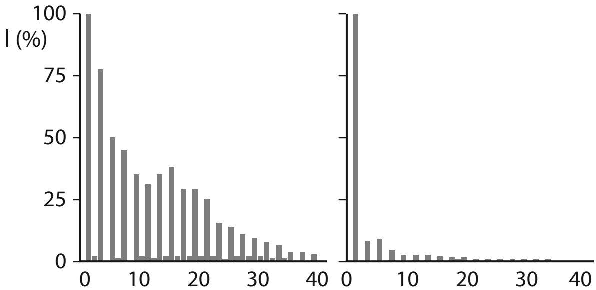

Fig. 10.30 Relative harmonic currents of (*left*) a low-quality LED and (*right*) a high-quality LED system. Horizontal scale: harmonic wave number

dimmer or lamp, driver, dimmer combinations. Figure 10.30 shows an example of the harmonic currents created in a poor-quality LED and in a good-quality LED system, respectively. Nevertheless, electronic filters often have to be incorporated in the circuit to block the passage of higher harmonic currents.

10.4.5.2 Power Factor

As we have seen, the inductive operation of lamps in both electromagnetic and electronic ballast systems shifts the phase of the lamp current relative to that of the mains voltage. This shift is called phase shift. It is indicated by the angle φ between the sinusoidal-shaped current and voltage (as indicated in Fig. 10.26, right). An excessively large phase shift is undesirable, because for the same energy consumption a stronger current is drawn through the wiring and through the cables of the electricity-supply network, requiring thicker cables. Furthermore, the electricity companies cannot easily measure the stronger current and therefore do not get paid for all the energy that they deliver. The ratio of the measured power to the total power really drawn by the system is called the power factor:

$$power\ factor = \frac{W_{syst\ measured}}{W_{syst\ drawn}}$$

For sinusoidal waveforms, the power factor is equal to cos φ. Electricity companies require, especially for the higher-wattage lamps, that the power factor be high enough: for example better than 0.9. Power-factor correction, or as it is usually called, power-factor compensation, is often done by placing a capacitor in parallel or in series with the lamp. This works because capacitive systems shift the current in the opposite direction to inductive systems. Harmonic distortion makes accurate compensation more complicated or even impossible because it has to be done for all harmonics. This is one of the reasons for limiting harmonic distortion by employing high-quality products. With some lamps the phase shift, and thus the power factor, changes over the lifetime of the lamps. Such lamps therefore call for an even more complicated power-factor compensation.

10.4.6 *Electromagnetic Interference*

Lamp control gear should ensure that lamp circuits strictly comply with these EMI requirements.Electrical and electronic devices may emit unwanted electromagnetic radiation that could interfere with other electrical or electronic devices such as computers and radios. The disturbance is called electromagnetic interference, or EMI. Also, gas-discharge and solid-state lamp circuits, especially those employing electronic devices, may cause interference problems. In order to prevent electromagnetic interference problems, all countries or regions have requirements aimed at restricting radiation levels. Lamp control gear should ensure that lamp circuits strictly comply with these EMI requirements.

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Chapter 11
Equipment: Luminaires

Abstract Luminaire characteristics are widely different for the different lamp types and for the different areas of application. The luminaires employed in road lighting are of three basic types: those that throw the main part of their light along the road, which is the case for most of the luminaires used for motorway lighting; those that have a more rotation symmetrically light distribution, as sometimes used for the lighting of non-linear areas such as squares and some residential areas; those used for high-mast lighting, which may have a rotationally-symmetrical light distribution, but more often have an asymmetrical distribution that permits the lighting of complicated multi-level junctions.

The light distribution itself and the efficiency with which it is created by its optical system are key quality aspects of a luminaire. However, the mechanical, electrical and thermal aspects of the luminaire are also important. These aspects determine both the lifetime of the luminaire itself and of the components it houses, like the lamp and gear. They are also important in view of safety and of ease of maintenance. Finally, since road lighting luminaires are part of the daytime scene of an area, also their aesthetical aspect has a role to play. All these aspects will be discussed in this chapter.

A luminaire is a device that controls the light distribution of the lamp contained within it and which includes all the items necessary for fixing and protecting the lamp (and sometimes the control gear as well) and for connecting them to the electrical supply circuit. In American English, the term fixture is usually used instead of luminaire, while in Anglo-Saxon countries the term fitting is also sometimes used.

The principal characteristics of luminaires can be listed under the following headings:

- photometrical
- optical
- mechanical
- electrical
- thermal
- aesthetical

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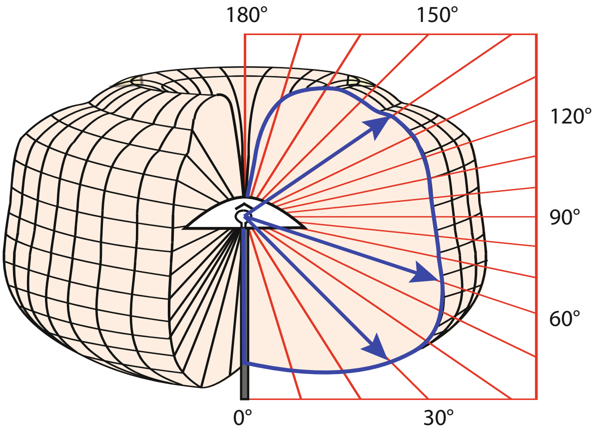

Fig. 11.1 Light distribution of a luminaire. The lengths of the arrows represent the luminous intensities. Drawing after Jansen (1954)

11.1 Photometric Characteristics

A naked lamp radiates its light in all directions with more or less equal strength giving a uniform light distribution. It is the function of the luminaire to "shape" this light into directions where it is needed and to screen it from going in those directions where it could be disturbing. This should be achieved with a minimum loss of light. In lighting-engineering terms: the light distribution of the luminaire should suit the application in question, while the luminaire should have a high light output ratio; the light output ratio being the quotient of lamp luminous flux and luminaire luminous flux.

11.1.1 Light Distribution and Light-Output Ratio

The light distribution of a luminaire defines how the luminous flux radiated by that luminaire is distributed in the various directions within the space around it. This is also called luminous intensity distribution, since it is specified in terms of luminous intensities in all the directions in which the luminaire radiates its light. Figure 11.1 shows the light distribution of a luminaire. The arrows represent the luminous intensities in the various directions. In fact the light distribution is the fingerprint of a luminaire.

To specify the complete light distribution of a luminaire in all directions, different standardized systems of coordinates are employed. The system normally used for road-lighting luminaires (as well as for indoor-lighting luminaires) is the so-called C-Gamma or short C-γ system. In the C-γ system of coordinates the axis of rotation of the C-planes is vertical and passes through the centre of the luminaire (Fig. 11.2). For road-lighting luminaires the C0°–C180° plane is the plane parallel to the longitudinal

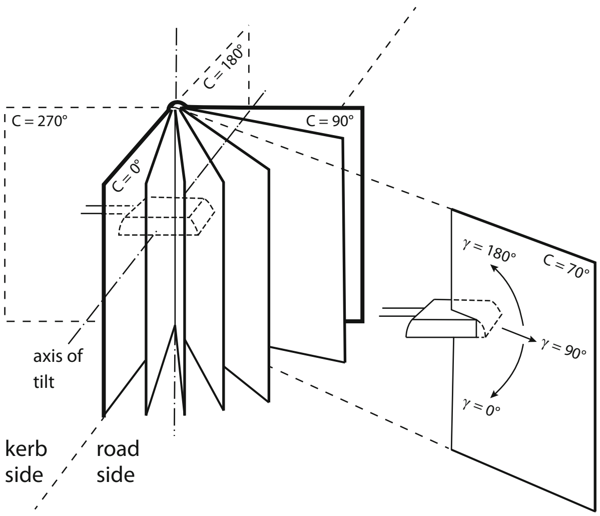

Fig. 11.2 The C-γ system of coordinates used for specifying the light distribution of a luminaire

axis of the road. A direction in a particular C-plane is indicated by the angle γ, which ranges from 0° (down) to 180° (up).

The luminous intensities table, or I-Table, of a luminaire is the digital form of the light distribution of a luminaire and is the basic input for all lighting-calculation software. Table 11.1 shows part of an I-Table in the C-γ coordinate system. The intensity tables usually give relative intensity values viz. candela/1000 lamp lumen values so as to make the values solely dependent on the luminaire and not on the actual lumen of the lamp. Apart from the luminous intensity values, the photometric data file also needs to contain information on the dimensions of the light-emitting surface of the luminaire in order to enable glare calculations.

Different lighting-calculation software programs use different input formats for the photometric data file. The most often used formats are IES and EULUMDAT. The IES format is standardized by the Illuminating Engineering Society of North America (IES 2002) and approved by ANSI. It is also used outside the USA, including Europe. EULUMDAT (Stockmar 1990) is widely used in Europe, where it is the de-facto industry standard, although it is not defined and maintained by a recognized standardization body.

The optical devices that shape the light distribution of a luminaire absorb light. This is why the total lumen output of the luminaire is lower than the lumen output of the lamp (or lamps) contained within the luminaire. The light-output ratio (η) is the ratio of the total lumen output of the luminaire to the lumen output of the lamp(s):

$$\eta = \frac{\Phi_{luminaire}}{\Phi_{lamp}}$$

The light-output ratio of a luminaire is sometimes—somewhat misleadingly—called "luminaire efficiency". A truly efficient luminaire is one that has a light distribution that brings the light from the lamp efficiently to the area where it is needed—that

Table 11.1 I-Table with the luminous intensity values for a specific luminaire

Gamma	C 90°	C 105°	C 120°	C 135°	C 150°	C 165°	C 180°	C 195°	C 210°	C 225°	C 240°	C 255°	C 270°
0.0°	205	205	205	205	205	205	205	205	205	205	205	205	205
5.0°	221	221	218	216	212	207	201	197	192	188	186	185	185
10.0°	237	236	231	226	219	209	197	188	178	171	167	165	165
15.0°	247	246	241	236	230	219	203	184	168	160	155	152	152
20.0°	257	256	251	246	241	229	208	179	158	149	143	139	139
25.0°	261	259	260	271	283	272	236	184	154	144	139	134	134
30.0°	266	262	269	296	325	316	264	189	149	139	134	128	128
35.0°	257	262	276	323	377	369	283	191	145	136	131	124	122
40.0°	260	266	277	325	381	379	286	182	143	134	127	118	114
45.0°	225	250	274	267	372	403	315	183	142	131	122	111	105
50.0°	142	175	211	212	349	389	328	192	147	132	114	101	94
55.0°	92	107	121	140	308	428	372	195	140	125	109	93	83
60.0°	60	71	78	106	276	452	397	196	131	115	100	82	74
65.0°	36	50	63	90	214	416	408	188	123	104	88	70	60
70.0°	21	33	52	79	142	306	361	171	117	89	70	53	41
75.0°	10	23	37	25	41	126	191	83	52	52	35	21	13
80.0°	4.01	4.61	9.02	7.41	6.01	25	55	26	18	13	9.02	5.01	3.01
85.0°	1.00	1.20	1.00	1.00	2.00	3.81	8.12	5.66	2.91	2.20	1.30	1.00	0.00
90.0°	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Values in cd/klm

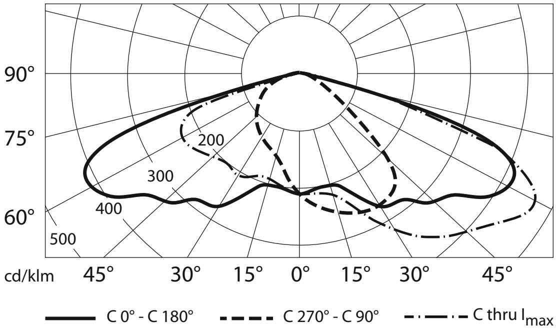

Fig. 11.3 Polar luminous intensity diagram of the luminaire for which Table 11.1 gave the I-Table

is to say it is a luminaire with a suitable light distribution and a good light output ratio. A luminaire with an extremely high light-output ratio but an unsuitable light distribution is not efficient. Road-lighting luminaires have light-output ratios varying between 0.65 and 0.90, depending on their quality and the application field for which they are intended. Sometimes, in addition to the straight-forward light-output ratio, the division into upward and downward light-output ratio is also given. The lower the upward light-output ratio, the lower the disturbing sky glow (one of the aspects of light pollution) will be.

For the selection of suitable luminaires for a certain application clear insight into the photometric quality of a luminaire is needed. This is why luminaire manufacturers produce photometric data sheets containing at least the light-output ratio and polar intensity diagrams. The polar luminous intensity diagram provides a good indication of the suitability of the light distribution for a certain application. In such diagram, the luminous intensities are presented using the C-γ system of coordinates in the form of curves in terms of cd/1000 lm of the nominal lamp flux of the lamps employed. Each curve represents one C plane. Curves are given for only the more important planes. Figure 11.3 gives an example of a polar luminous intensity diagram for a road-lighting luminaire. That, in this example, the light distribution across the luminaire is asymmetrical is clearly evident from the curve through the plane across the road (C270°–C90° plane): more light is radiated towards the road rather than towards the kerb. How well the light is thrown in the direction parallel to the road can be seen from the curve through the C0°–C180° plane. The same curve, at the higher elevation angles, also gives an insight into how good or how poorly glare is restricted by the luminaire.

In this example, above about 65°, the intensities fall off quickly so as to avoid creating glare. Finally, the upper part of the diagram shows how well light above the horizon is restricted,which is an important criterion in preventing light pollution. In this example there is hardly any light radiated above the horizon. The light distribution curve through the C plane where the maximum intensity is radiated is also shown. Rotationally-symmetrical luminaires have the same light distribution in all C-planes (see Fig. 11.1). They are especially used on squares and in residential areas having non-linear road layouts.

Table 11.2 CIE luminous intensity classes. (CIE 2010)

	I_{max} (cd/1000 lm) at and above			
	70°	80°	90°	95°
G4	500	100	10	1
G5	350	100	10	1
G6	350	100	1	1

The beam spread is an important characteristic of the light distribution of floodlights. It is defined as the angle, in a plane through the beam axis (direction of maximum intensity), over which the luminous intensity drops to 50 % of its peak value. To provide extra information on the beam characteristics, the beam spread for another percentage (for example 10 %) is sometimes stated as well.

11.1.2 Luminaire Classification

The luminaires employed in road lighting can be divided into three basic types: conventional road-lighting luminaires that throw the main part of their light along the road, rotationally-symmetrical luminaires, and floodlights with relatively narrow beams (one exception is the catenary type of luminaire that will be described in Sect. 13.1.8). While the CIE and the European Standard classify light distributions only according to their glare aspect, IESNA in North America classifies light distributions based on many more aspects.

CIE (2010) classifies luminaires into six luminous-intensity classes G1–G6 according to the luminous intensities per 1000 lamp lumen for the angles of elevation 70, 80 and 90° and for the area above 90°. Table 11.2 shows the requirements for the three most stringent classes. The European Standard uses the same classes.

IES defines a luminaire classification system (LCS) based on the lumen distribution within solid-angle areas (IES 2007). It replaces the previously used full-cutoff, cutoff, semi-cutoff and non-cutoff system. The LCS system divides the light distribution of a luminaire into three zones (Fig. 11.4):

- the back-light quarter sphere, denoted by the letter B,
- the up-light hemisphere, denoted by the letter U,
- the forward-light quarter sphere, denoted by the letter F, responsible for the lighting of the area to be lit. The higher elevation angles in this quarter sphere are also responsible for possible glare to road users outside the area, which is the reason why this zone is also denoted by the letter G.

Each zone is divided into solid-angle subzones denoted by low (L), mid (M), high (H) and very high(VH). Depending on the total luminous flux radiated in each of the solid angles of a subzone, the luminaire is classified into one of six back-light classes (B0–B5), and one of six up light classes (U0–U5) and finally one of six forward-classes expressed as glare classes G0–G5. The classification system, with

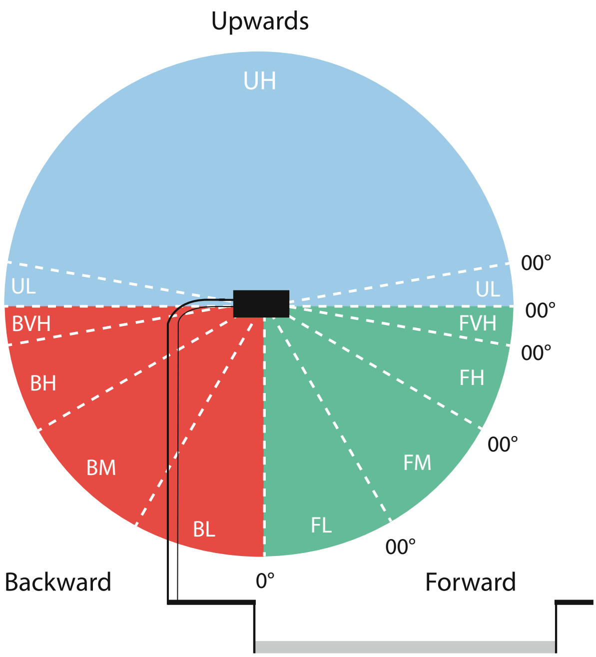

Fig. 11.4 The solid angles of the light distribution that are the basis for the BUG luminaire classification system

its B, U, and G classes, is often referred to as the BUG classification system. The higher the luminous flux in the relevant solid angles areas, the higher the class rating. Table 11.3 gives, as an example, the lumen values for B, U, and G classes 0, 1 and 5. The luminous flux values that determine the BUG classes are in absolute values. This means that a lower lumen package lamp in a luminaire results in lower BUG classes.

Some examples will serve to illustrate the practical meaning of the system. A luminaire with a BUG classification of, for example, 102 is strongly limited as regards its back light, emits hardly any upward light, and restricts glare reasonably well. A BUG classification of 254 denotes reasonable backward limitation of light, very bad upward limitation, and bad glare restriction. It should be noted that the expression "forward" makes no distinction between the light radiated in the lengthwise and crosswise directions on the forward or road side. In this respect it would be interesting to combine the BUG classification system with a former CIE classification system that distinguishes the amount of light radiated forward into different classes of throw (light radiated in lengthwise direction) and spread (light radiated in crosswise direction) respectively (CIE 1976).

Table 11.3 Maximum lumens for BUG classes 0, 1 and 5 of the IES luminaire classification system. (IES 2007)

Solid angle area	B0	B1	B5
BH	110	500	> 5000
BM	220	1000	> 8500
BL	110	500	> 5000
	U0	U1	U5
UH	0	10	> 1000
UL	0	10	> 1000
FVH	10	75	–
BVH	10	75	–
	G0	G1	G5
FVH	10	250	> 750
BVH	10	250	> 750
FH	660	1800	> 12000
BH	100	500	> 5000

11.2 Optical Characteristics

The desired light distribution of a luminaire is obtained through the application of one or more of the physical phenomena: reflection, refraction, and diffuse transmission. Many luminaires also make use of shielding in one form or another, principally to obtain the required degree of glare control and to limit light pollution. The shielding function may be performed by refractors, diffusers, mirror reflectors or, where very stringent glare control is required, by black surfaces. The way in which these various control techniques are employed in a given luminaire and the optical properties of the materials used also determine the light output ratio of the luminaire.

11.2.1 Reflectors

Specular reflectors (also called high-gloss mirror reflectors) are often used when a precise form of light distribution is required. The reflector creates multiple images of the light source which, with a suitable reflector shape, overlap each other to form a uniform luminance pattern on the area to be lighted. The most widely-used material is sheet aluminium, which has the strength needed to produce a stable reflector. To obtain a highly-specular finish, the aluminium is polished: mechanically, chemically, electrolytically, or by a combination of these processes. Reflectance values are around 0.70. Alternatively, commercial-grade aluminium can be clad with a thin layer of super-purity aluminium or silver. With aluminium, reflectance values of up to 0.80 can be obtained, while with silver a reflectance of more than 0.90 is possible. Finally,

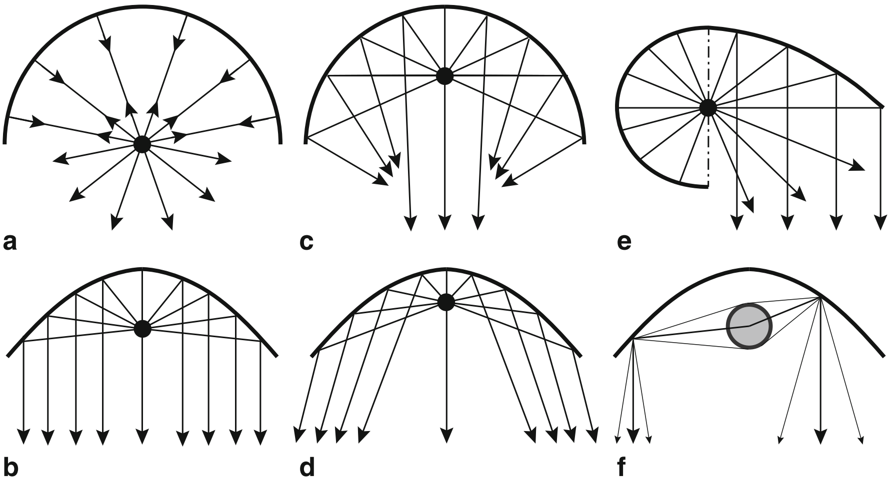

Fig. 11.5 Reflector shapes: **a** cylindrical and **b** parabolic reflector with point light source at focal point; **c** and **d** point light source outside focal point; **e**: combination of cylindrical and parabolic reflector; **f** diverging rays because of a non-point source (not to scale)

there is vacuum metalising, in which a specular layer of aluminium is deposited on a suitably-smooth substrate (metal, glass or plastics).The resulting reflectance, which is somewhere between 0.80 and 0.90, is dependent on both the substrate material and the quality of the metalising process.

The best optical performance is obtained when using a curved reflector. Depending on the curvature, many different types of beams can be created. A curved reflector may be cylindrical, parabolic, elliptical, hyperbolic, or some other contour to suit a particular application. The cylindrical and parabolically-shaped reflectors are the ones often used. In some cases, these shapes can be combined (Fig. 11.5).

The most important optical property of a parabolic reflector is that a point source of light placed at its focus will produce a parallel beam of reflected rays (Fig. 11.5b). If the light source is not at the focus but in front or behind it, the reflected rays are no longer parallel (Fig. 11.5d). Thus, by choosing the position of the light source relative to the focal point, the desired beam shape (narrow to wide) can be created. Combinations of different reflector shapes in one luminaire are employed as well (Fig. 11.5e). Since a lamp is never a real point source, deviations from the theoretical beam shape as obtained from a point light source, will always occur (Fig. 11.5f). The final shape of the light distribution depends on the size of the light source relative to the focal length of the reflector, the width of the open mouth of the reflector and the shape of the light source (Coaton and Marsden 1997). The smaller the light source relative to the size of the reflector, the more accurately can the beam be shaped—but glare control then becomes more challenging.

Fig. 11.6 Road-lighting luminaire with a lens for each individual LED

11.2.2 Refractors and Lenses

Refracting devices are either lenses or prisms. They bend the light that passes through them. The angle through which the light is bent is dependent on both the shape of the refractor and its refractive index (Snell's law). Plastic prismatic controllers are used in road lighting, especially in residential area lighting applications. Refracting glass bowls were in the past sometimes used for high-pressure mercury and sodium road-lighting luminaires, but have now become obsolete. This is partly because they are heavy, but more so because lighting control in the upwards direction, and therefore control of light pollution, is not easily attainable. Today, in LED luminaires, advanced lens-type refractors, one for each individual LED point, are often employed (Fig. 11.6). These make it possible to accurately shape the light distribution. Such a system makes it possible to modify the light distribution by switching or dimming different individual LEDs with different lenses in front of them. This allows the designer to adapt the light distribution to suit the actual luminaire spacing and road width or to changing weather conditions and changes in the road-surface reflection properties.

11.2.3 Diffusers

Translucent diffusers increase the apparent size of the light source. They scatter the light from the lamp in all directions without defining its light distribution. They serve mainly to reduce the brightness of the luminaire and thus the glare created by it. Diffusers are made of translucent plastics, commonly acrylic or polycarbonate. The material should be such that it scatters the light whilst producing the minimum amount of absorption. Diffusers are normally only employed where optical control is not critical, which is sometimes the case in the more decorative luminaires designed for use in pedestrian areas. Usually a top mirror or shield is incorporated into the design to restrict at least some of the upward light so as to help limit some light pollution.

11.3 Mechanical Characteristics

The mechanical function of the luminaire housing is threefold: it accommodates the various component parts of the luminaire, such as the optical system and the various components of the electrical system; it protects these against external influences; and it provides the means of mounting the luminaire in the installation.

11.3.1 Material

Aluminium alloys, in which other elements have been added to the pure aluminium to improve its mechanical and physical properties and its chemical protection, are used in the manufacture of cast, extruded and sheet-metal luminaires. Cast aluminium refers to the process in which molten aluminium alloy is poured (cast) in a mould. Extrusion is the process in which softened aluminium alloy is pressed through the openings of a die. Cast and extruded aluminium alloys are much used in housings for road, tunnel and floodlight luminaires. They can be employed in humid and damp atmospheres without having to add protective finishes.

Plastics may be used for complete luminaire housings, for transparent covers, and for many smaller component parts. All-plastic housings can, of course, only be employed for light sources that have a relatively low operating temperature. In the case of LED luminaires it is important to take into account the fact that plastic is not a good heat conductor. Plastic covers are of methacrylate or polycarbonate. Methacrylate maintains its high light transmission properties over a long period, but its impact resistance is relatively low. The impact resistance of polycarbonates is very high and thus offers a high degree of protection against vandalism. It can be chemically treated to protect it from yellowing under the influence of ultraviolet radiation.

11.3.2 Strength

The luminaire and its mounting attachments should be of sturdy construction to ensure a good, steady positioning of the luminaire and its contents. Any weakness here could lead to changes in the luminaires light distribution and consequent changes in the planned lighting quality of the installation as a whole. The most critical part of a luminaire as far as its strength is concerned are the mounting brackets. The strength required here is covered by a safety factor: the mounting bracket(s) must be able to support at least five times the weight of the luminaire itself. With road-lighting and outdoor floodlighting luminaires, the mounting brackets must also be strong enough to withstand the highest conceivable wind loading for the location. Here a good aerodynamic shape for the luminaire can be advantageous, as it also serves to reduce the strength required for the lighting mast. The term windage is used to refer to the resistance a luminaire presents to the wind. It is the projected area of the luminaire in the vertical plane. The smaller the windage, the lower is the resistance to the wind.

Where protection against vandalism is called for, the impact resistance of the luminaire itself is also important. Reference can be made in this respect to an IEC Standard (IEC 2002) that defines so-called IK codes. These vary from IK01 (low impact resistance: resistance to the impact of a 200 g object falling from a height of 7.5 cm), to IK10 (vandal-proof: able to withstand the impact of a 5 kg object falling from a height of 40 cm.) These requirements are also expressed in impact joules from a pendulum or spring hammer as used in luminaire-testing laboratories. For example, for IK01 an impact of 0.14 Joules and for IK10 an impact of 20 J.

11.3.3 Dirt and Humidity Protection

The luminaire should protect the optical and electrical components contained within it against dirt and humidity. The degree of protection provided by the luminaire is classified according to the International Protection code (IP code) as described in IEC (2013). The IP code consists of two numerals: IP.

- The first numeral classifies the degree of protection against the ingress of solid foreign bodies (ranging from fingers and tools to fine dust) and protection against access to hazardous parts (Table 11.4 first part).
- The second numeral classifies the degree of protection against the ingress of moisture (Table 11.4 second part).

The higher the IP values, the better the protection.

Dust and watertight (or waterproof) luminaire covers must always be used in conjunction with a sealing strip fitted in a strip channel, provided in the luminaire housing, for maximum effect. Due to the variation in temperature between the air inside and that outside the luminaire after switching on or off, pressure differences across the luminaire's cover-seal are bound to occur. The seal or gasket should prevent corrosive gases, moisture and dust from being sucked into the luminaire during cooling off. The effectiveness with which the front cover seals the luminaire against ingress of solids and liquids, and the durability of this sealing function, is determined by the type and quality of the sealing material employed.

11.3.4 Installation and Maintenance

Many luminaires are of such a shape, size and weight as to make mounting them a difficult and time-consuming operation. Mounting, but also relamping and cleaning, must usually be carried out high above ground. This means that the ergonomic design of the luminaire should be such as to make these operations as easy and as safe as

Table 11.4 IP code according to protection against ingress of solid foreign bodies (first digit) and against ingress of water (second digit). (IEC 2013)

	Description	Protected against
IP 1st digit		
1•	Hand protected	Solid objects > 50 mm
2•	Finger protected	Solid objects > 12 mm
3•	Tool protected	Solid objects > 2.5 mm
4•	Wire protected	Solid objects > 1 mm
5•	Dust protected	Harmful accumulation of dust
6•	Dust tight	Penetration of dust
IP 2nd digit		
•1	Drip proof	Vertical falling water drops
•2	Drip proof	Falling water at an angle of 15°
•3	Rain proof	Falling water at an angle of 60°
•4	Splash proof	Falling water from any direction
•5	Jet proof	Water from a 6.3 mm nozzle (30 kPa)
•6	Jet proof	Water from a 12.5 mm nozzle (100 kPa)
•7	Water tight	Temporary immersion in water
•8	Pressure water tight	Continuous submersion in water

possible to perform. For example, for good serviceability covers should be hinged so that the electrician has his hands free to work on the lamp and gear. A luminaire of simple construction with clean lines will, by improving accessibility and facilitating cleaning, not only help to shorten relamping and cleaning times (thereby reducing maintenance costs), it will also reduce the time a road or part of a road is out of commission whilst maintenance of the lighting installation is in progress.

11.4 Electrical Characteristics

The construction of a luminaire should be such as to render it safe electrically to all those involved in its handling. IEC (2009) classifies luminaires according to the degree of protection afforded against electrical shock (Table 11.5).

The sizes of the electrical conductors (wires and connecting blocks) used in the luminaire should be suitable for the actual electrical load. The cable insulation must be sufficient for the high ignition voltages, which may be far higher than the operating voltage and must withstand the often high temperature in the luminaire during operation. To relieve possible strain on the cables and their connections, a means of clamping the cables is required.

Table 11.5 IEC electrical safety classes. (IEC 2009)

Safety class	Protection
I	Basic insulation with protective earth connector
II	Double or reinforced insulation without earthing
III	Extra-low-voltage circuits referred to as SELF (safety extra-low voltage)

11.5 Thermal Characteristics

A considerable amount of the electrical energy supplied to the lamp is converted into heat. The ballast adds to this heating effect within the luminaire. To protect the ballast from overheating, it is sometimes (especially with high-power lamps) screened off from the heat radiation of the lamp by having it placed in a separate compartment of the luminaire. Very-high-powered lamps, as used in some floodlights, should be placed outside the luminaire in a special ballast box.

For a given lamp/ballast combination, the working temperature reached by the luminaire is dependent upon three factors:

- The volume of the luminaire. The greater the volume, the lower will be the temperature rise inside the luminaire.
- The ease with which the heat generated within the luminaire can be conducted through it to the surrounding air. One way of promoting air flow through the housing is to make use of heat-conducting materials in its construction. Most metals are good in this respect, while plastics, on the other hand, are thermal insulators and cannot therefore be employed as housing materials where high-power lamps are involved.
- The cooling effect of the surrounding air. Good heat dissipation calls for large surface areas to be in contact with the surrounding air. Luminaires for high-power lamps, such as some floodlights, and some LED luminaires, that are very sensitive to high temperatures, are therefore provided with cooling fins.

Luminaires are designed to meet the conditions under which they are most likely to be used. The maximum ambient temperature, Ta, at which a luminaire can be operated safely, is indicated on the type label on the product. If no temperature indication is given, the product is intended for use at a maximum ambient temperature of 25 °C. The use of luminaires above their specified maximum ambient temperature may reduce safety margins and will generally lead to a reduction of the lifetime of the various luminaire components. With LED luminaires, not only will the lifetime be reduced but also the lumen output and the luminous efficacy.

11.6 Safety Approval

Luminaires always have to comply with the appropriate safety rules. ENEC (European Norms Electrical Certification) is the European mark for demonstrating compliance with all European Safety Standards. UL (Underwriters' Laboratories) is the similar USA mark. Both certification institutes offer both prototype testing and testing of the production process.

11.7 Aesthetical Characteristics

No less important than the functional characteristics of a luminaire is what may be termed its aesthetic appeal, that is to say its general appearance and styling. It must be remembered that during the hours of daylight, while the lighting installation is not in use, it will be clearly visible to all. In pedestrian areas especially, even a dormant installation can make a positive contribution to the attractiveness of the locality.

11.8 Smart Luminaires

In Chap. 13: "Design Aspects", intelligent dynamic lighting systems that both control and monitor the lighting, will be discussed. Controlling in this context refers to, for example, traffic flow, speed and density, weather conditions, time and presence of other traffic, be this motorised or pedestrian traffic. For this purpose different types of sensors and communication devices for remote control are needed. The main part of many of these devices consists of chips just as LEDs consist of chips. Smart luminaires are being introduced in which these devices are integrated in the luminaire, or sometimes even mounted on the housing of the LED array. "Digital light systems" is an appropriate description for systems making use of such smart luminaires.

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Chapter 12
Equipment: Road Surfaces

Abstract It may at first seem strange to find "road surfaces" dealt with under the heading "Equipment". But the luminance of the road surface is an important quality-determining factor with regard to both visual performance and visual comfort. That luminance is determined by the amount of light directed towards the road surface from the lamps and luminaires and reflected by that road surface in the direction of the motorist. So the lamp, luminaire and reflection properties of the road surface together determine the final lighting quality. By tuning the lamp, luminaire and road surface to each other, the light needed from the lamp-luminaire combination can be minimized. The reflection properties of the road surface thus influence both the lighting quality and the cost and energy effectiveness of a road-lighting installation. Unfortunately, a theoretical approach to the reflection properties of road surfaces has not led to a workable system for describing these properties. So far as road lighting is concerned, however, it is possible to work with a simplified description system, the so called Q_0-S1 system. A classification system for road surfaces, based on this description system, can be used to facilitate all calculations met with in road lighting. This description and classification system will be described in this chapter. The ways in which the values of Q_0 and S1 can be obtained for a particular road surface will be discussed as well.

12.1 Road-Surface Reflection Table

The reflection properties of a road surface cannot be given by a single value. The amount of light reflected from the road surface is dependent on the position of the observer, the position of the point on the surface that the observer is looking at, and the direction of light incidence at that point (Fig. 12.1).

One way to completely specify the reflection characteristics of a road surface is to employ a set of so-called luminance coefficients. The luminance coefficient, q, is defined as the ratio of the luminance at an element on the road surface to the illuminance at the same element, as given by a single light source. Thus:

$$q = \frac{L}{E}$$

The luminance coefficient depends upon the nature of the road-surface material and upon the positions of the light source and the observer relative to the element under

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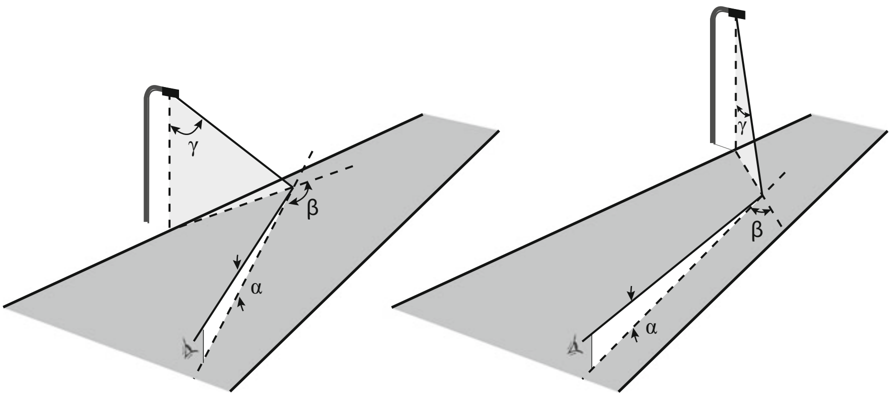

Fig. 12.1 The luminance coefficient of a road surface is dependent on the angle of observation α, the angle β between plane of light incidence and plane of observation and the angle γ of light incidence

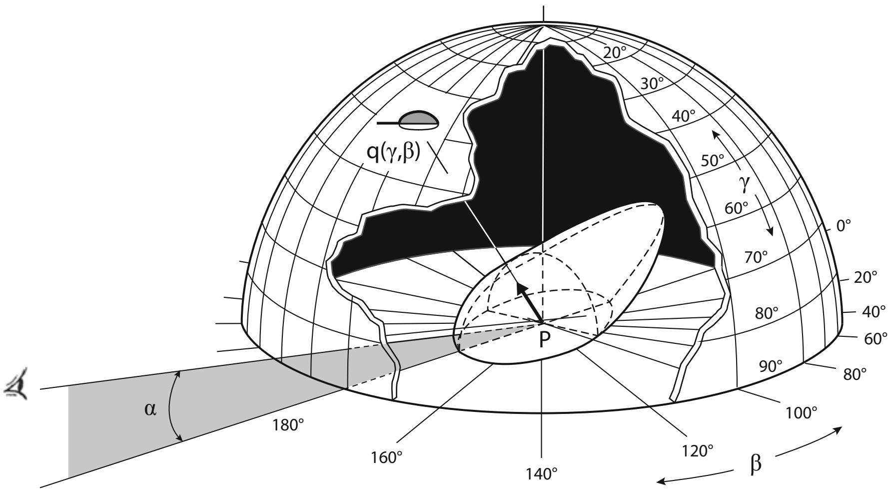

Fig. 12.2 Luminance coefficient indicatrix for a moderately specular road surface; after De Boer (1967)

consideration, as defined by the three angles α, β, and γ (alpha, beta and gamma) in Fig. 12.1. The luminance coefficient q for a given road surface can, visually, be represented by an indicatrix as shown in Fig. 12.2.

In this reflection indicatrix the length of an arrow drawn in any direction represents the luminance coefficient at point P of the road surface when illuminated from the direction indicated by β and γ and viewed under angle α. The more diffuse the reflection of the road surface (equal reflection in all directions), the more the indicatrix approaches a sphere shape. The more specular the road surface, the more pronounced will be the peak of the indicatrix.

In practice, for motorized traffic, the influence the angle of observation α has, can, for motorized traffic, be neglected since it varies between only 0.5 and 1.5° for the stretch of road important to a road user (60–160 m ahead) (De Boer et al. 1952). Luminance coefficients are therefore determined with α held constant at 1°. At the time of writing, research is being considered on finding a practical road surface reflection system for different observation angles; as for example, those relevant for pedestrians (Chain 2008; Chain et al. 2011). For the conditions of observation for car drivers, the luminance coefficient of a road surface can be said to be dependent upon only two angles: β and γ:

$$q = q(\beta, \gamma)$$

The calculation of luminance is made somewhat easier if the so-called reduced luminance coefficient, R, is used in place of q, where

$$R = q(\beta, \gamma) * cos^3\gamma$$

The luminance, L, at an element on the road given by a single source can then be written as

$$L = q * E = q * \frac{I}{h^2} * cos^3\gamma = R * \frac{I}{h^2}$$

where:

R Reduced luminance coefficient of an element on the road surface as defined by β and γ ($cd/m^2/lux$)
I Luminous intensity in the direction of the point (cd)
h Mounting height of the luminaire (m)

The complete reflection characteristics of a road surface can be given in a table in which R values are specified for a number of β-γ combinations. Such a table is called a reflection or R-table for the road-surface in question. An example of an R table is given in Table 12.1. Using a table such as this, it is a simple matter to calculate the luminance produced by a single luminaire at any point on the road surface with the formula given above. Repeating this for adjacent luminaires and summing the results will then give the total luminance at the point. All road-lighting-calculation software makes use of this method.

The remaining question now is how to obtain a reflection table for a particular road surface so as to be able to carry out luminance calculations when designing a road-lighting installation for that particular surface. The many values needed in order to draw up a reflection table can only be accurately determined by performing lengthy and tedious laboratory measurements on a representative sample of the road surface (see Chap. 13). Portable reflectometers suitable for the measurement of road surfaces in the field are not generally available, as will be discussed in Sect. 12.7. Moreover, the road-lighting design often has to be made before the road has even been constructed. Fortunately, there is an alternative method for obtaining a proper reflection table on which to base the lighting design. This method uses a classification

Table 12.1 R-Table (in this case, road surface R3) the 396 R values are given in terms of 10,000*R. The values for the situations sketched in Fig. 12.1 are indicated by the small rectangles

β (°) / tanγ	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0.00	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200	4200
0.25	4657	4657	4585	4585	4528	4457	4400	4400	4328	4257	4200	4000	3871	3742	3685	3614	3557	3485	3428	3428
0.50	4914	4914	4842	4842	4657	4528	4400	4257	4128	3942	3742	3357	3100	2914	2842	2842	2842	2842	2771	2771
0.75	5100	5042	5042	4842	4585	4328	4071	3814	3485	3171	2914	2514	2257	2128	2128	2128	2071	1942	1942	2000
1.00	5171	5171	5028	4657	3942	3557	3228	2914	2585	2257	2000	1685	1485	1428	1428	1428	1428	1428	1428	1428
1.25	5100	5100	4971	4257	3485	2971	2514	2200	1942	1685	1485	1185	1042	1000	1014	1057	1100	1100	1100	1114
1.50	5042	4971	4657	3814	3100	2514	2071	1671	1428	1228	1114	1029	857	814	828	857	857	857	871	885
1.75	4842	4785	4328	3300	2457	1814	1485	1271	1128	1000	885	728	642	628	642	657	642	642	657	671
2.00	4657	4585	4000	2714	1942	1428	1171	1014	885	771	685	557	485	485	485	500	514	514	528	542
2.50	4128	4000	3171	1814	1228	928	771	628	542	485	357	328	314	328	342	342	342	342	342	357
3.00	3614	3357	2328	1214	757	542	442	357	328	285	257	214	214	200	214	214	228	228	242	242
3.50	3100	2771	1742	857	500	357	314	271	228	214	185	142	128	128	142	157	157	171	171	185
4.00	2714	2328	1285	614	371	285	228	200	171	142	128	100	100	100	114	114	128	128	128	142
4.50	2328	1942	1042	442	285	214	171	142	128	114	114	71	71	71	71	85	100	114	114	128
5.00	2071	1557	857	342	228	171	128	114	114	100	85	57	48	42	57	57	71	100	100	100
5.50	1814	1342	671	257	200	142	114	100	85	85										
6.00	1614	1100	514	214	157	128	114	100	71											
6.50	1485	971	428	157	114	85	71	57												
7.00	1357	857	342	128	100	71	57	42												
7.50	1242	757	300	100	71	57	57													
8.00	1185	671	242	85	57	57	42													
8.50	1114	600	214	71	57	42	42													
9.00	1042	542	171	57	42	28														
9.50	985	485	142	57	57	28														
10.00	928	457	128	42	28	28														
10.50	885	414	114	42	28	28														
11.00	842	371	100	42	28	28														
11.50	800	342	85	28	28															
12.00	757	314	85	28	28															

system of road surfaces. It can be used because it has been found that the reflection properties of most dry road surfaces occurring in practice can be described with just two characteristic parameters.

12.2 Description System

The description system for the reflection characteristics of a road surface (and thus of its reflection table) is based on the consideration that most surfaces can be reasonably well described in terms of two basic qualities: their lightness (or degree of grayness from white to black), and their specularity (or shininess). A description system based on this consideration was first described in the sixties of last century (De Boer and Westermann 1964; De Boer and Vermeulen 1967) . Based on many further investigations (Erbay 1974; Sørensen and Nielsen 1974) CIE adopted in 1976 the so called Q zero-S1 description system, which today is still the recommended system and used all over the world (CIE 1976, 1984, 2001).

The parameters of this system are called:

- for lightness: the average luminance coefficient Q_0,
- for specularity: the specular factor S1.

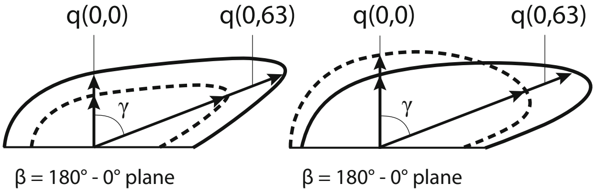

Fig. 12.3 Reflection indicatrices. Arrows indicate q(β = 0,γ = 0) and q(β = 0,γ = 63). S1 = q(0,63)*cos3γ/q(0,0). *Left*: same S1 but different Q_0. *Right*: different S1 but similar Q_0

A low Q_0 value represents a dark road surface and a high Q_0 value a light surface. A low S1 value represents a diffuse surface (low glossiness) and a high value a more-shiny surface (high specularity). The numerical values of Q_0 and S1 can be calculated from the reflection table. Q_0 as the solid angle weighted average of all the luminance coefficients and S1 as the ratio of two R values:

$$Q_0 = \frac{1}{\Omega} * \int \int_{\Omega} q d\beta d\gamma$$

$$S1 = \frac{R(\beta = 0, tan\ \gamma = 2)}{R(\beta = 0, tan\ \gamma = 0)}$$

with Ω being the solid angle measured from the point on the surface containing all those directions from which light is incident and contributes to reflection. The boundaries of these directions of light incidence are standardized (CIE 2001). Based on these boundaries Appendix C gives a table with weighting factors which can be used as multipliers for the R-Table of a road surface to get its Q_0 value (Sørensen and Nielsen 1974; CIE 2001). The tangent of 2 equals 63° and thus R(β = 0, tan γ = 2) corresponds to steep angle of light incidence. That also means that R(β = 0, tan γ = 2) in the definition of the specular factor S1, corresponds in the reflection indicatrix to a position near to the peak of the indicatrix, and thus indeed is representative for the specular reflection of the road surface (Fig. 12.3).

That Q_0 and S1 are indeed suitable for describing the road surface is illustrated in Fig. 12.4, which shows four different road surfaces. The two road surfaces shown on the left have a different lightness but the same specularity. That means that their reflection indicatrices have a similar shape (Fig. 12.3 left).The two surfaces at the top of Fig. 12.4 have the same lightness but different specularity, and consequently a different indicatrix shape (Fig. 12.3 right). In fact Q_0 is indicative for the volume of the indicatrix. Similarly, the two surfaces on the right of Fig 12.4 have the same degree of specularity (more shiny than the two on the left), while the two surfaces on the bottom have the same lightness (darker than the two top ones) but different specularities. Each particular road surface is, for practical luminance calculations, sufficient-well characterized by its lightness (i.e. Q_0) and specularity (i.e. S1).

The fact that for the determination of Q_0 all 396 values of an R table are required, makes the actual measurement difficult and time consuming. This will be discussed in some detail in Sect. 12.2.4. Several methods have therefore been proposed to

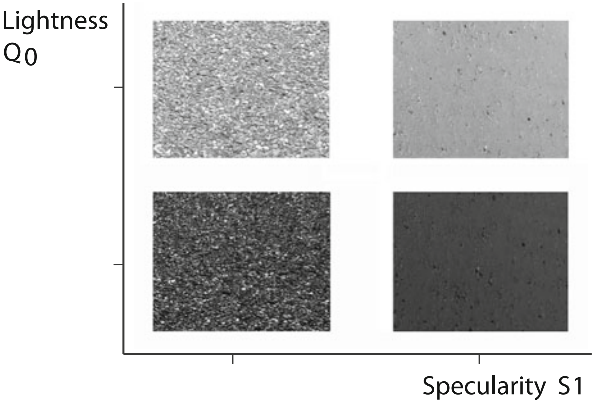

Fig. 12.4 Four different road surfaces. *Left* compared to *right*: low as opposed to high specularity (S1), i.e. a diffuse and a shiny surface. *Bottom* compared to *top*: low as opposed to high lightness (Q0), i.e. a dark and a light surface

determine Q_0 or, more generally, the reflection properties of a road surface, by a limited number of carefully-chosen luminance coefficients. Some of these proposals are based on the consideration that the average luminance coefficient is for an important part determined by the diffuse part of the reflections viz. by the "sphere-shaped" part of the reflection indicatrix. Burghout (1979) proposed the use of the luminance coefficient for perpendicular light incidence, $q(\beta = 0, \gamma = 0)$, instead of Q_0, which however was shown to lead to unacceptable large deviations in luminance calculations for road lighting (Van Bommel 1980). Demirdes (2008) assumes in his considerations the average luminance coefficient Q_0 to be the sum of a diffuse and, a smaller, specular component. Based on 244 different R-tables, obtained from actual road surface reflectance measurements (Erbay 1974), Demirdes concluded that Q_0 can be approximated with sufficient accuracy by:

$$10.304 * \{R(\beta = 90, tan\gamma = 2) + 0.085\ R(\beta = 0, tan\gamma = 2)\}$$

The first R value in this equation stands for the diffuse reflection contribution and the second one for the specular reflection contribution to Q_0.

It has to be noted that these considerations have been based on road surfaces measured in the 1960s and 1970s. Actual measurements on road surfaces carried out recently, show that the older, last-century road surfaces are no longer representative enough for today's practice (Fotios et al. 2005; Chain et al. 2007; Dumont and Paumier 2007; Iacomussi et al. 2011). Explorations have been started to find good approximations for Q_0 and possible alternatives for S1, based on an extensive set of more recent R-tables (Dumont and Paumier 2007; Chain et al. 2011). First results have shown that Demirdes approach (as above described), using two R values to approximate Q_0, is not accurate enough. A third or fourth R value improves the accuracy. For example, using $R(\beta = 0, tan\gamma = 2)$, $R(\beta = 0, tan\gamma = 0)$ and $R(\beta = 5, tan\gamma = 5)$ in an approximation formula for Q_0 improves the accuracy considerably (Chain et al. 2011). Korobko (2013) is trying to approximate the spatial distribution of luminance coefficients (i.e. the reflection indicatrix) with the help of a mathematical model considering the indicatrix as an ellipsoidal body. In this way it would perhaps

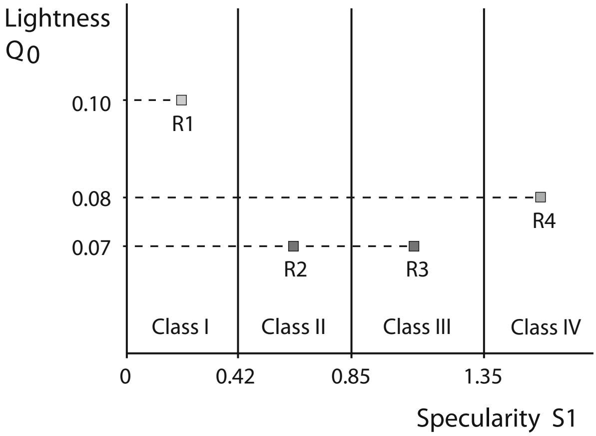

Fig. 12.5 Road-surface class limits of the R classification system with the standard Q0 value for each class

be possible to determine the parameters of the model, and subsequently the whole R-table by just a few luminance coefficients. Possibly, this method would also enable us to determine from a model valid for an observation angle of 1°, indicatrices, and thus R-Tables, for observation angles other than 1°. CIE has set up a new Technical Committee to draft a report based on current road surfaces.

12.3 Classification System

A classification system of road surfaces has been developed with the purpose of obtaining a reflection table without the need for measuring the actual road surface. The requirement in developing the system, of course, was that luminance calculations based on such a reflection table would give accurate enough results. Each type of dry road surface is placed in one of four classes according to its S1 value and thus according to its degree of specularity. Figure 12.5 shows the four classes with the class limits of the R-classification system defined by CIE (1984, 2001). The higher the class, the larger the degree of specularity of the road surfaces in that class. By accepting a certain inaccuracy it is possible to characterise each road surface in each class by only one reflection table typical for that class. In other words, each class can be assigned a standard reflection table with which luminance calculations for surfaces falling in that class can be made. CIE has specified these standard reflection tables, the so-called R1–R4 tables. The reflection table shown in Table 12.1 is in fact the standard reflection table R3 for class 3. As the standard reflection tables are scaled for a Q0 value of 1.0, the tables must be rescaled according to the actual average luminance coefficient Q0 of the road surface in question for which the luminance calculations are to be made. Often, however, the actual Q0 value of a road surface will not be known. For these situations CIE defined standard Q0 values for the different

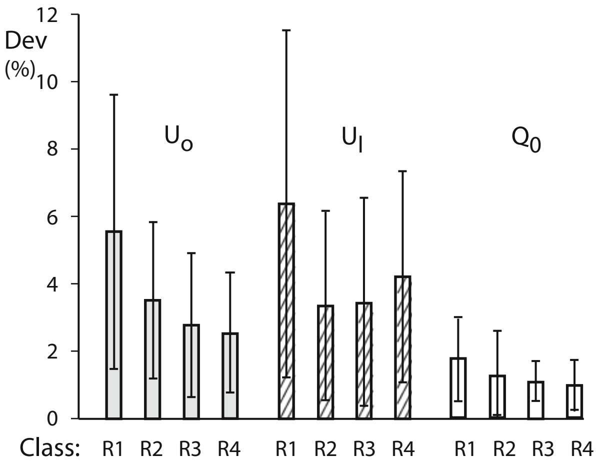

Fig. 12.6 Average deviations (with standard deviation) between U_o and U_l calculation results for 60 road surfaces compared with the result for the standard table of the relevant R-class. Single-sided and staggered arrangements at a mounting height of 10 m and a spacing of 45 m on a 10.8 m wide road. The deviations between the Q_0 values of the 60 surfaces compared with the standard Q_0 value of the relevant class, are also given

classes based on the average Q_0 value of a large number of measured road surfaces of each class. These standard Q_0 values are also shown in Fig. 12.5.

To get an idea of the inaccuracies involved in the R-classification system, the overall and longitudinal uniformities, U_o and U_l have been calculated using a representative luminaire, with good glare control, in single-sided and staggered arrangements for sixty different road surfaces spread over the four R-classes. Uniformity calculations are chosen for this purpose because they are more strongly affected by the S1-classification system than are luminance-level calculations are. The uniformity results for each of the sixty road surfaces is compared with the results obtained for the standard R table of the relevant class. The average deviation for each class, for U_o and U_l respectively, are shown in Fig. 12.6 together with the spread (standard deviation).

The deviation between Q_0 of an actual surface and the standard Q_0 value of the relevant class, affects the average luminance calculation but not the uniformity calculation. The average deviations of Q_0 for the four classes are also shown in Fig. 12.6.

Burghout (1979) proposed a two-class classification system. By careful selection of two appropriate standard R-tables for the two classes, the inaccuracies hardly increase relative to the use of a four-class R-system (Van Bommel 1980). CIE defined two standard reflection tables for this system and adapted it as the C-class system (CIE 2001). The S1 class limits of this system are given in Table 12.2 together with the limits of the R system and of the N-system that will be described below. Although, in its 2001 Publication, the CIE proposed the C-classification system with its C1 and C2 reflection tables as the preferred system, it is the R-system that is used most widely.

The most suitable class limits, standard tables and standard Q_0 values for each class, depend to a certain extent on the type of road surfaces likely to be encountered in practice. This is why that CIE also defined an N or Nordic-classification system for

Table 12.2 R, C and N-class limits and class-standards

Class name	Class limits	Class standard	Standard Q_0
RI	$S1 < 0.42$	R1	0.10
RII	$0.42 \leq S1 < 0.85$	R2	0.07
RIII	$0.85 \leq S1 < 1.35$	R3	0.07
RIV	$1.35 \leq S1$	R4	0.08
CI	$S1 < 0.40$	C1	0.10
CII	$0.40 \leq S1$	C2	0.07
NI	$S1 < 0.28$	N1	0.10
NII	$0.28 \leq S1 < 0.60$	N2	0.07
NIII	$0.60 \leq S1 < 1.30$	N3	0.07
NIV	$1.30 \leq S1$	N4	0.08

road surfaces typically occuring in Scandinavian countries where artificial surface brighteners are often employed, which makes surfaces very diffuse. All good lighting-calculation software packages have the R, the C and the N-standard reflection tables stored in their database.

The R and C-classes as well as the N classes and their standards, are based on the set of road surfaces measured in the 1960s and 1970s of last century. As has been mentioned before, actual measurements recently carried out on road surfaces show that the road surfaces of last century are no longer representative enough for today's practice. The technical committee of CIE, already referred to, that is working on the subject of refection properties of road surfaces, will also try to define class limits and standard tables based on road surfaces that are in use today.

12.4 Influence of Spectrum of Light

The reflection of a road surface, like most surfaces, is not constant over the whole wavelength area: in other words, road surfaces are not completely achromatic. Ekrias et al. (2009) measured the spectral reflectance of eight different stone-mastic asphalt surfaces, while Adrian and Jobanputra (2005) measured a concrete surface. Their results are shown in Fig. 12.7 on a relative scale where the reflectance at 400 nm is put at 100 %.

As can be seen, for all surfaces the reflectance is higher for longer wavelengths. Consequently, light sources that emit more light at longer wavelengths (warmer tinted light) reflect more light from the road surface and thus are more efficient in creating road-surface luminance. From Fig. 12.7 the effect seems to be considerable. However, one has to bear in mind that the eye sensitivity is low at long wavelengths. For the asphalt road surface, having the largest spectral effect (the bold drawn curve in Fig. 12.7), the resulting road surface luminance has been calculated for different

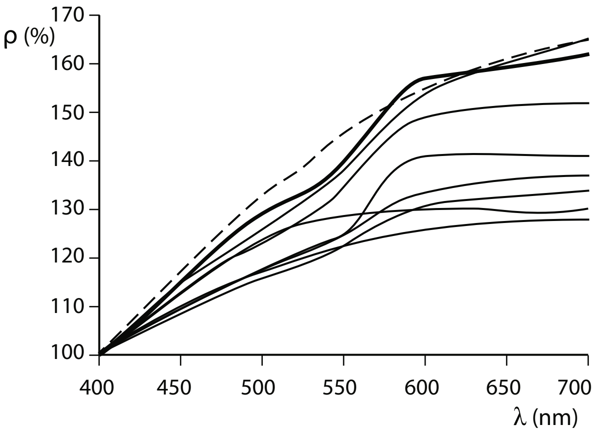

Fig. 12.7 Relative spectral reflectance of asphalt road surfaces, *solid curves* (Ekrias et al. 2009), and of a concrete road surface, *broken line* (Adrian and Jobanputra 2005)

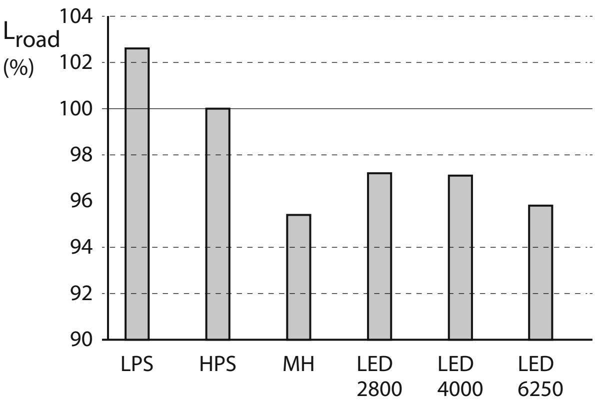

Fig. 12.8 Relative road surface luminance as resulting from the spectral reflectance effect of the asphalt surface shown in Fig. 12.8 (bold drawn curve) for low-pressure sodium (*LPS*), high-pressure sodium (*HPS*), metal halide 4500 K (*MH*) and different versions of LEDs indicated by their colour temperature

light sources. Figure 12.8 shows the results relative to the results of the high-pressure sodium lamp.

For the road surface with the highest spectral effect the metal halide lamp results only in approximately a 5 % lower road surface luminance than high pressure sodium does. The various LED lamps result in 3–4 % lower road surface luminances. So, the differences are relatively small.

12.5 Wet Road Surfaces

For specular or near-specular road surfaces the luminance coefficient ceases to be a characteristic of the surface alone, and becomes dependent upon the luminance and size of the light source providing the illumination. Figure 3.26 of Chap. 3 shows a photograph of an inundated road where it can indeed be seen that it is the luminances

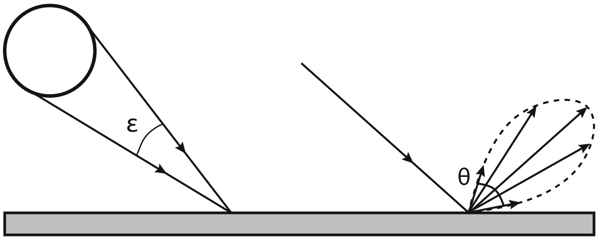

Fig. 12.9 The influence of the luminance of the light source on the magnitude of the luminance coefficient can be neglected if the solid angle ε of light incidence is small compared with the solid angle θ of the reflected light

of the luminaires that determine the road-surface luminances. As the road surface becomes more diffuse, the influence of the luminance of the light source decreases, but only disappears completely for a perfect diffuser. In practice, however, this influence that the luminance of the source has on the magnitude of the luminance coefficient can be safely neglected when the specularity of the road surface is such that the solid angle (ε) subtended by the source at the point of measurement (Fig. 12.9 left) is small compared with the solid angle (θ) within which a parallel beam of light from the source would be reflected by the surface (Fig. 12.9 right) (De Boer 1967). This condition is in practice fulfilled for all types of luminaire so long as the road surface is not inundated.

For wet but not inundated surfaces, the luminance coefficient can be meaningfully defined, and this means that for these conditions valid luminance calculations can indeed be made using reflection-table values. The first requirement when designing for wet weather conditions is, of course, a definition of what exactly constitutes a wet, but not inundated, surface. The CIE defines for this purpose the condition of a sample of the road surface obtained 30 min after having been uniformly sprayed with water at a rate equivalent to 5 mm of rain per hour in a draught-free room at a temperature of 25 °C and with a relative humidity of 50 % (CIE 1976). This condition of the sample is called the standard wet condition. It has been chosen on the basis of measurements of Danish roads, from which it appeared that under Danish weather conditions the specularity of a road surface only surpasses the specularity of its standard wet condition during 10 % of the time (Frederiksen and Gudum 1972). With the attention today for well-drained road surfaces, the standard wet condition will be surpassed for an even shorter time. If a road surface changes from the dry to the standard wet condition, both the specular factor S1 and the Q_0 value increase. This is illustrated in Fig. 12.10.

The S1 part of the figure clearly shows that road surfaces with relatively small specular S1 values in the dry condition, also have relatively small S1 values in the wet condition. In other words, road surfaces with small S1 values in the dry condition (class RI) do not change so much in the wet condition and are therefore the road surfaces to be preferred.

In addition to the dry road-surface classification system, CIE (2001) also defined a classification system for wet road surfaces based on the S1 value of the standard wet condition: classes WI–WIV. Wet road surfaces are represented by a standard R-table in each class: the W1–W4 wet-surface standard R-tables. The wet surface S1 limits

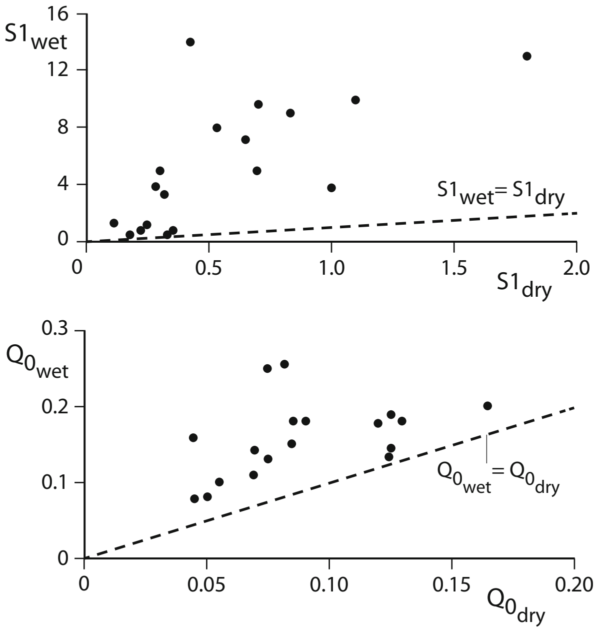

Fig. 12.10 Specular factor S1 and average coefficient Q_0 for a road surface in its dry and standard wet condition. The *dashed lines* indicate the condition where there is no difference between the dry and the wet condition. Based on Danish road surfaces (Sørensen and Nielsen 1974)

for the W classes and the properties of the W standard tables are given in Table 12.3. The W classification system with its W1–W4 standard R-tables makes it possible to make luminance calculations not only for the dry condition but also for the (standard) wet condition. Comparing the class limit of the WI class with Fig. 12.10 shows that most road surfaces of class WI correspond to road surfaces that belong to class RI in the dry condition.

Because of the fact that, as we have seen, in the wet condition both the S1 and Q_0 value of a road surface changes, Frederiksen and Sørensen (1976) defined a specific specular factor for the wet condition. This they called the corrected specular factor S1'. It is defined on the basis of both the S1 wet and Q_0 wet value as follows:

$$\log\left(\frac{S1'}{0.147}\right) = \frac{\log\left(\frac{S1wet}{0.147}\right)}{1 - Q_{0wet}/0.687}$$

Table 12.3 W-class limits and class-standards for wet road surfaces

Class name	Class limits	Class standard	Standard Q_0
WI	$S1 < 4.5$	W1	0.114
WII	$4.5 \le S1 < 7.2$	W2	0.150
WIII	$7.2 \le S1 < 9.8$	W3	0.196
WIV	$9.8 \le S1 < 12.0$	W4	0.247

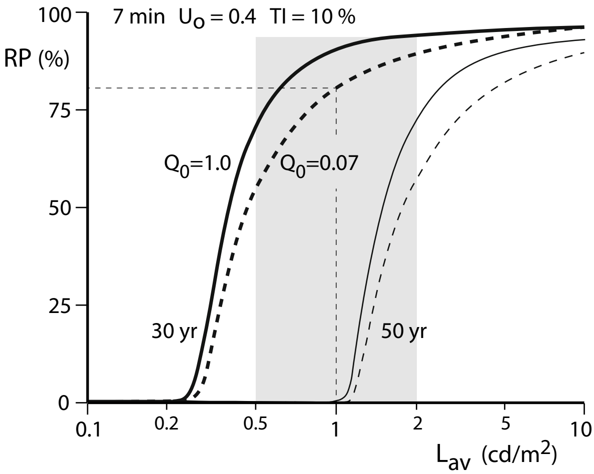

Fig. 12.11 Revealing power curves for a vertical illuminance to average road-surface luminance ratio of 3.5 and 5 respectively. These ratios correspond to a road surface with an average luminance coefficient Q_0 of 0.1 and 0.07 respectively

A classification system based on this corrected specular factor S1' is probably more accurate. However, before further progress can be made towards developing a more accurate system, further investigations into wet-weather road-surface conditions based on today's road surfaces are clearly needed.

12.6 Q_0 and Visual Performance

As we have seen, the average road-surface luminance is proportional to the average luminance coefficient Q_0 of the actual road surface. The higher the Q_0 value, viz. the lighter the road surface, the lower the luminous flux of the lamps needed to obtain the specified road-surface luminance level. The luminous flux needed is inversely proportional to the increase in the value of Q_0. The application of high-Q_0 road surfaces therefore saves energy. At first sight, it would perhaps appear that, for the same road surface luminance, the choice of the road surface does indeed have an influence on energy consumption, but not on visual performance. However, a road surface with a higher Q_0 value also has a positive influence on visual performance as far as object seeing is concerned. With a higher Q_0 value of the road surface, the decrease of the luminous flux from the luminaires results in a reduction of both the vertical and the horizontal illuminance. However, thanks to the higher Q_0 value, the road surface luminance itself does not decrease. The ratio of vertical illuminance (on objects) relative to the road surface luminance decreases so that more objects are seen in stronger negative contrasts, thus improving the silhouette-effect of vision. This positive effect on visual performance is demonstrated in Fig. 12.11, where the revealing power is calculated for a ratio of vertical illuminance to average road luminance of 3.5 and 5 respectively; these ratios correspond to a Q_0 value of 0.1 and 0.07. The ratio of 5 was used in all previously-shown revealing-power calculations (Chaps. 3 and 7).

It can be seen that a lower lighting level suffices for an identical visual performance. For example, to get the same revealing power value at 1 cd/m^2 the brighter surface does not need 1 cd/m^2 but only approximately 0.7 cd/m^2: an extra saving of 30 %. Of course, the positive effect of visual performance only concerns those objects seen against the road surface, which, as we have seen, is especially the case for roads meant for motorized traffic.

12.7 Acquirement of Reflection Data

Here we will discuss the ways in which the reflection properties of a particular surface may be determined. This in order to learn to which class the surface belongs and which of the standard reflection tables should be used as a basis for the lighting design. In this respect it is important to realize that most surfaces will show a change in their reflection properties with wear, the change normally being greatest during the first few months of use, after which the surface characteristics more or less stabilize. This stabilized surface condition is, of course, the one that should be taken for lighting-design purposes. The change in reflection properties will not be constant over the whole road surface. Ideally, therefore, the reflection properties should be determined for a number of different locations on the road in order that its 'average' reflection properties may be defined. It also means that it has little practical meaning to determine the reflection properties to a very high degree of accuracy.

There are various ways of determining the reflection properties of a given road surface: laboratory measurements, in-situ measurements, and by a comparison of road-surface materials.

12.7.1 Laboratory Measurements

An complete reflection table can be drawn up based on measurements performed on a small sample of the road surface concerned. This method is both complicated and time consuming: the sample must be cut and then transported to a suitably-equipped lighting laboratory. The sample (or preferably samples) should be taken from a part of the road that is representative of the whole. For new road surfaces this method is not possible, because the road surface reflection properties are not yet stabilized.

12.7.2 In-situ Measurements

Few portable reflectometers for in-situ measurements with sufficient accuracy are available. Normally, therefore, this method is not feasible for daily road lighting design practice. Chapter 14 will describe the working principle of some of the portable reflectometers.

12.7.3 Comparison of Materials and Construction Methods

When, in a given region, similar materials are used in the composition of road surfaces, and the construction method is also similar, it can be expected that roughly similar reflection properties will be obtained for all roads in that region. It follows, therefore, that once the class and Q_o value of just some of the roads in the area have been determined by measurement, the same class and Q_o value can be used for all the roads in that region. This is, in fact, the common practice.

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Chapter 13
Design Aspects

Abstract The basic lighting arrangements that a lighting designer can use to satisfy the lighting requirements of lighting level, uniformity, visual guidance and glare restriction, are described in the first part of this chapter. The quality of the lighting installation may deteriorate too much under adverse weather conditions, if those conditions are not considered in the design process. Guidance on how to optimize installations for adverse weather circumstances are therefore given. The lighting quality will also deteriorate due to lamp-lumen depreciation, lamp failure and luminaire fouling. It is therefore the task of the lighting designer to advise a suitable maintenance period and to design the initial installation so that the lighting quality will never fall below specification. Lighting design and maintenance optimization will therefore be discussed in a further part of this chapter. Another task of the lighting designer is to make a plan for how the lighting installation will be controlled and operated. This subject will also be dealt with in this chapter. Finally, the environmental aspects of road lighting will be discussed in order to ensure that the installation is sustainable.

Road-lighting design principally involves making a plan of how to illuminate the area of road surface ahead so that it can be surveyed as efficiently as possible. This is achieved by combining the T-shaped luminance patterns produced by individual luminaires (Fig. 13.1). This has to be done so that the final pattern is uniform enough while staying within the glare-restriction limits. The isoluminance diagrams shown in Fig. 13.2 are a representation of the T-shaped pattern. The grid of the diagram is specified in terms of the luminaire mounting height. This diagram is calculated for an observer stationed in the vertical plane parallel to the road axis passing through the luminaire and a distance 10 h (mounting height) from it. The isoluminance contours are specified as percentages of the maximum luminance.

The final result of covering the road with the luminance patterns of the individual luminaires depends on:

- the luminance patterns of the individual luminaires (blue shapes in Fig. 13.1), which in turn depends on:
  - the reflection properties of the road surface (the T-shaped pattern becomes smaller and longer when the road surface changes from more diffuse to more specular: compare Fig. 13.2 left and middle)

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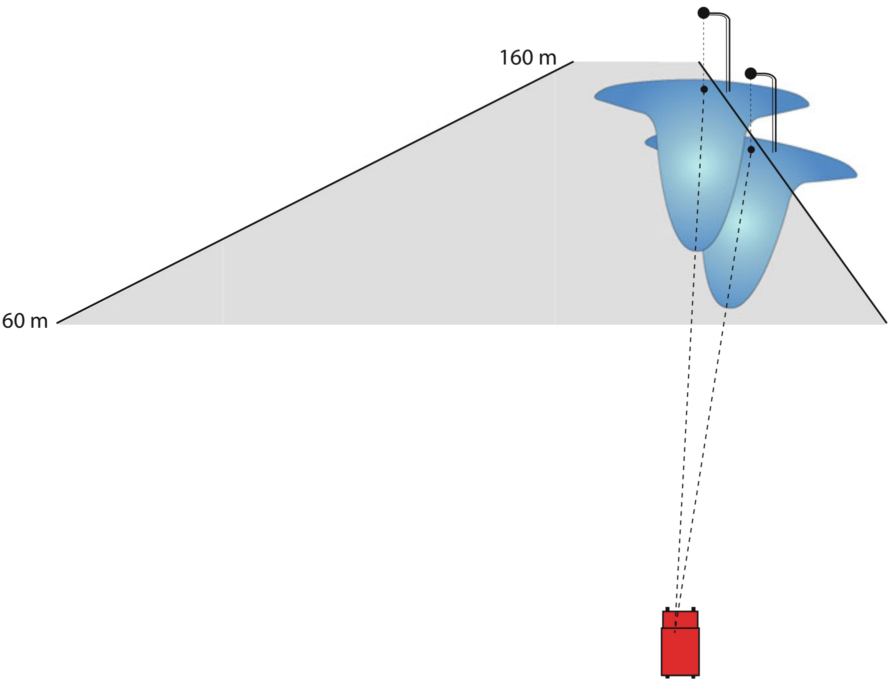

Fig. 13.1 *T-shaped bright areas* of two (axially-symmetrical light distribution) luminaires

  - the light distribution of the luminaires (many road-lighting luminaires will, for example, make the T-shaped pattern asymmetrical so that the road itself will be brighter than the kerbside: compare Fig. 13.2 middle and left
- the overlapping of the luminance patterns of the different luminaires, which in turn depends on:
  - the installation geometry (lighting arrangement in terms of mounting height, spacing and lateral luminaire position),
  - the road geometry (road width).

The design process is, normally, carried out with the aid of lighting-calculation software that accurately predicts the resulting luminance pattern and glare restriction obtained for a given light distribution, road surface, installation and road geometry.

In those parts of residential areas where motorized traffic is allowed, the lighting should be aimed at promoting road safety on the one hand and security and amenity on the other. This means that the lighting quality parameters for both motorized traffic and for pedestrians, cyclists and residents (as defined in Chap. 8 "Lighting Quality Parameters") should satisfy the requirements specified in Chap. 9 "Standards and Recommendations". Here it is the designer's task to not only cover the road surface efficiently with light, but also to take care that the total space receives the required amount of light as efficiently as possible (vertical or semi-cylindrical and/or façade illuminance). Here, once again, the lighting-calculation software programs are important tools for the lighting designer.

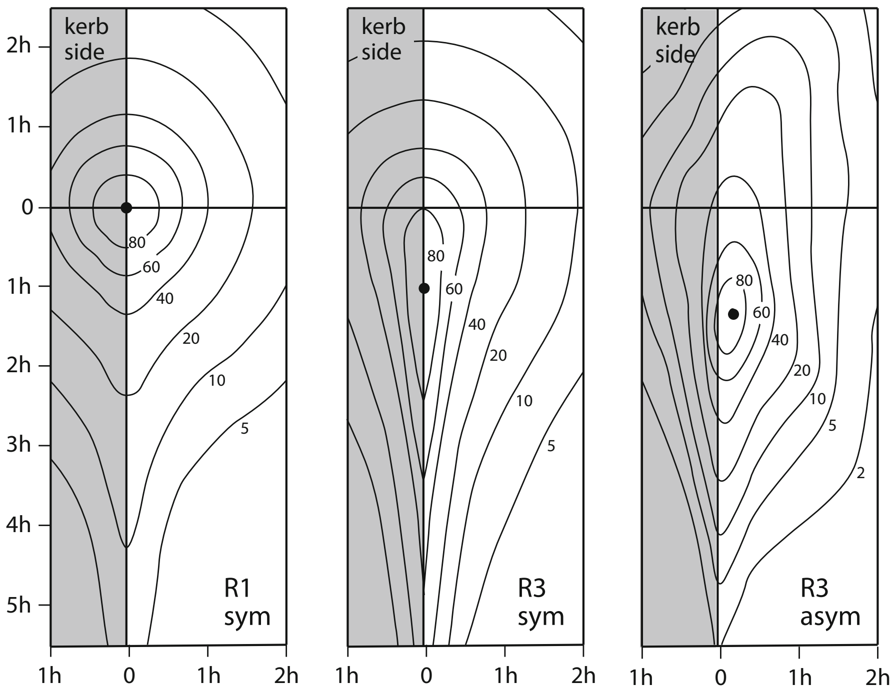

Fig. 13.2 Isoluminance diagrams. *Left* and *middle*: theoretical symmetrical luminaire, the luminous intensity of which is constant in all directions, for a diffuse and glossy type of road surface respectively (R1 and R3). *Right*: a tightly glare-controlled, asymmetrical luminaire on road surface R3

In pedestrian areas closed to all motorized traffic, road safety for motorized traffic ceases to be a design consideration and full scope can be given to providing effective security and amenity lighting. The lighting in both residential and pedestrian areas should, and can if properly designed, increase their attractiveness to local residents and visitors alike. This challenge can be met by architects, town planners and lighting engineers working together, each drawing on the knowledge and experience of the other.

13.1 Lighting Arrangements

There are five basic lighting arrangements. As shown in Fig. 13.3, these are: the single-sided, the staggered, the opposite, and the central (span-wire) and the twin central. Combinations of these arrangements are, of course, also employed. For a given road width, the type of arrangement determines to a large extent the required minimum mounting height of the luminaires, and with that the luminaire spacing.

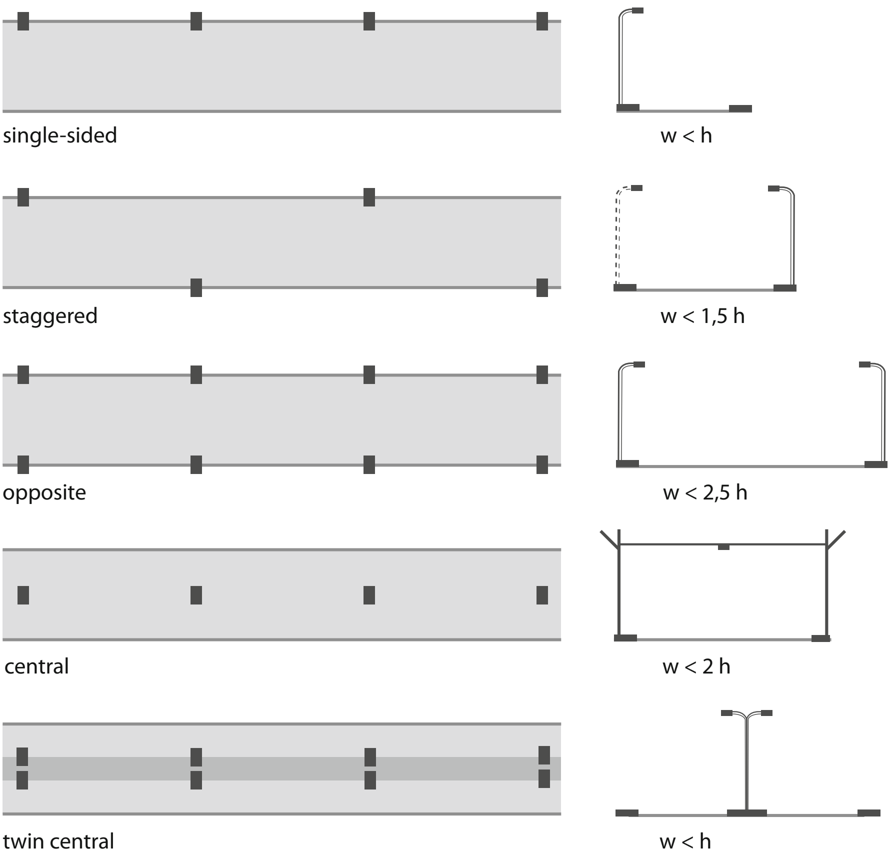

Fig. 13.3 The five basic lighting arrangements

In residential areas with a non-linear street layout, far more flexible non-standard arrangements may, of course, be used. The type of arrangement, together with the width of the road, determine for an important part the mounting height, spacing, overhang and inclination of the luminaires.

13.1.1 Effective Road Width

The amount of luminaire overhang (viz. the distance that the luminaire projects out or is placed back from the kerb (Fig. 13.4) serves to determine the effective width of the road and thereby the minimum mounting height required for the luminaires.

Inclining or tilting the luminaires up from the horizontal is done to increase the road width covered with a given mounting height. But this measure is not very effective. If the effective road width is large compared to the mounting height, tilting

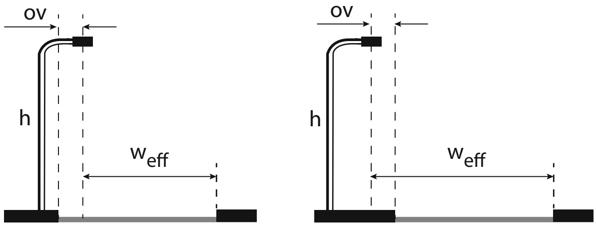

Fig. 13.4 Positive and negative overhang and effective road width

the luminaires will increase the amount of light reaching the far side of the road, but the luminance here will not be increased in proportion. This is because of the unfavourable angle of light incidence relative to the approaching motorist. Tilting, especially at bends in the road, also increases the chances of glare being produced, increases light pollution, and makes it difficult to provide good visual guidance. In view of the above, it is recommended that the angle of tilt with respect to the normal angle of mounting be limited, with horizontal mounting being preferred.

13.1.2 Single-Sided Arrangement

In a single-sided arrangement all the luminaires are located at one side of the road. The luminaires are usually mast mounted, although wall mounting occurs as well, especially in situations where the pavement is too small for locating masts. With this type of arrangement the luminance of the road surface at the side farthest from the luminaires is usually lower than that of the side nearest to them. Therefore, in order to ensure that the overall uniformity will be adequate, the single-sided arrangement should only be adopted in conjunction with mounting heights approximately equal to or greater than the effective width of the road. In the case of curved roads, visual guidance is good with this arrangement. Unlike the other arrangements dealt with here, the single-sided arrangement gives different lighting conditions for the two directions of traffic flow.

13.1.3 Staggered Arrangement

Here the luminaires are placed alternately on either side of the road in a so-called staggered or zig-zag fashion. As with the single-sided arrangement, this arrangement is employed for both mast and wall mounting. The overall uniformity obtainable by siting the luminaires in this way will be adequate so long as the effective road width is smaller than approximately 1.5 times the luminaire mounting height. The longitudinal luminance uniformity is generally low, the alternate bright and dark patches on the road creating a sort of ‘leopard-skin’ effect. The zig-zag positioning of the luminaires can also sometimes create a rather confused impression of the run of the road where curves are involved. For these reasons, it is sometimes advisable to employ instead a single-sided arrangement with increased mounting height, the higher cost of the taller columns perhaps being offset by the savings in trench cutting and cabling (one run of cable instead of two) that such an arrangement brings with it. The staggered arrangement does, however, exhibit advantages over the single-sided one during periods of wet weather. This is because the shiny patterns then occurring cover the whole road better than do the bright mirror-strip patterns created with the single-sided arrangement, thus minimizing dark patches.

13.1.4 Opposite Arrangement

This arrangement, with the luminaires placed opposite one another, is usually employed on relatively wide roads. The road width can be up to 2–2.5 times the mounting height. As with the single-sided and staggered arrangements, this arrangement too employs both mast and wall-mounted luminaires.

When an opposite arrangement is employed on a dual carriageway having a central reserve wider than about one-third of the carriageway width, it effectively becomes two independent single-sided arrangements and must be treated as such. The same, of course, holds true when obstructions (e.g. trees, anti-glare screens) are placed along the central reserve. In the case of curved roads, visual guidance may deteriorate because from a distance it is not clear whether a given luminaire is positioned on the left or on the right-hand side of the road, thus making the run of the road ahead less clear.

13.1.5 Central Arrangement

In the central arrangement the luminaires are hung from so-called span wires strung across the road. (This arrangement should not be confused with the catenary arrangement, which will be described later in this chapter). The spanwire arrangement is normally used at rather low mounting heights (around 6–8 m) for narrow roads in built-up areas when there is no possibility of employing road-side lighting columns. The suspension cables are then simply strung between buildings on either side of the road. A road width of some two times the mounting height can be adequately lit with this arrangement. This arrangement may also offer a solution to the problem of where to site the luminaires such that their light output will not be shielded by roadside trees.

The principle of using cables instead of columns to support the luminaires can, of course, be applied to any of the three arrangements considered above.

13.1.6 Twin-Central Arrangement

The twin-central arrangement is intended for dual carriageways, the luminaires being mounted on T-shaped masts in the middle of the central reserve. Since this is essentially two single-sided arrangements placed back to back, the condition that the luminaire mounting height should be equal to or greater than the effective carriageway width applies. The luminance of the road surface in the lanes nearest to the luminaires, viz. the ‘fast’ lanes, will usually be higher than that on the ‘slow’ lanes.

With the twin-central arrangement both the road and kerb-side parts of the luminaire light output contribute to the luminance on the road surface, provided that is that the central reserve is not too wide. This is in contrast to the opposite arrangement, where it is mainly the road-side part of the luminaire light output that provides the luminance. The twin-central arrangement is therefore the more efficient of the two. It should be noted, however, that the opposite arrangement may give slightly better lighting under wet-weather conditions; provided, that is, that the central reserve is rather narrow and does not contain obstructions. The visual guidance obtained with the central arrangement is good.

13.1.7 Irregular Arrangement

On squares and non-linear street layouts a more flexible positioning of the luminaires is often wanted. This is possible, but special care should then also be given to the orientation of the luminaires to avoid glare in those directions where it must be avoided, such as windows of houses and shops.

13.1.8 Catenary Installation

Catenary lighting installations use closely-spaced luminaires suspended from a cable (the catenary) stretched between widely-spaced columns along the central reservation between two carriageways (Fig. 13.5).

The special catenary luminaires employed, which are orientated such that the longitudinal luminaire axis is parallel to the road axis, shed most of their light across the road rather than along it. Thanks to this feature, catenary installations can light a wider road than can conventional installations. Good overall uniformity of $U_o = 0.4$, can in fact be obtained with a luminaire mounting height that is less than 0.5 times the effective width of a carriageway. Because the luminaires are viewed almost axially by the motorists, the amount of discomfort and disability glare produced is small. Moreover the fluctuation in the glare stimulus experienced by the driver by virtue of his movement along the road is less disturbing under catenary lighting than under any of the conventional lighting arrangements. Visual guidance for motorists (as will be

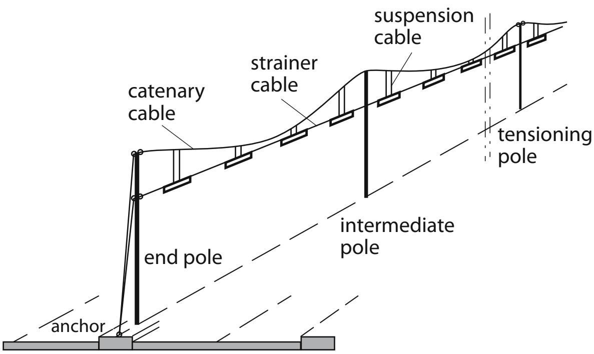

Fig. 13.5 The main construction features of a catenary lighting installation

described in more detail in Sect. 13.3) is excellent with catenary lighting installations because of the short luminaire spacings. As will be discussed in the section "Bad-Weather Lighting" further on in this chapter, catenary systems also have advantages under bad-weather conditions. In practice, the quality of catenary lighting is such that average luminance values equal to about 80 % of those normally recommended are often acceptable where such catenary lighting installations are used. On the other hand, the predominantly transverse light distribution means that the luminance yield is lower for catenary installations than for conventional installations. Because the installation costs of catenary lighting installations are higher than those of conventional installations, and because the only mounting position is in the central reservation of dual carriageway roads, catenary installations have become less popular over the last two decades.

13.1.9 High-Mast Lighting

The term high-mast lighting is generally used to describe lighting in which the luminaire mounting height is 20 m or more, the luminaires normally being mounted several to a mast to give the necessary degree of light coverage. This form of lighting is often employed in complex junctions on main roads and in motorway interchanges. The principal feature of high-mast lighting in such applications is that it leaves the lighted area almost free of columns and so gives the road user an uncluttered view of the road junction and its exits. Glare is also often less of a problem with this form of lighting, even when the junction involves a difference in height between roads. Maintenance can often be carried out without having to disturb the traffic flow.

Three luminaire mounting arrangements are commonly in use: plane symmetric, radial symmetric, and asymmetric (Fig. 13.6).

The plane-symmetric arrangement is generally employed in conjunction with conventional road-lighting luminaires and is particularly suitable for the lighting of more or less straight runs of wide road. Each luminaire is orientated at right angles to the road, with the major part of the light being thrown along the road as in a conventional installation.

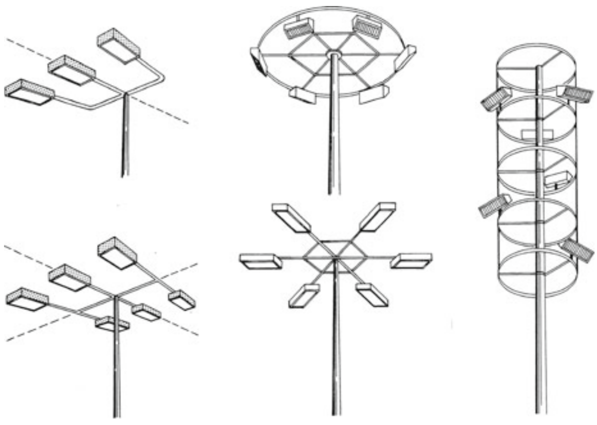

Fig. 13.6 High-mast mounting arrangements

The radial-symmetric arrangement is used where the aim is to spread the light more or less evenly in all directions. Such a distribution, which can be obtained using either conventional luminaires or floodlights, is often suitable for lighting rather compact road junctions from a central position. At motorway interchanges and similar grade-separated junctions there is the risk with this type of lighting that the elevated sections of the road relatively close under the luminaires will be unevenly illuminated. Radial-symmetric high-mast lighting is sometimes chosen partly on aesthetic grounds.

In the asymmetric arrangement, symmetry is totally lacking. Here each luminaire (floodlights only are used) is individually aimed so as to make the best possible use of the light available. This is a technique especially well suited to the lighting of complex junctions, particularly those in which the carriageways are spread out over a rather large area, as it allows the light to be directed where it is needed, viz. on the road and not on its surrounds. To avoid glare in critical directions with this type of installation the floodlights are sometimes fitted with special screens or louvres.

13.2 Mounting Height and Spacing

Table 13.1 summarizes the minimum mounting heights as discussed in the previous section. It should be born in mind that glare increases with reduction in mounting height. On the other hand, too great a mounting height relative to the road width will result in over-lighting of the surrounds of the road (spill light). The actual mounting height chosen has also a visual impact during the night, and more so during the day. The height should be in harmony with the scale of the street. If the masts with luminaires are higher than most of the buildings and trees in the street, they will be seen during the day as dark silhouettes against the bright sky and during the night as very bright areas against a black sky. Limiting the mounting height to less than about

Table 13.1 Minimum mounting heights and spacings needed to fulfil the lighting requirements for different types of luminaire arrangements as a function of the effective road width, w

Arrangement	Minimum height h_{min}	Minimum spacing s_{min}
Single sided	1 w	3–5 h
Staggered	0.7 w	3–5 h
Opposite	0.4–0.5 w	3–5 h
Central	0.5 w	3–5 h
Twin central	1 w	3–5 h

half of the average height of the buildings usually gives satisfactory results from a visual-impact point of view.

Luminaire spacing for a given lighting arrangement and luminaire light distribution is dependent on the mounting height and the longitudinal uniformity planned for the installation. The greater the mounting height, the larger can be the spacing for a given longitudinal uniformity. For the range of longitudinal uniformities, U_l, of 0.7 to 0.5, a spacing-to-mounting-height ratio of 3 to 6, depending principally on the quality of the light distribution, are common.

13.3 Visual Guidance

The extent to which a road-lighting installation serves to guide the road user through the scene ahead is an aspect of visual performance. It is termed visual guidance. Good visual guidance makes it easier for the road user to see and correctly interpret the run of the road ahead of him and to distinguish the boundaries of the traffic lane he is in and the points of intersection of this with other lanes or roads. Of primary importance with regard to visual guidance are the design of the road, the road markings, and the guidance provided by the run of possible crash barriers. The guidance so provided should be strengthened by the lighting. A lighting installation can be made to provide good visual guidance—during the day as well as by night—by paying special attention to the alignment and arrangement of the masts with luminaires. These should clearly indicate any changes important to a driver in the situation ahead (Fig. 13.7). This type of visual guidance gives information over a much greater distance than does retro-reflective road markings (Boyce 2009).

The siting of luminaires on curves of small radius should be given extra attention. A simple three-dimensional sketch often helps the road-lighting designer to avoid misleading situations attributable to wrongly-sited luminaires. For example, as Fig. 13.8 shows, luminaires on the outside of a curve mark the run of the road better than do luminaires sited on the inside, or luminaires placed in an opposite arrangement. Visual guidance works during the day by virtue of the visible row of lighting columns and during the night by the visible row of bright luminaires.

The siting of luminaires on curves also strongly influences the luminance pattern obtained on the road surface on the curve. Luminaires placed on the outside of a curve

Fig. 13.7 Example of good visual guidance obtained by the alignment of the luminaires

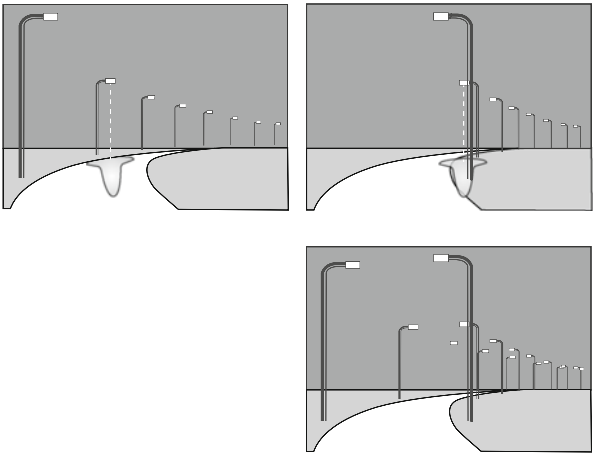

Fig. 13.8 Luminaire siting on curves and its consequences for visual guidance and ease of creating luminance patterns on the road

contribute more to the luminance of the road than do luminaires along its inside, where the light is mainly reflected not by the road but by the road verge (illustrated by the T-shaped luminance pattern of two individual luminaires in Fig. 13.8 top).

The systematic use of light sources of different colour can also contribute to the quality of the visual guidance obtained. An example of this is the lighting of exits from a motorway in a different colour than the lighting on the motorway itself. Different light colours can also be used to guide road users through the road network in and around a city by the consequent use of different colours for main through roads and local roads. The effect can be strengthened by combining this with a consequent difference in mounting height and or luminaire style. Of course, this requires master planning of the road lighting in the whole area.

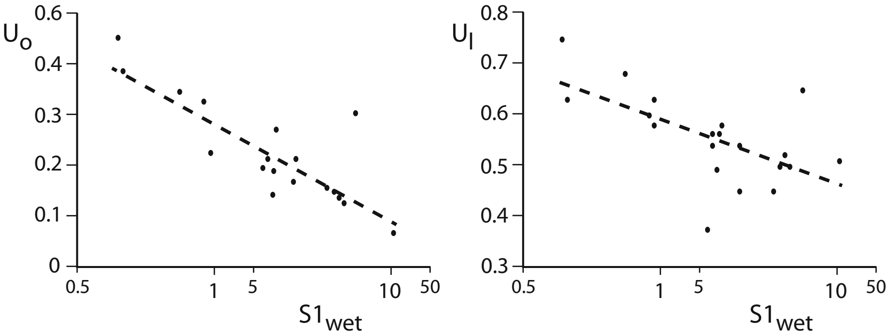

Fig. 13.9 Increase in overall and longitudinal uniformity, U_o and U_l, with decrease in wet-surface specular factor $S1_{wet}$.Each point represents the average uniformity value obtained using 24 different luminaires employed in a twin-central arrangement

13.4 Bad-Weather Lighting

13.4.1 Wet Weather

As we have seen in Chap. 12 "Equipment: Road Surfaces", the influence that a wet road surface has on the visibility obtained with a given lighting installation is a direct result of the changed nature of that surface's reflection properties. The average luminance of a surface increases when it becomes wet, while the overall and longitudinal uniformities decrease. The main problem is the decrease in uniformity. As a general rule, it is logical to expect that quality losses in the lighting occurring during wet weather can be kept low by the use of road surfaces that show only small changes in their reflection properties when they become wet: in practice, the lower the specularity of the wet surface, the better the overall and longitudinal uniformities will be. This is illustrated in Fig. 13.9, where for a twin-central arrangement on a dual carriageway with central reservation these two uniformities have been plotted as a function of the specular factor S1 of the wet road surface (Van Bommel 1976; Van Bommel and De Boer 1980).

The increase in uniformity with decrease in S1 is clearly shown. Road surfaces having a low degree of specularity under dry conditions generally tend to have a low specularity under wet conditions also. This was shown already in Fig. 12.10 of Chap. 12. So to optimize wet-weather road-lighting quality it is important to use road surfaces with low dry-weather specularity, preferably of class I (R, C or N).

Without doubt, the nature of the road surface has the most important influence on quality of wet-weather road lighting. However, the light distribution of the luminaires and the type of arrangement also have an influence, although be it smaller. Light coming from the luminaires of a road lighting installation and reflected specularly by the wet road towards a road user will produce bright patches on its surface, so reducing the luminance uniformity. Luminance uniformity can be improved by employing luminaires that have a reduced luminous intensity in the directions in

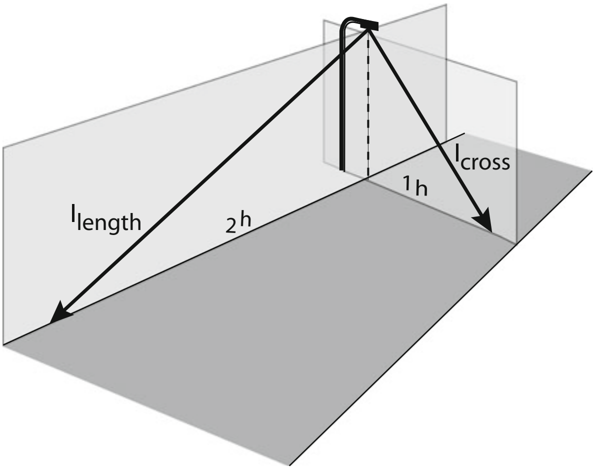

Fig. 13.10 Definition of the cross factor, CF, of a luminaire

which specular reflection towards an observer can occur, whilst throwing as much light as possible in other directions. Following this line of reasoning, Van Bommel (1976) derived a luminaire figure of merit, the so-called cross factor, CF, with which it is possible to describe the suitability for use of any given luminaire under wet conditions

He showed that such a figure of merit could best be defined as:

$$CF = \frac{I_{c\ 1h}}{I_{l\ 2h}}$$

in which (Fig. 13.10):

$I_{c\ 1h}$ The luminous intensity of the luminaire in the direction of a point equal to the mounting height (h) across the road (45°); and

$I_{l\ 2h}$ The luminous intensity of the luminaire in the direction of a point equal to twice the mounting height (h) along the road (63.4°).

Figure 13.11 gives the results of calculations in which the overall uniformity (U_o) has been calculated for different wet road surfaces and for luminaires having different CF values. The figure clearly illustrates that the higher the CF value of a luminaire, the better will be the overall uniformity achieved with it on different types of wet surface, and thus the better also will be the wet-weather quality of the lighting installation as a whole.

A good wet-weather road lighting installation is the catenary installation described in Sect. 13.1.8. Catenary luminaires have a large cross factor, CF of 10 or more, where most conventional luminaires have CF values of less than 1.

Another way of improving the wet-weather quality of a road lighting installation is to ensure that what bright patches do occur are evenly distributed over the entire road surface. A noticeably-greater improvement in luminance uniformity can be brought about in this way by employing a staggered or an opposite arrangement of the lighting columns rather than a single-sided or a twin-central pole arrangement.

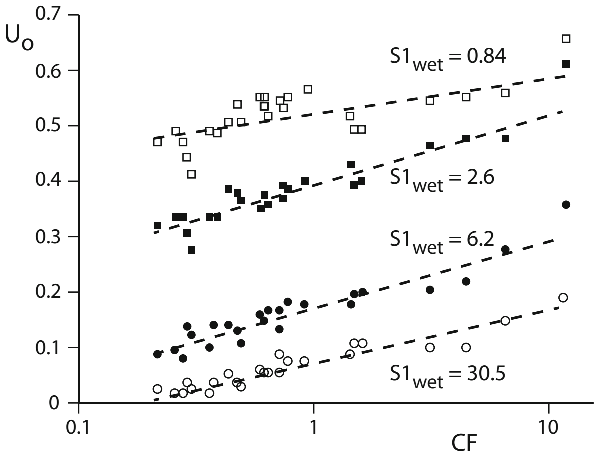

Fig. 13.11 Relationship between overall uniformity, U_o, for a twin-central arrangement and cross factor CF, for various wet road surfaces characterized by $S1_{wet}$

13.4.2 Foggy Weather

The poor visibility that may occur on a lighted road during foggy weather can be ascribed to light being absorbed and scattered by the fog-producing water droplets suspended in the atmosphere. Some of this light is lost, and some is reflected towards the road user in the form of a bright veil of fog that obscures details on the road ahead. In vehicle lighting, this is commonly known as the "white-wall effect". Whilst nothing can be done regarding the loss of light, there are some measures that can be taken to reduce the disturbing light scatter towards the road user.

The degree to which fog scatters light in a given direction is dependent upon the angle θ that this direction makes with the incident light beam. The relative degree of scatter for both dense and light fog conditions is shown in Fig. 13.12.

From the figure it can be seen that scatter drops to a minimum as the angle θ approaches 90°. It therefore follows that any luminaire having a high cross factor (CF) radiating relatively much light across the road, results in the lowest scattering from the fog particles towards a motorist with a viewing direction mainly along the road. As mentioned above, the highest cross factor is that possessed by the catenary luminaire. The catenary installation is therefore ideally suited for use in situations where fog is frequently encountered, especially since the visual guidance obtained with such an installation is also excellent.

At some areas where fog very often occurs, it can be advisable to mount the luminaires very low down, clearly lower than the eye-height of a motorist. In this way disturbing scattering from fog particles above eye level is avoided to a large extent and absorption of light is minimized because of the short path the light has to travel through the fog from the luminaires towards the road surface. These types of lighting installations, with their closely-spaced row of bright luminaires, may strengthen visual guidance and increase visibility of objects under eye height (Girasolet et al.1998). Because of the low mounting height involved, it may be difficult to

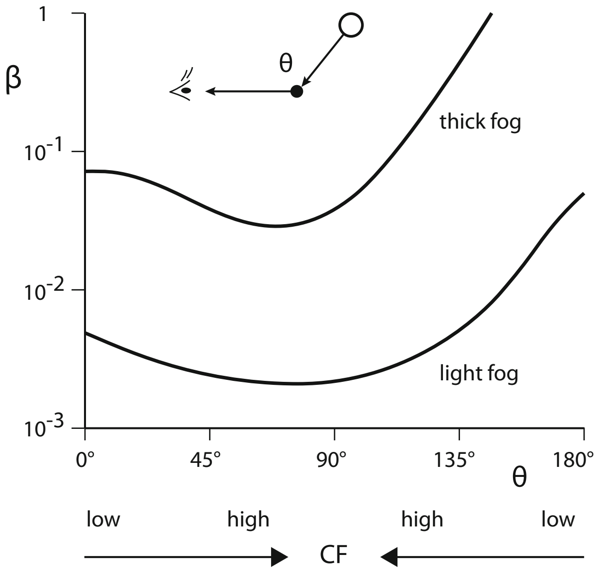

Fig. 13.12 Scattering function β in fog as a function of angle θ between direction of light incidence on the fog and direction of scatter (Foitzik and Zschaeck 1953)

light the total width of the road, and the spacing has to be very short, both of which make the installation rather expensive.

13.4.3 Snowy Weather

When it is snowing, much of the light from the road-lighting luminaires is lost through absorption in the snowflakes and some is scattered in the direction of the driver, giving rise to glare. No special measures can be taken to overcome this negative influence on visibility. When the road is covered with snow, the average road-surface luminance increases by a factor of 4 to 5 while, due to the diffuse character of snow, the uniformity does not deteriorate much (Ekrias et al. 2007). If the installation permits of dimming, the lighting level can be reduced as long as the settled snow remains clean.

13.5 Maintenance

A road-lighting installation will continue to operate efficiently and deliver a sufficient quality of lighting only so long as it is well maintained. Some deterioration in quality is, of course, inevitable, even with a well-maintained installation. The deterioration will be greatest just prior to maintenance being carried out. The task facing the lighting designer is that of fixing the maintenance period and the initial lighting level given by the installation such that the lighting level and quality can never fall below specification. Here not only the lighting quality aspect plays a role, but cost and energy aspects as well.

The factors influencing the rate of deterioration are lamp failures, lamp-lumen depreciation and luminaire fouling. In Chap. 10 "Equipment: Lamps" the lifetime of lamps has been defined and examples have been given of possible lifetime values for the different lamp types. Accurate information has to be obtained from the lamp manufacturer for the actual lamp type and wattage in use. It should be noted that the actual lamp life is influenced by several factors not controlled by the lamp manufacturer; for example: type of ballast, ambient temperature, operating voltage, voltage fluctuations, frequency of the on/off switching, burning position, severity of mechanical vibrations, and so forth. Variations in lamp life also occur according to the wattages of the lamps considered. Lamp-lumen depreciation, that is to say the fall in light output because of lamp ageing, occurs with all lamps. How great this is at a given moment in the life of a lamp is dependent upon the type and wattage of the lamp. Again, actual information should be obtained from the lamp manufacturer. As with lamp life, lumen depreciation is also dependent on practical operating factors, such as ambient temperature, voltage fluctuations, burning position and severity of mechanical vibrations.

Another, serious, loss in light output is that brought about by the accumulation of dirt on the light-emitting surfaces of the luminaires. The severity of the fouling will, of course, depend on the type of luminaire involved and the amount of pollution locally present in the atmosphere. Closed luminaires with a high IP factor (see Chap. 11) afford much better protection against dirt accumulation and also corrosion than do open luminaires. CIE (2003) published luminous maintenance factors for dirt accumulation for different type of luminaires characterized by their IP code, the type of environment (low, medium and high pollution) and the period the luminaires are in use after the last serious cleaning operation. The maintenance factor is defined as the value of the average luminance or illuminance on the plane to be lighted, after a certain period, relative to the average luminance or illuminance as obtained from the new installation. Table 13.2 shows part of the CIE maintenance factors required due to dirt accumulation on luminaires.

In the United Kingdom, measurements of different IP6x luminaires used in different pollution-category environments, have been carried out more recently (Sanders and Scott 2008). The conclusion to be drawn from these tests is that high-IP type of luminaires accumulate less dirt than would be expected from the CIE values. The values resulting from these tests are given in Table 13.2 under the heading "UK". Interestingly, their tests show that luminaires mounted at heights of 8 m or more accumulate less dirt than do luminaires mounted at lower heights of 6 m and especially 4 m. The Table therefore gives, for high conditions of pollution, one maintenance value for higher mounting heights and one for lower mounting heights.

The total effect of the various factors influencing the light depreciation experienced by a road lighting installation can easily reduce the lumen output by as much as 25–40 % at the end of the maintenance interval. By contrast, in pollution-free areas, a reduction of 15–30 % per year is quite possible. The total effect has to be

Table 13.2 Maintenance factors covering dirt accumulation on luminaires with different IP codes in different polluted environments for an operation period of 1 and 3 years; according to CIE (2003) and UK: Sanders and Scott (2008)

IP code	Pollution category	CIE 1 year	UK 1 year	CIE 3 years	UK 3 years
IP2x	High	0.53		0.42	
IP2x	Medium	0.62		0.53	
IP2x	Low	0.82		0.78	
IP5x	High	0.89		0.76	
IP5x	Medium	0.90		0.82	
IP5x	Low	0.92		0.88	
IP6x	High	0.91	0.94–0.97	0.83	0.89–0.94
IP6x	Medium	0.92		0.87	
IP6x	Low	0.93	0.98	0.90	0.94

estimated in advance, and the lighting level of the new road-lighting installation should be increased above the specified lighting level according to this estimation; only then will there be a guarantee that the lighting will remain within specification throughout the life of the installation. The longer the interval between maintenance periods, the lower the maintenance costs will be. But, at the same time, the greater will be the effect of lamp failures, lamp lumen depreciation and dirt accumulation on lumen output and thus the higher the lighting level required for the installation when new. For each situation, therefore, a specific cost calculation has to be made, based on the actual cost and light-depreciation conditions, in order to determine the optimum maintenance schedule. Lamps can be replaced individually, as they burn out, or all the lamps in the installation can be replaced in a group-replacement maintenance action at one time, after a reasonable number of burning hours, whether they have failed or not. It is usual, during the group-replacement operation, to clean the luminaires and inspect the electrical and mechanical connections. Sometimes a combination of group replacement and individual spot replacement (for failed lamps at critical locations) is adopted. Group replacement (combined with luminaire cleaning and inspection) generally offers the most advantageous solution as far as cost and energy consumption is concerned. The fall in light output of the luminaires due to lamp-lumen depreciation and luminaire fouling can in this way be kept relatively low; as a consequence, the required 'initial' lighting level given by the installation will be comparatively close to the specified level.

Even where systematic maintenance is employed, the lighting level can easily drop by as much as 20–30 %, or more, by the time lamp replacement is due. A maintenance factor (MF) corresponding to the drop anticipated (e.g. 0.8 for a 20 % drop and 0.7 for 30 % drop) should therefore be applied when setting the initial lighting level to be given by the installation according to the formula:

$$L_{initial} = L_{spec}/MF$$

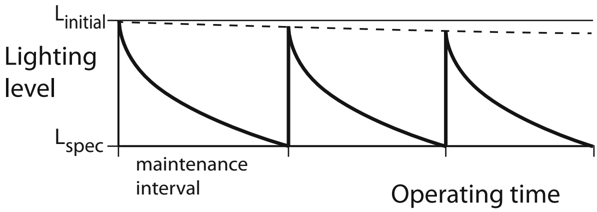

Fig. 13.13 Lighting level variation in the case of group replacement of lamps

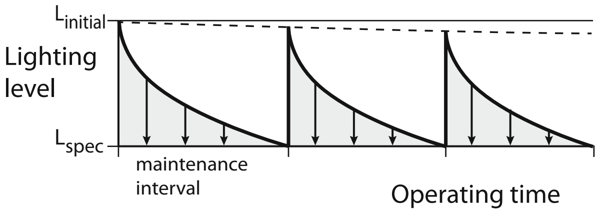

Fig. 13.14 Savings that can be obtained with automated light depreciation compensation

The fall in the lighting level with time under group-replacement conditions as described here is sketched in Fig. 13.13. The thin broken line indicates the non-regainable losses of reflectivity of reflectors or loss of transparency of refractors. With the use of high-quality materials these losses can in practice be neglected.

From the figure it is evident that the actual lighting level has to be higher than the specified level during a considerable time ("overlighting"). Of course, this has negative consequences for the actual energy consumption. As will be described in the next section, with automated lighting control systems it is possible to automatically compensate for light depreciation by continuously monitoring the actual lighting level obtained from the installation, and by using the result as input for dimming the installation to the lighting level specified, L_{spec}. In this way there is constant light output with no over-lighting. This method of controlling the maintained lighting level is therefore usually referred to as CLO control (constant light output control). The resulting energy savings are given in Fig. 13.14 by the shaded area.

Dirt accumulation on luminaires affects not only the light output of the luminaire but often also its light distribution. For example, with some prismatic optics of LED luminaires dirt collects in the edges of the optics, which has a relatively large effect on the luminous intensities at high angles. This in turn has a negative effect on road-surface luminance uniformity.

13.6 Lighting Control

Today, lighting control systems in most road-lighting installations are still often limited to switching on and off groups of installations as determined by a central time clock or photocell. However, more-modern, automated management of lighting installations can greatly increase the cost effectiveness and energy efficiency of the installation while ensuring the correct lighting under all circumstances. The most advanced automated control system uses a set of input devices such as photocells, timers, traffic-flow detectors and weather indicators that together are centrally programmed to control the lighting status of a large number of individual or grouped luminaires. Such a dynamic lighting system has the following characteristics:

- the lighting installation can be adapted to the changing traffic conditions in terms of traffic flow, speed and density,
- the lighting installation can be adapted to changes in visibility due to adverse weather conditions such as rain, fog and snow,
- the lighting installation can be adapted to special circumstances such as accidents, road works and school-travel times,
- the lighting level can be adjusted to the actual lighting level specified so as to avoid overlighting, as discussed in the previous Section,
- the lighting can be adjusted to cope with the changing presence of pedestrians and cyclists,

As a consequence, unnecessary lighting and thus unnecessary energy usage is avoided, with no negative effects for road safety.

As has been discussed in the chapter "Standards and Recommendations", most recommendations for road lighting explicitly mention adaptive lighting as a possibility to significantly reduce energy consumption. They also give guidance as to what conditions permit the lighting level to be reduced.

The next step brings us to truly-intelligent lighting systems that both control and monitor. Here, not only is information on the required lighting status sent to the luminaires, but the operational state of the luminaires themselves (e.g. burning hours of the lamps, actual lamp voltages, lumen output and system failures) is sent back to a central location for evaluation, inspection and administrative purposes. Such systems have additional advantages:

- maintenance operations can be optimized based on actual burning hours and system failures,
- street patrols to check the status of the installation at regular intervals are no longer needed,
- dangerous situations on the road due to failures in the installation are reduced to an absolute minimum.

Figure 13.15 shows the principle of a control and monitoring system for road lighting. The system is two-directional so that information on the status of each individual luminaire is centrally available. The communication can be done through power-lines (mains network), as is done in the example shown. Power-line systems have been in use for some time for the simple switching of road-lighting installations in two steps (evening and night switching). The lighting can be adapted locally with a wifi-connected smart phone. Instead of power-line communication systems, complete wireless systems are also available.

For the control and monitoring, different types of sensors and communication devices for remote control are needed. Smart luminaires are being introduced in

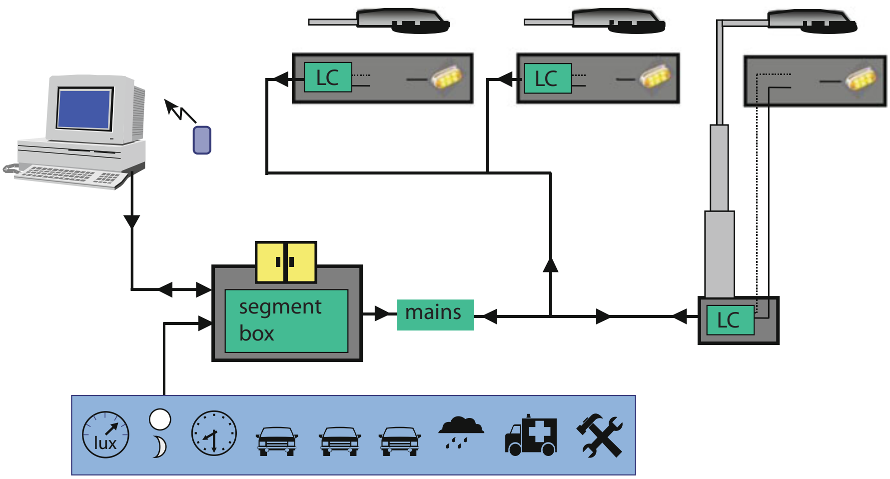

Fig. 13.15 Principle of a control and monitoring system for road lighting. Dynamic lighting controlled by: the actual, measured lighting level; the amount of natural light (day/night); the time; the traffic density; the weather conditions; and by the presence of accidents or road works. *LC* Lighting Controller

which these devices are integrated in the luminaire, or sometimes even mounted on the housing of the LED array. Intelligent dynamic lighting systems making use of such smart luminaires are also termed "digital lighting systems".

13.7 Light Pollution

Lighting that not only lights the area intended but that also spreads out uncontrolled into the surrounding areas and into the sky is an annoyance to society. It may disturb residents and wildlife and be dangerous for road users. Keeping our sky dark allows both professional and amateur astronomers to do their research work and for all of us to see the stars. We should realize that sky glow is a visible sign of unprofessional lighting; lighting that wastes energy and as such contributes to CO2 emissions and the associated climate change. Only professional, carefully-designed lighting that brings the light only to where it is really needed and only when it is really needed fulfils the requirement of sustainability as dealt with in the next section. Detailed guidelines to restrict light pollution for both functional and decorative outdoor lighting are dealt with in Part 2 of this book.

13.8 Sustainability

Sustainability means for lighting: "balancing the positive effects of lighting with the negative impacts of that lighting on the environment". The positive effects have been comprehensively described in the first chapters of this book. Those actions having a negative impact on the environment include:

- the use of polluting or hazardous materials such as mercury in fluorescent, high-pressure sodium and metal halide lamps,
- the use of non-renewable materials, and especially the use of materials with limited availability such as the rare-earth metals needed for the phosphors employed in white LEDs,
- the waste of energy and the associated emissions of greenhouse gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2),
- the light pollution that disturbs residents, astronomers and wild life.

The first two of the above continue to be addressed by the lighting manufacturers in work that is sometimes referred to as "eco-design". The use of hazardous materials in lamps has been substantially reduced over the years. For example, high-pressure sodium lamps containing no mercury have been developed. The search for alternative materials of limited availability is a key topic in lamp laboratories. The significant increase of lifetime of existing, and especially of new, lamp types reduces the use of materials considerably. The energy efficiency of light sources has gradually improved over recent decades, and particularly over the last decade. Luminaires have been developed with professional optical systems with higher utilisation factors that bring more of the lamp light to the road surface. Intelligent lighting systems can control the lighting level in response to many factors, including traffic density, weather conditions, time and twilight level, thus taking care that "over-lighting" is limited to an absolute minimum. More and more lighting products are recyclable, and recyclable programs are in place in more and more countries. The subject of limiting light pollution will be dealt with extensively in Part 2 of this book.

It is the responsibility of the lighting designer to select the right products for his installation and to design an energy-friendly installation that can be operated so that it always provides the minimum amount of lighting required. Energy performance indicators may be used to arrive at optimized installations by comparing the energy performance of different solutions fulfilling the same specifications in a particular road-lighting project. One such indicator is the power density defined as:

$$Power\ density = \frac{Power}{\sum Area_i * Specified\ Level_i}$$

The power is the total power of the lighting installation, including the power for lamps, gear and lighting control devices. The area is the size of the sub-area to be lit; the surrounding areas that are part of the lighting specifications should be dealt with as sub-areas. The specified lighting level is the average illuminance or average luminance level specified for the area considered. If the lighting installation

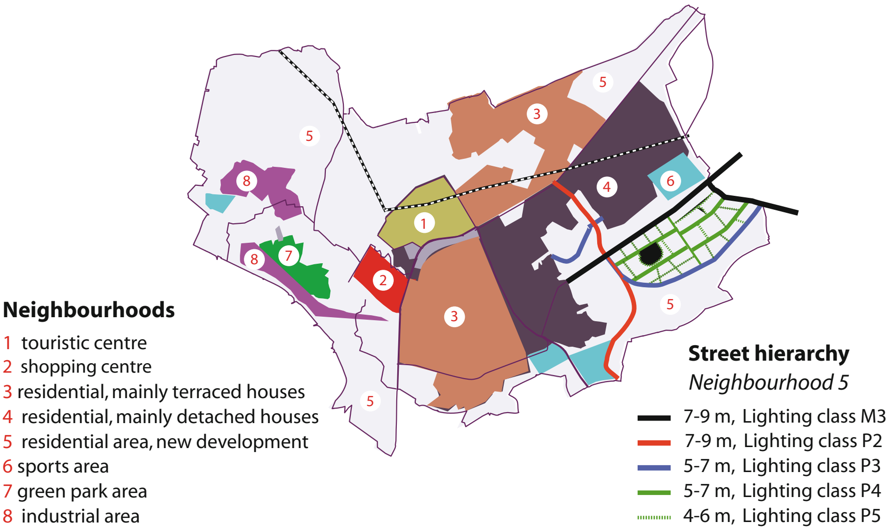

Fig. 13.16 Conceptual city map used as a basis for master-planning of outdoor lighting

specifications are different for different circumstances such as traffic density, weather, time of the night, the power density has to be calculated for the different specifications for these different circumstances. By having the specified lighting level and not the actual lighting level obtained from the lighting installation in the formula, the indicator also takes into account the negative effect of installing lighting levels higher than those specified. National and international standards for lighting energy performance are considering different indicators and different benchmarks (Iacomussi et al. 2011; Schwarcz 2011; CEN 2013).

13.9 Master Planning

So far, all the guidelines given relate to individual lighting installations. There is much to be gained if lighting installations are not planned and designed individually but as a well-defined framework for a whole area, a whole district, or a whole city. Master planning, as this is called, is based on a classification of neighbourhoods and on a hierarchy of roads and streets. An example of this concept is illustrated in Fig. 13.16. Neighbourhood classes, can for example, be: pure residential with mainly terraced houses, or purely residential with mainly detached houses, shopping streets, shopping centres, touristic areas, industrial areas, and so forth.

For determining an unambiguous and recognizable hierarchy of roads and streets, the lighting classes specified separately for motorized traffic and pedestrians and residents in the different Standards and Recommendations for road lighting can be used (for example, CIE lighting classes M1 to M6 for motorized-traffic areas and

Table 13.3 Example of some elements of a master plan for neighbourhood 5 of the city plan of Fig. 13.15

		Elements of masterplan					
Road	w (m)	lighting class	arrangement	h (m)	T_k (K)	luminaire style	adaptable to class
	7-9	M3	single-sided	9	2500	A	M4
	7-9	P2	staggered	6	3500	B	P3-P4
	5-7	P3	staggered	6	3500	B	P4
	5-7	P4	staggered	6	3500	B	-
	4-6	P5	single-sided or staggered	4	3500	C	-

classes P1 to P6 for pedestrian and slow-moving traffic areas). Both short and long-term goals should be taken into account here. The master plan should specify not only the lighting quality values to be met per neighbourhood and street hierarchy, but also the type of arrangement, the mast height, the colour of the light, the mast and luminaire style and, when adaptable lighting to a lower lighting class is possible, the switching and dimming employed. As an illustration of this, Table 13.3 gives an example of some elements of a master plan for one of the neighbourhoods sketched in the city map above.

A good master plan should also take into account the decorative lighting of statues, monuments and buildings; a subject that is not within the scope of this book. A well-defined and executed master plan improves the attractiveness of an area to both residents and visitors; it helps to guide them through the area; it avoids the over or under lighting of streets and/or areas; it prevents the negative mutual influence of individual lighting installations; it minimizes initial investment and maintenance costs because of standardization of equipment; and it simplifies the short and long-term budgeting process.

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Chapter 14
Calculations and Measurements

Abstract The lighting designer has to perform lighting calculations in order to arrive at solutions that will satisfy the relevant lighting requirements. Universally-applicable computer programs are available for this purpose. The basic formulas have been described in previous Chapters of this book. In this Chapter the conventions for the number and position of calculation points and the position of the observer will be discussed. Different Standards and Recommendations, such as those of CIE and of the European and American Standards, apply different conventions. It is extremely important that specifications for road-lighting installations clearly specify which convention method has to be followed.

The measurements carried out in connection with road lighting fall into four categories: those to determine the lamp properties, the luminaire properties, the reflection properties of road surfaces and, finally the installation properties. The first three categories mostly concern laboratory measurements. Sometimes road-lighting engineers want to check the spectral lamp properties, especially the S/P ratio of the light source, in the field. The same holds true for the reflection properties of road surfaces where both laboratory measurements from samples and in-situ measurements on the real road with reflectometers can be carried out. Field measurements made on road lighting installations are carried out on new installations to check whether they fulfill the quality specifications, and on installations already longer in use, to reveal whether there is need for maintenance, modification, or perhaps replacement. The principles of both laboratory and field measurements will be discussed here.

14.1 Calculation Conventions

During the actual lighting-design phase of a lighting project, the lighting designer has to perform lighting calculations in order to arrive at solutions that will satisfy the relevant lighting requirements. Since the performance of lighting calculations, especially those involving luminance, is relatively time consuming, extensive use is being made of computers. Universally-applicable computer programs are available for this purpose. The basic formulas have been described in previous Chapters of this book. Here the conventions for the number and position of the calculation points and the position of the observer will be discussed.

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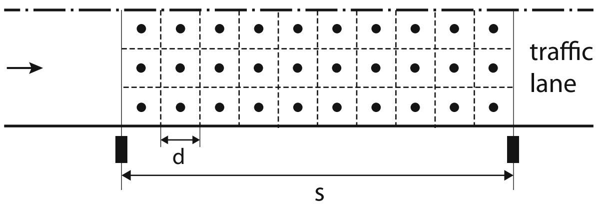

Fig. 14.1 Calculation grid; *s* luminaire spacing, *d* calculation-point spacing. CIE and CEN: three transverse calculation points (as in drawing); ANSI/IES: two transverse points

14.1.1 Calculation Points

The values obtained for calculated averages and uniformities, whether they be illuminances or luminances, are only of course meaningful if both the number and the position of the calculation points employed are specified. For luminance calculations it is generally accepted that the area on the road for which the calculations are performed—the calculation grid— should be representative of the road between 60 and 160 m in front of the road user, which is the area of greatest interest to him. Test calculations have, in fact, shown that this requirement will be fully satisfied if the calculation grid covers at least one span (this being the area between successive luminaires on the same side of the road). CIE (2000)) and the European Standard (CEN 2013) recommend that the span should lie between two luminaires in the same row, the first luminaire being located 60 m ahead of the observer. The American Standard (ANSI/IES 2014) takes the beginning of the span as lying 83 m ahead of the observer. The number of calculation points in the longitudinal direction is 10 according to CIE, CEN and ANSI/IES (Fig. 14.1).

CIE and CEN, however, add that for larger luminaire spacings the longitudinal distance between calculation points should not exceed 3 m. In the crosswise direction CIE and CEN recommend three calculation points per traffic lane (see again Fig. 10.1) while ANSI/IES recommends two calculation points per traffic lane. The outermost calculation points are always spaced half a calculation point spacing from the edge of the span viz. from the edge of the traffic lane and from the first and last luminaire line as indicated in Fig. 14.1.

A road user sees the road ahead of him in perspective and gives weight to luminance according to the apparent size of the area concerned: the closer the area is to him, the larger will it appear and the more influence will it have in comparison with other areas of equal real size farther away. With the uniformly-distributed grid points for luminance, as specified by CIE, CEN and ANSI/IES, the individual luminance values are not weighted according to the apparent size of the areas concerned, that is to say too little weight is given to the areas close to the observer position and too much to those farther away (Fig. 14.2 top).

By distributing the individual calculation points uniformly over the perspective picture of the road surface (Fig. 14.2 bottom) proper weight is given to the areas at different distances from the observer. However, in practice such a grid is not normally employed, especially because it makes marking grid point positions for measurement purposes more difficult. It should be noted, however, that so-called

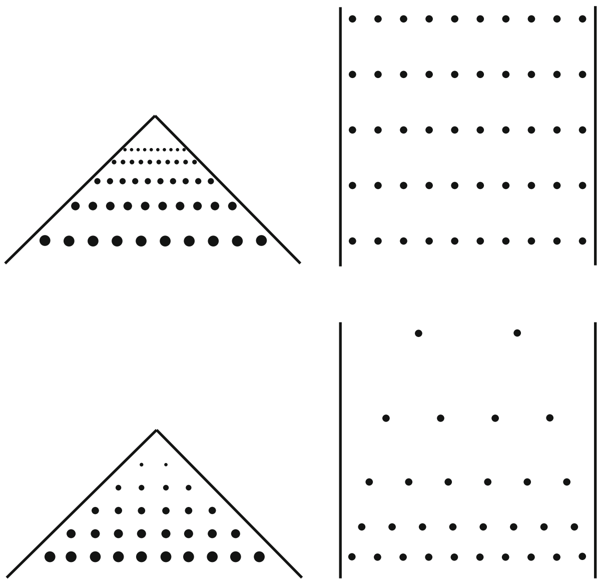

Fig. 14.2 Distribution of grid points, *top*: uniformly distributed over the non-perspective scene of the road; *bottom*: uniformly distributed over the perspective scene of the road

integrating luminance meters that make use of a trapezium-shaped slide to project the perspective area of the road on its light sensitive cell (see Sect. 14.2.1), measure the perspective-weighted average luminance.

14.1.2 Observer Position

14.1.2.1 Longitudinal Position

During his drive a road user continually scans the whole road area in front of him. As he travels along the road, his area of interest naturally moves along in front of him. Ideally, therefore, different calculation grids should be evaluated for different longitudinal positions of the observer. This is illustrated in Fig. 14.3.

Given the variations in individual light distributions and mounting positions of luminaires and the variation in refection properties of different road surface areas, such a complicated, precise system is not needed. This leaves us with two possible methods:

- a fixed longitudinal observer position with one fixed calculation grid, again covering one typical span between the area of interest,
- a longitudinally-moving observer position with one fixed calculation grid, covering one typical span between the area of interest.

CIE and CEN use the first possibility with a fixed longitudinal observer position at 60 m from the beginning of the fixed calculation grid. This is typical for the situation

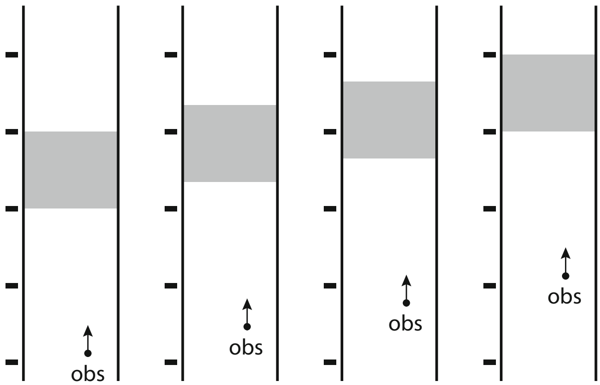

Fig. 14.3 Observer moving along with the calculation grid

experienced by a driver scanning the road area in front of him from one typical, momentary position. As a consequence, the angle of observation with the horizontal road surface varies for the different calculation points. For the area between 60 and 160 m in front of the observer, the variation in this angle lies between 0.5° and 1.5° for which the reflection tables are applicable as discussed in Chap. 12.

ANSI/IES use the second possibility. They position the longitudinally-moving observer at a longitudinal distance from each calculation point so that he always views the road surface under an angle of 1°, which is the same angle for which road surface reflection tables are measured. However, this method does not give a picture of what one observer momentarily sees when scanning the road area in front of him. As ANSI/IES works with a standardized eye height of 1.45 m, the longitudinal distance of their observer is 83 m from each calculation point.

For calculating the veiling luminance needed for glare evaluations (threshold increment TI for CIE and CEN or veiling-luminance ratio for ANSI/IES), the longitudinally-moving observer positions are used, as in the second method described above, so as to obtain the maximum glare value experienced during the drive. The maximum value obtained from these positions represents the glare value that has to fulfil the relevant specifications. CIE and CEN take a standardized screening angle of 20° into account in the calculation of the veiling luminance because the car's roof screens some of the light reaching the driver's eyes direct from the luminaires.

14.1.2.2 Transversal Position

CIE and CEN recommend that in the transverse direction an observer should be positioned in the middle of each traffic lane. For each of these observer positions the average luminance, L_{av}, the overall uniformity, U_o, and the threshold increment, TI, is calculated for the entire carriageway (Fig. 14.4 top). The longitudinal uniformity, U_l, is calculated for each centre line (Fig. 14.4 bottom). For L_{av}, U_o and U_l the lowest value obtained for these observer positions is the determining value that should satisfy the relevant specifications. For TI it is the highest value.

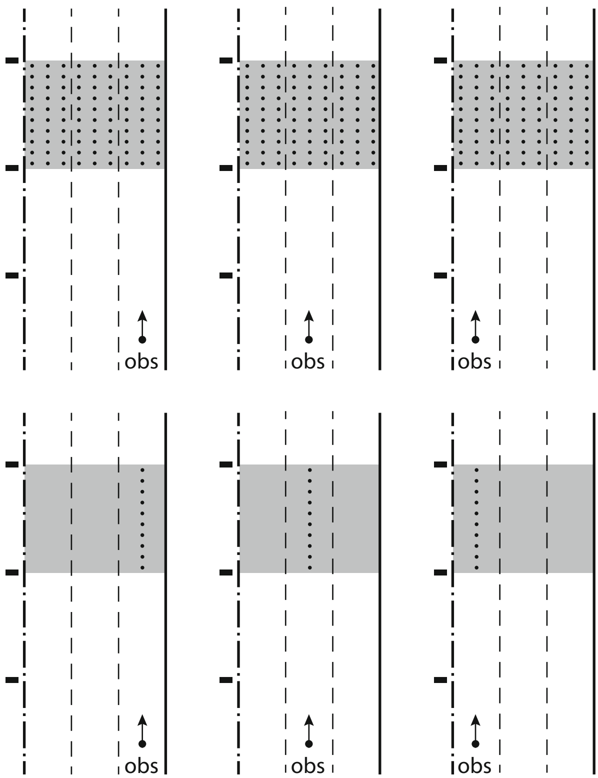

Fig. 14.4 Example of observer positions in relation to the field of calculation according to CIE and CEN, for a three-lane dual carriageway. *Top*: for L_{av}, U_o and TI; *bottom*: for U_l

ANSI/IES recommend the use of an observer moving transversally in each traffic lane. As shown in Fig. 14.5, for each of the two rows of calculation points of a traffic lane, the observer is positioned in line with the row of calculation points. The advantage is that in this way the observer always looks under exactly 1°, the viewing angle for which the road surface reflection tables are also measured. However, this method does not give a picture of what one observer momentarily sees when viewing across the carriageway. As already shown in the previous Section, ANSI/IES also recognise a longitudinally-moving observer as shown in Fig. 14.5 where the different longitudinal observer positions are indicated by grey dots. The worst value obtained for each of the calculated quality parameters is the determining value that should satisfy the relevant specifications.

As shown above, different Standards sometimes employ different conventions for the observer positions and calculation points to be taken into account, each with certain advantages and disadvantages. It is extremely important that specifications for road lighting installations should clearly specify which convention method has to be followed. Most lighting calculation software programs available have a setting specific for the different calculation conventions.

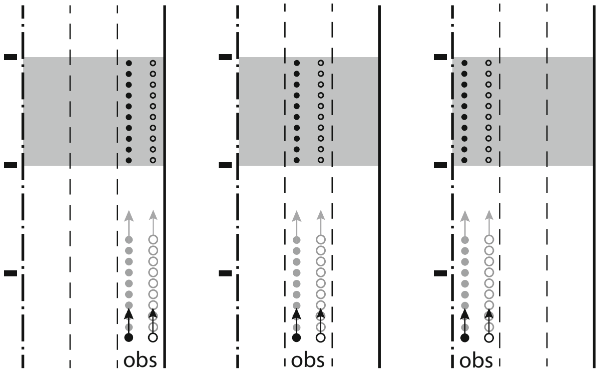

Fig. 14.5 Example of observer positions in relation to the field of calculation according to the American Standard, for a three-lane dual carriageway

14.2 Measurements

The measurements carried out in connection with road lighting fall into four categories, namely those to determine the lamp properties, the luminaire properties, the reflection properties of road surfaces, and the installation properties. The first three categories mostly concern laboratory measurements. Sometimes, however, road-lighting engineers want to check the spectral lamp properties, especially the S/P ratio of the light source, in the field. The same holds true for the reflection properties of road surfaces where both laboratory measurements from samples and in-situ measurements with reflectometers can be carried out. Field measurements made on road lighting installations are carried out on new installations to check whether they fulfill the quality specifications and on installations already in use, to reveal whether there is a need for maintenance, modification, or perhaps replacement. The principles of both laboratory and field measurements will be outlined here.

14.2.1 Light Detectors

14.2.1.1 Types

For all light measurements photoelectric cells are used that convert the light incident upon them into electrical energy, the amount of which is measured. The principle of these cells is basically the same as that of solar cells of the photovoltaic type: they convert incident light directly into electric power without the need for an external voltage source. However, photovoltaic cells used for accurate and low lighting-level measurements usually employ external batteries to amplify the output current of the cell. Photovoltaic cells consist of two layers of semiconductor material: n and p types (as with LED light sources). Again as with LED light sources, they are in fact semiconductor diodes and are therefore often referred to as photodiodes. Formerly, selenium, with a barrier layer in between the n and p layers, was used as

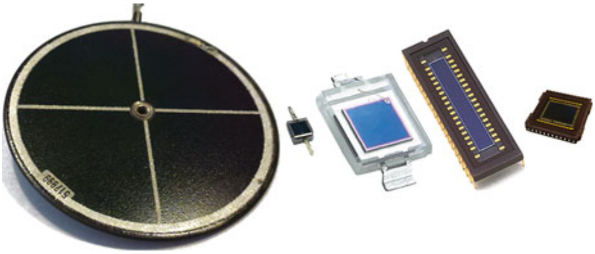

Fig. 14.6 Detector cells. From *left* to *right*: selenium cell, two silicium cells, silicium array, and a 2 megapixel CCD cell

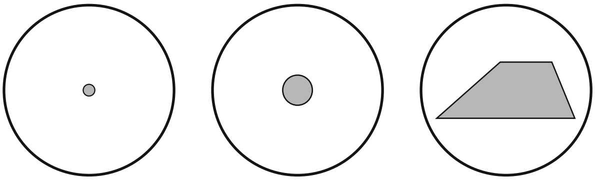

Fig. 14.7 Field of view of a luminance meter with different diaphragms giving different measuring fields

semiconductor material. They were referred to as barrier-layer cells. Today, silicon and silicon dioxide are commonly used for light-measuring photodiode cells. They are available in sizes ranging from 0.5 mm to something like 30 mm in diameter (Fig. 14.6).

Since photoelectric cells measure the light falling on the surface area of the cell, it is the illuminance that is measured. In photometry, therefore, all photometric quantities that have to be measured have to be converted to illuminances. For luminance measurements this means that the image of the surface whose luminance has to be measured, as for example the bright area of a luminaire or the area of a road section or a point of the road, has to be projected on the face of the photocell. A luminance meter therefore contains a photocell with an optical system in front of it that projects an image of the scene to be measured onto the face of the photocell. Normally, the luminance meter has a second optical system that enables it to be aimed accurately at the location to be measured. By employing an adjustable diaphragm, the size of the area projected onto the cell can be changed from spot measurements to larger, area measurements. By employing a trapezoidal diaphragm that coincides with the perspective view of the road area in front of the meter, the average road-surface luminance is measured direct (Fig. 14.7). Such meters are called integrating luminance meters. For very small spot measurements very sensitive photo cells are needed because of the small amount of light finally reaching the photocell[1].

An interesting possibility for measuring the complete luminance pattern of a scene in just one measurement, is obtained with the introduction of CCD (charge-coupled device) and CMOS (complementary metal-oxide semiconductor) chips, which were

[1] For this reason some spot luminance meters make use of so-called photomultiplier tubes in which the electrons released by the incident light on the cathode, are multiplied in a cascade effect between a series of consecutive anodes.

developed for digital photo and video cameras. CCDs consist of one piece of n-p silicon semiconductor material, which is in fact a silicon photodiode cell. The top layer is divided by lines of electrodes, often of aluminium, and lines of insulator material, into a raster of many tiny dots called pixels. Today, chips with a size smaller than 1 cm^2 containing more than 10 megapixels are no exception: a matrix with more than 3000 × 3000 dots. The light incident on each pixel area is, as in normal photodiodes, transformed into an electrical charge. CCDs have no traditional wiring to all individual pixels. They transport the charge at a pixel across the chip to the edge of the chip where it is converted into a voltage and read, while memorizing the precise location from where it originates in the cell's matrix. In CMOS chips, which are made of metal-oxide silicon, each individual pixel has its own charge-to-voltage conversion and reading circuit. This reduces the area for light capture and thus the resolution and sensitivity of the chip. Whereas CCDs require a complicated manufacturing process, CMOS chips are manufactured in much the same way as most microchips and can therefore be produced considerably cheaper in a mass-production process. Today, CMOS technology is rapidly developing to include high-end applications, thus decreasing the quality gap with CCDs.

A digital photo camera with a CCD or CMOS chip records and remembers the amount of light arriving from each scene element, which in turn is proportional to the luminance of that element. With specific software it is now possible to analyse the complete luminance pattern of that picture. In the case of a picture of a road scene, the average road-surface luminance and the road-surface luminance uniformities, as well as the luminances of the luminaires are obtained. For absolute values, appropriate calibration is required. For certain digital photo cameras such specific software is commercially available. Specific luminance meters that need no separate calibration, also using CCD or CMOS chips, are being produced as well.

14.2.1.2 V(λ) Correction

The spectral response of a photocell differs considerably from that of the eye as defined by the spectral sensitivity V(λ) of the CIE Standard Observer, on which all light units are based. For this reason, a so-called correction filter or filters must be employed over the cell window in the cell housing. The various makes of cell, and even cells from the same manufacturer, differ in the degree of correction needed to match cell to eye. Each cell should therefore be supplied with its own appropriate correction filter. It should be realised, that exact correction by means of filters is difficult to achieve and makes meters expensive. Cheaper meters, those with insufficient V(λ) correction, need "colour-correction factors" for each different type of light source. These correction factors have to be supplied by the meter manufacturer. Such meters are not suitable for the measurement of mixtures of different light sources especially those including daylight. Given the great number of different spectra that LED light sources may have, it is impossible for a meter manufacturer to supply correction factors for all the possible different types of LEDs. Poor V(λ) corrected light cells should therefore not be used for the measurement of LEDs or LED installations.

Fig. 14.8 Example of photocell housings with protective layer that together provide cosine correction, and (on the *right*) an adapter for the measurement of semi-cylindrical illuminance

14.2.1.3 Cosine Correction

Light falling on the surface of the cell should, according to the definition of illuminance, be weighted according to the cosine of the angle of incidence. A possible source of measurement error can occur due to the fact that at large angles of light incidence part of the light is reflected by the transparent, somewhat glossy, protective layer covering the cell. This part does not reach the light-sensitive surface of the cell and therefore the cell does not exactly follow the cosine law. In high-quality photometers, the cell and its housing, in conjunction with the covering material of the cell, are so shaped as to obtain correct cosine correction (Fig. 14.8). In road lighting, where light incident at large angles of incidence is an often-occurring situation, the use of photometers that are correctly cosine corrected is essential.

For semicylindrical and hemispherical illuminance measurements there are special adapters available that have to be placed over the normal photocell (Fig. 14.8 right).

14.2.1.4 Pulsed Light Measurement

To dim LEDs, pulse-width modulation (PWM) is employed (see Sect. 10.4.4.2). When measuring the dimmed lighting level it should be noted that the measuring result of the photometer may deviate from the arithmetic average of the modulated light. The deviation especially depends on the modulation frequency and on the internal response time of the photocell and of the amplifier.

14.2.1.5 Ambient Influences

Some photocells are affected more than others by changes in ambient temperature. Where this affects measurement accuracy it will be necessary to have the instrument calibrated for different ambient temperatures. Appropriate correction factors can then be applied to the readings obtained.

Moisture on the photocell, or on any filter or corrector in use, can detract considerably from the accuracy of the measurements. The cell should therefore be kept dry, and it is better to avoid making measurements altogether during periods of high humidity.

Although photodiode cells have only very small fatigue effects, the amplification and reading circuitry may have a larger fatigue effect exhibiting hysteresis. This leads to a too high or too low reading, depending on the previous light condition in which the photometer was used. In situations where there are large differences in lighting levels being measured, adaptation times of up to as much as several minutes may be required until a stable reading is obtained.

14.2.1.6 Age Effects

The absolute and spectral sensitivity of a photoelectric cell and its sensitivity to ambient temperature, changes with time. Also, the electrical amplification circuitry and reading circuitry may undergo changes with time. The complete instrument has therefore to be calibrated at least once a year. Many high-quality manufacturers offer a calibration service for this purpose.

14.2.1.7 Accuracy

The previous Sections have shown that the accuracy of light measurements depends on the operational conditions, but perhaps even more so on the characteristics of the photometer itself. The CIE Standard, "Characterization of the performance of illuminance meters and luminance meters" (ISO/CIE 2014), defines quality indices for different quality aspects of photometers, the more relevant ones having been dealt with in the previous Sections. Table 14.1 lists the quality aspects that are defined in this Standard, together with the quality index. The smaller the value of the index, the smaller the inaccuracy and thus the better the quality of the relevant aspect. If photometer manufacturers were to provide the values of the relevant quality indices for their meters, it would allow not only for mutual comparison of the quality of different meters but also for determining which meter is more suitable for use in specific applications and under specific conditions.'

14.2.2 Measuring Lamps

14.2.2.1 Luminous Flux

The luminous flux of a lamp or of a luminaire can be obtained by measuring the luminous intensities in all directions with a goniophotometer. This will be described in Sect. 14.2.3.1 "Light Distribution". Through the calculation of the solid-angle-weighted average of all intensities, the total luminous flux is obtained. This is an accurate but time consuming method. Thus, especially for quality control in the production process, an easier and more rapid method is required. With a sphere-shaped integrating photometer, called an Ulbricht's sphere after the scientist who

Table 14.1 CIE quality indices for photometers. (CIE 2013)

Quality aspect	Quality index	Remark
V(λ) mismatch	f_1'	
UV response	f_{UV}	
IR response	f_{IR}	
Cosine response	f_2	Illuminance only
Directional response	$f_{2,g}$	Luminance only
Surround field influence	$f_{2,u}$	Luminance only
Linearity	f_3	
Display-unit	f_4	
Fatigue	f_5	
Temperature dependence	$f_{6,T}$	
Humidity resistance	$f_{6,H}$	
Modulated light	f_7	For relevant frequencies
Polarization	f_8	
Spatial non-uniformity response	f_9	
Range change	f_{11}	
Focusing distance	f_{12}	Luminance only

described the principle in 1900, a much more direct measurement of luminous flux is possible (CIE 1989, 2007). The hollow interior of the sphere is painted matt-white so that it reflects the light of a lamp suspended in the interior of the sphere perfectly diffusely (Fig. 14.9). Every point of the interior surface reflects both the light arriving direct from the lamp and that arriving by way of inter-reflection from every other point of the sphere. Consequently, the illuminance on any part of the sphere's interior wall due to reflected light is proportional to the luminous flux of the lamp in the sphere, independent of its light distribution. A small window in the wall, which is screened from direct lamp light by a small baffle, allows this illuminance to be measured and the luminous flux of the lamp to be calculated. In practice the baffle and the lamp itself disturb part of the interreflections. And, in addition to these disturbances, the matt-white paint will in practice not be completely uniform and not reflect perfectly diffusely. Because of this, the integrating sphere has to be calibrated against a standard lamp of known luminous flux and, preferably, of comparable shape. To further limit measurement inaccuracies, the sphere dimensions have to be large relative to the lamp to be measured and relative to the window size required (integrating photometers with a diameter of 2–4 m are not unusual). Nevertheless this is still too small for accurate measurements of absolute values of the luminous flux where large luminaires are concerned. However, for relative luminous-flux measurements of luminaires for quality-control reasons, they may be adequate.

Fig. 14.9 Integrating photometer or sphere of Ulbricht with a diameter of 4 m

14.2.2.2 Spectral Data

For road lighting purposes the following spectral data may be relevant: correlated colour temperature T_k, colour rendering index R_a and, for mesopic considerations S/P, which is the scotopic-photopic ratio.

The parameters T_k and R_a can be measured with a so-called colorimeter that has at least three filtered detectors that simulate the x, y and z CIE colour matching functions, which are the basis for the definition of both T_k and R_a. Often a fourth detector with a $V(\lambda)$ filter is used in conjunction with the other three detectors. From the resulting chromaticity coordinates x and y, the values for T_k and R_a are calculated (Schanda 2008). For the measurement of the S/P ratio two detector photometers are sometimes used. One detector is filtered according to the scotopic eye-sensitivity curve $V'(\lambda)$ and the other by the photopic sensitivity $V(\lambda)$. The ratio of the readings of the two detectors is the S/P ratio. However, measurement with such photometers may lead to inaccuracies in the parameter values because perfect filtering to match the required functions is difficult. This disadvantage does not exist with the use of spectrophotometers that measure the whole spectrum of the light source. In a spectrophotometer the light from the light source entering the meter is dispersed into its spectral colours, that is to say into different wavelengths, by a diffraction grating that works as a prism (Fig. 14.10). In traditional spectrometers a moving, unfiltered detector scans the dispersed radiation and so measures the energy radiated at the different wavelengths.

From the energy spectrum obtained all the spectral parameter values can be calculated. Normally, the instruments have built-in software that makes the required calculations and directly yields the resulting values of the parameters directly. Many newer spectrometers employ an (unfiltered) CCD linear array detector instead of a single scanning detector. The light that is dispersed by the diffraction grating is projected onto the detector array so that in one measurement all information over the whole wavelength range is collected (see again Fig. 14.10). Such a spectrophotometer without moving parts is also available in portable versions. These allow the

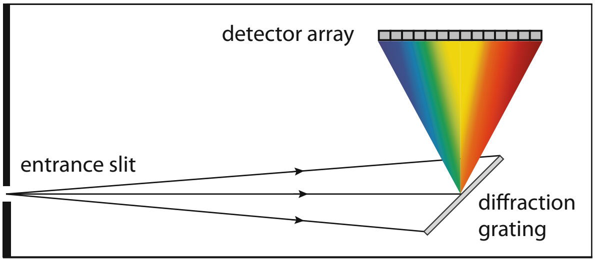

Fig. 14.10 Principle of a spectrophotometer with a detector array

instrument to be used in the field to determine the spectral data with a reasonable degree of accuracy. For road lighting, the determination of the S/P ratio value in the field is especially of interest. This can be determined from the spectrum measured with the spectrophotometer. Most such meters have the software needed for this, embedded in the instrument so as to show the value direct after the measurement.

14.2.3 Measuring Luminaires

14.2.3.1 Light Distribution

The luminous intensity distribution of a luminaire is the basis for all lighting application calculations. In the calculations, the luminaire is considered as a point source. Luminous intensity measurements therefore have to be done at a great distance from the luminaire. Inaccuracies will be negligible provided the optical path length of the measuring set-up is ten times the length of the largest size of the light-emitting area of the luminaire (CIE 1996). Measurements satisfying this requirement are called far-field measurements. A set-up that enables the measurement of the luminous intensity together with the measurement of the angles of azimuth and elevation of each light direction of a luminaire (C and Gamma angles), is called a goniophotometer. The simplest form is a set-up in which the luminaire intensities are measured by rotating the luminaire about its horizontal and vertical axes, while the photocell remains in a fixed position (Fig. 14.11 left). However, with a luminaire rotated around its horizontal axis, the burning position of the lamp changes which, with many lamps, affects the lamp's light output and luminance distribution. This, in turn, may lead to unacceptable errors in the measured light distribution. A technique in which this problem is avoided is shown in Fig. 14.11 right, where the luminaire only rotates around its vertical axis while the photocell is moved over a spherical path.

An advanced modification of this technique is that in which photo detectors are mounted at many locations on the spherical path. For the normal requirement of measurements to be made each 2.5° in the vertical plane, 72 detectors are required. They can be used in a circuitry that permits for simultaneous measurement of all detectors, so considerably reducing the total measuring time. However, the laboratory space then has to be very large. If only compact LED luminaires have to be measured, this technique can become feasible.

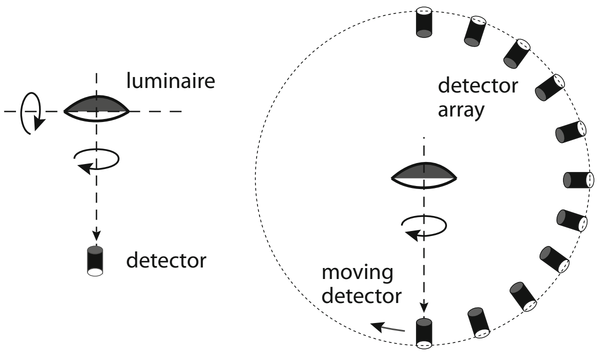

Fig. 14.11 Schematic representation of goniophotometers. *Left*: luminaire is rotated about two axis while the photometer detector is stationary; *right*: luminaire remains stationary while the detector is moved over a spherical path

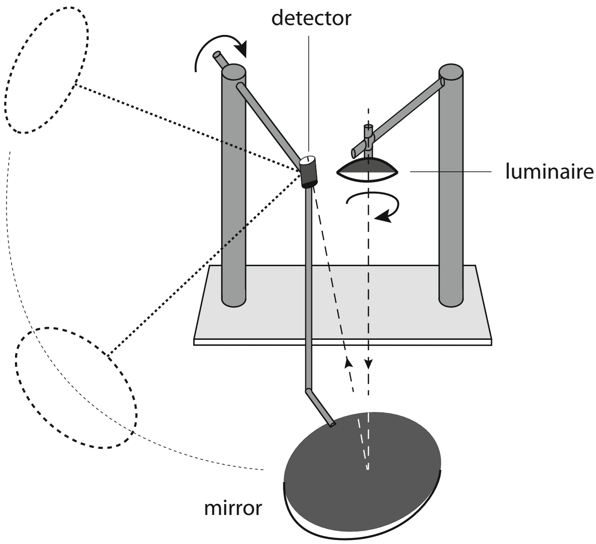

Fig. 14.12 Example of a goniophotometer with the luminaire rotating about its horizontal position and with rotating mirror that directs the light towards a stationary photocell

To decrease the laboratory space needed, a rotating mirror or mirrors are generally employed. The principle is sketched in Fig. 14.12. Here the luminaire rotates about its vertical axis, always remaining in its horizontal position, so as to radiate its light towards a fixed photocell via a mirror mounted on a boom that rotates about a horizontal axis. By the combination of the rotating luminaire and the rotating mirror all relevant directions can be successively measured. The angular settings at which measurements are made must be precisely reproducible. Many different alternative solutions using a rotating mirror in conjunction with a moving, horizontal, luminaire are in practical use. Figure 14.13 shows a photograph of a typical commercial example.

If the luminous flux of the lamp in the luminaire is known, only relative values are needed for the light distribution measurement. This means that unfiltered photocells can be used, thus avoiding inaccuracies due to incorrect V(λ) correction.

Results from near-field photometry can be used to calculate the far-field light distribution (Ngai 1987). With the introduction of CCD matrix photo detectors,

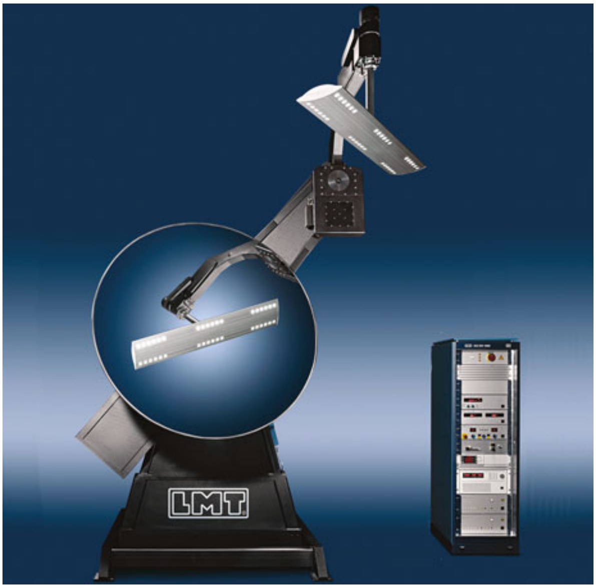

Fig. 14.13 Commercial photometer with rotating mirror and fixed luminaire position

near-field photometry requiring only a limited laboratory space, has become feasible. In near-field photometry, the luminaire is not considered as a point source but as a combination of bright surfaces, each with its own photometric properties that can be characterized by their luminances in many different directions. Near-field goniophotometers map the luminance distribution of these light-emitting surface areas using a luminance meter with CCD detectors.

14.2.3.2 Light Output

As has been mentioned in the Section about the measurement of luminous flux, the total luminous flux of a lamp or luminaire can be obtained from the calculation of the solid angle weighted average of all luminous intensities. In fact, using high-quality goniophotometers for obtaining these luminous intensities offers the most accurate method for determining the luminous flux or light output of a luminaire. Since here absolute values are required, calibration against a light source with known luminous flux is needed.

14.2.4 Measuring Road Surfaces

It has been shown in Chap. 12 that the reflection properties of a road surface can, for the purpose of luminance calculations, be characterized by a reflection table containing 396 reduced luminance coefficients. These road surface reflection properties can

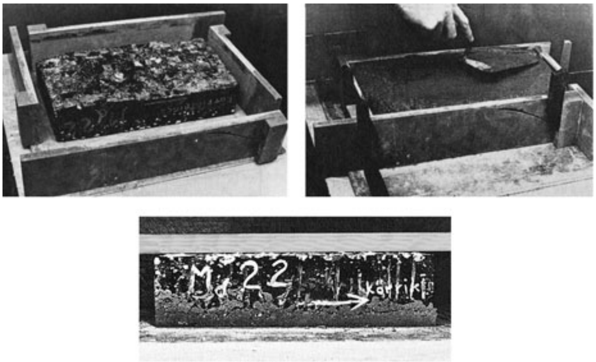

Fig. 14.14 Sample being cast in concrete; *arrow* indicates driving direction. (Sørensen and Nielsen 1974)

be measured in a laboratory on a road surface sample cut or drilled out of an actual road surface, or in-situ with a portable reflectometer on the actual road.

14.2.4.1 Laboratory Measurements

The road surface sample being measured must, of course, be as representative as possible of the road surface as a whole. The size of the sample is important: too small, and the chances are that it will not be truly representative of the surface from which it was removed. A typical size for laboratory measurements would be something like 10 × 30 cm. If one works with drilled road surface cores of 15 cm diameter, three cores of the same area of the actual road surface should be measured to get a representative measurement. The cutting or drilling-out must be performed in such a way that the sample is not distorted or its surface damaged. To guard against distortion in the case of cutting-out a large sample, the sample should immediately be supported in some way: for example, in a cement mould so that the surface cannot bend and the top part remains flat (Fig. 14.14). An alternative, resulting in a less heavy sample, is to use rigid steel plates and to fix the samples with glue. The measurements should then be completed as soon as possible, before significant surface changes can take place due to drying out. The driving direction on the road should be noted, because often the reflection properties are influenced by the vehicles driving over the surface.

The size of the area being measured should cover a large part of the sample, again to obtain representative results for the actual road surface. Since the luminance coefficient is defined as the ratio of the luminance to the illuminance, the values of this coefficient for each of the 396 combinations of β and γ can be obtained from a series of luminance measurements carried out under the standardized observation angle of 1°. With proper calibration, there is no need to also measure the illuminance at the sample. Figure 14.15 illustrates the principle behind two measurement set-ups commonly employed.

The range of angles from $\beta = 0°$ (meter facing the light source) to $\beta = 180°$ (meter looking away from source) are set by rotating the road sample together with the

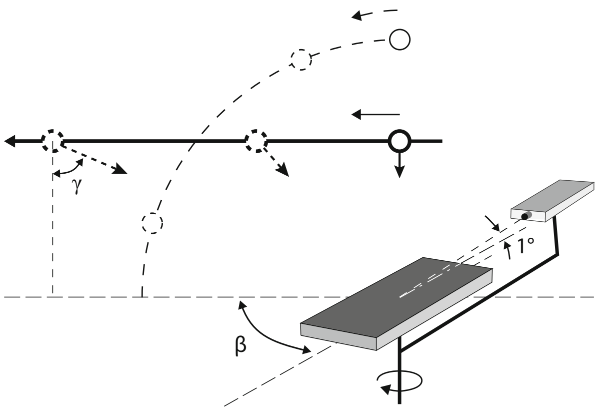

Fig. 14.15 Schematic laboratory set-up for obtaining the reflection table of a sample of road surface

meter about the vertical axis through the point of measurement. The sample should be mounted with the driving direction parallel to the 0°–180° β direction. The γ angle can be set by moving the light source along a straight line such that its vertical distance above the sample remains constant. A long (dark) corridor is needed for this purpose. The solid angle subtended by the source at the point of measurement will increase with decrease in the angle of light incidence (smaller angle γ); as is the case in an actual road-lighting installation. If the measuring area covers the sample more or less completely at large γ angles, it means that at smaller angles the measuring field covers only part of the sample. Alternatively, as also illustrated in Fig. 14.14, the light source can be rotated over an arc about the sample. Here the solid angle subtended by the light source at the point of measurement is constant, as is the measured size at the sample. It is possible to introduce a variable-aperture diaphragm in front of the source to make the solid angle change (just as is the case with the method of the light source moving along a straight line). Of course, as with the measurement of the light distribution of luminaires, here too a mirror or set of mirrors can be employed to make the measuring set-up more compact. As an alternative to using one moveable source, a number of fixed sources located so as to give the necessary range of γ angles, and switched on in turn to give a short flash, can be used. Such a set-up has the advantage that the time needed to complete the rather large series of measurements can be kept to a minimum. This is especially important where wet sample measurements are concerned to avoid inaccuracies due to premature drying.

14.2.4.2 Field Measurements

The use of reflectometers makes it possible to measure a larger number of locations on the actual road surface in order to get an impression of the variation in reflection properties over entire surface, thus obtaining the most representative values of S1 and Q_0.

Different types of portable reflectometers have been developed. These are based on four different principles of operation:

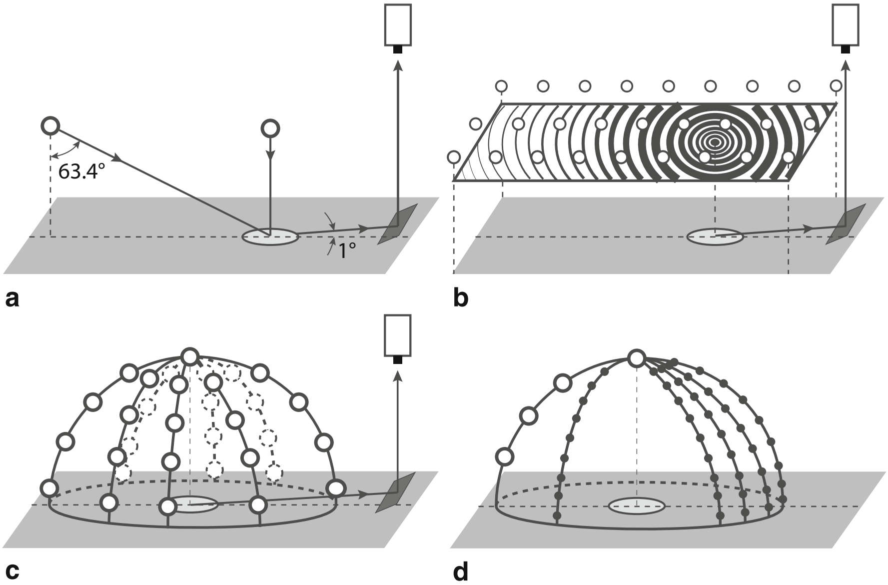

Fig. 14.16 Examples of different working principles of reflectometers. *Open circles* are light sources and the *small black dots* (in d) are luminance detectors (see text for detailed descriptions)

- S1 and $Q_0$are measured direct, under an observation angle of 1°,
- part of the reflection table is measured for a limited number of angles of light incidence (again under an angle of observation of 1°), and the complete table is constructed by extrapolation. S1 and Q_0 are then calculated from that table,
- a modification of the previous system makes use of the physical principle that says that when the angles of light incidence and directions of observation are interchanged, the light rays will behave in the same way. A device based upon this principle illuminates the road surface under an angle of 1° and measures luminances with luminance detectors at many positions,
- the need to measure under a small angle of 1° makes the design of suitable reflectometers difficult. For this reason, some reflectometers do not measure under such a small angle of observation but under one or more larger angles. The reflection table valid for the observation angle of 1° is then derived from a mathematical model.

The measurement of the specular factor S1 requires two angles of light incidence towards the point on the road surface to be measured, corresponding to r(0,2) and r(0,0) viz. 63.4° and 0° respectively. Normally this is realized by two light sources at fixed positions in the reflectometer that can be switched separately (Fig. 14.16a).

The luminance of the point of interest is measured under an angle of 1°. The ratio of the two measurement results multiplied by $\cos^3(63.4°)$ then gives the value of S1. However, given the actual size of a luminance meter, to measure under an angle of only 1° from a short distance is clearly impossible. Therefore, at least one mirror is used as illustrated in Fig. 14.16a.

Measurement of the average luminance coefficient Q_0 is much more complicated. According to its definition, $Q_0$is directly proportional to the luminance at the point of the road surface considered that is lighted from a luminous ceiling with a constant intensity in the direction of that point. De Boer and Vermeulen (1967) described this rule of proportionality and constructed a reflectometer based on it. Their reflectometer employed a large number of small lamps uniformly distributed above a ceiling with a filter of alternating black and white rings to provide the required luminance distribution of that ceiling (Fig. 14.16b). Measurement is done under an angle of 1° with a mirror system. This instrument was bulky, heavy and difficult to align correctly. A much more handy version working on the same principle has recently been prototyped. Here the required luminance distribution of the ceiling is obtained by means of several, separately-controlled arrays of LEDs arranged above a dome of diffusing acrylic glass (Panhans et al. 2009).

Some reflectometers have been developed that measure only a limited number of luminance coefficients for a limited number of angles of light incidence (see Fig. 14.16c)—(Debergh and Embrechts 2008; Fellin et al. 2009, Korobko et al. 2013). The results of the measured luminance coefficients are used for an extrapolation process to derive all luminance coefficients of the complete reflection table from which both Q_0 and S1 are calculated. The limited number of angles of light incidence are realized by small LEDs. The calculation software needed, is part of the control software of the reflectometer.

A method to overcome the problem of the small observation angle of 1° makes use of the physical principle that states: when the angle of light incidence and directions of observation are interchanged, the light rays behave the same. A device based upon this principle illuminates the road surface under an angle of 1° and measures luminances with luminance detectors at many fixed observer positions: these, in the normal reversed situation, represent light-source positions for important directions of light incidence (Muzet 2008). So the situation is as in Fig. 14.16c, with small luminance detectors at the positions of the light sources and a fibre-optics system that provides for light incidence under an angle of 1°. The measurement results are used as input for a mathematical model that delivers the S1 and Q_0 value of the road-surface area measured.

Some reflectometers do not measure under the small observation angle of 1° but under one or more larger and more convenient angles. For example, one such reflectometer (Laurent 2008) employs a set of luminance detectors mounted on four semi-arcs, that view the sample under α-angles of 5°, 10°, 20°, 30°, 40°, 50°, 60°, 70° and 80° (Fig. 14.16d). Only four fixed light sources (light incidence angles γ: 0°, 30°, 50° and 70°) are used. Detector arcs are mounted at five offset angles so as to measure all γ-angles under five different β-angles viz. 0°, 10°, 20°, 30°, and 150°. The luminance coefficients of the reflection table valid for the observation angle of 1° are, again, derived from a mathematical model. Of course, here too, the calculation software required is part of the control software of the instrument.

All reflectometers have a sturdy cover, which also serves to screen light from the lighting installation reaching the measuring area. Normally, measurements are made during the night. This because it is very difficult, given the unevenness of road surfaces, to prevent daylight from interfering with the area of the road surface being measured.

In Sect. 12.2 it was mentioned that investigations have been started to find good approximations for Q_0 from different sets of luminance coefficients, based on an extensive set of recent R-tables. This could ultimately lead to alternatives for both Q_0 and S1. If this proves possible, it could lead to the design of new types of road-surface reflectometers.

14.2.5 Measuring Installations

14.2.5.1 Illuminance and Luminance Measurements

Generally speaking, where the aim is to determine the overall quality of an installation this has to be done by way of measurements of the quality parameters, namely the illuminances or luminances that are relevant for the type of application. If luminances are the relevant parameters and the aim is to check whether or not a luminance-designed installation is in compliance with specification, this can be done on the basis of illuminance measurements alone. If a check of the illuminance pattern on the road surface reveals that the measured values are in close agreement with those calculated, then the luminance pattern that will result will also be in accordance with that designed. This is provided, of course, that the road-surface reflection properties are close to those on which the design was based. Such an illuminance check is the only approach in the case of an installation for a stretch of newly-laid road, the lighting design for which has been based not on the relatively unstable reflection properties of the new surface but on the reflection properties expected to exist after a specified 'running-in' period. The illuminance check can, unlike a check on luminance, be safely made during the running-in period. The fact that it is often possible to fall back on an illuminance survey means, of course, that it is advisable to have available a complete set of calculated illuminance values for the installation being investigated, even if its design is entirely luminance based. Knowing the designed illuminance values, it is also a simple matter to check whether an installation is in need of maintenance, modification, or even replacement. The measurement involved here is again one of illuminance, any deterioration in the quality of the lighting being made immediately apparent by comparing the calculated with the measured illuminances.

To perform accurate measurements of horizontal illuminance it is recommended that the measurements be carried out with the photocell cardan, or gimbal, mounted so that it is always in the true horizontal.

Measuring Grid Whatever the type of measurement to be made, a decision must be made concerning the number and positions of the measuring points: in other words, the measuring grid must be defined. When all that is needed are a few spot checks to see that the measured values are in agreement with those specified in the design, just a few measuring points will suffice—although these must, of course,

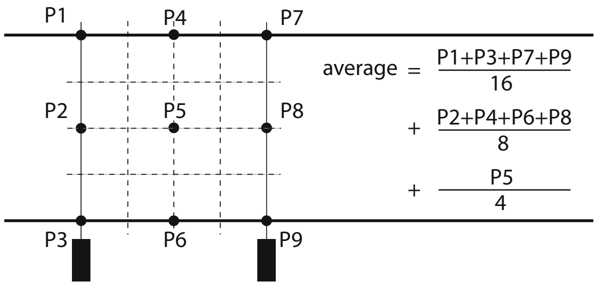

Fig. 14.17 Nine-point measuring grid suitable for obtaining a rough indication of the lighting level; with weighting formula for calculation of the average value

be evenly distributed over the road surface in question. Figure 14.17 illustrates the layout of a nine-point measuring grid of the kind sometimes used when checking new road-lighting installations.

The points are easy and quick to locate because they are in line with the luminaire locations and with their midway point. If these points are used to give a rough indication of the measured average lighting level, then the measured value of each point should be weighted as indicated in the figure.

Of course, where extreme accuracy is required, it is recommended to use as many measuring points as specified for calculations (see Sect. 14.1.1).

Observer Position When performing luminance measurements it is necessary to define the so-called observation point or points employed—points defining the positions of the luminance meter relative to the points whose luminance is being measured. These observation points should coincide with the observer positions defined for calculations. As has been shown in Sect. 14.1.2, the different Standards and Recommendations for road lighting use different observer positions. For determining whether an installation is up to specification, it is therefore important to accurately follow the relevant recommendations for observer positions as described in Sect. 14.1.2.

Size of Measuring Area In illuminance and luminance calculations, calculation points are points with infinitesimal-small dimensions. Given the small size of photocells, illuminance measurements can also be considered as point measurements. However, with luminance measurements that is not at all the case. The farther away the measuring point is from the luminance meter, the larger especially the longitudinal size of the measured point. Table 14.2 gives the sizes of the area covered by spot luminance meters with a measuring angle of 30′, 6′ and 2′ for measuring distances of 60, 100 and 160 m respectively.

From the table it is evident that 30′-spot-luminance meters are certainly not suitable for measuring the luminance pattern of a road: even at the shortest measuring distance of 60 m, the “spot” overlaps with a total length of road of more than 20 m. With a spot luminance meter with a measuring angle of only 2′, the measuring spot still overlaps with a total road length of 1.4 and 9.8 m for measuring distances of 60 and 160 m respectively. The phenomenon is illustrated in Fig. 14.18 which shows,

Table 14.2 Longitudinal and transverse sizes of the measuring area of spot luminance meters with different measuring angles from different measuring distances

Viewing angle	Area size (m) from 60 m			
	Length before	Length behind	Length total	Width total
30′	8.9	12.7	21.6	0.52
6′	2.0	2.2	4.2	0.05
2′	0.7	0.7	1.4	0.03
	from 100 m			
30′	22.5	41.1	63.6	0.87
6′	5.5	6.2	11.7	0.17
2′	1.8	2.0	3.8	0.06
	from 160 m			
30′	50.8	139.5	190.3	1.40
6′	13.6	16.5	30.1	0.28
2′	4.7	5.1	9.8	0.09

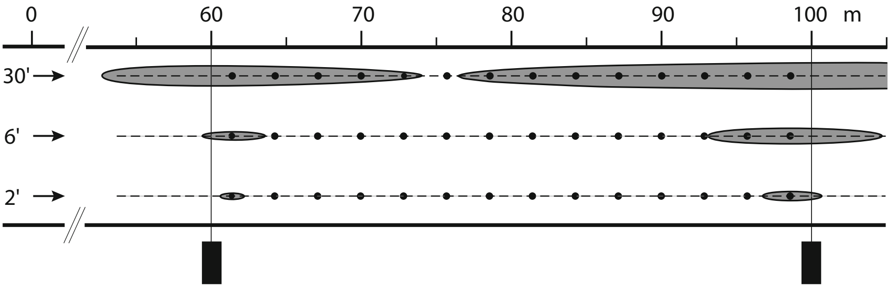

Fig. 14.18 Road-surface area being included in the measurement of a spot-luminance meter having a measuring angle of 30′, 6′ and 2′ respectively. The meter is located 60 m in front of the luminaire span and is aimed at 60 and 100 m respectively

for an installation with a spacing of 40 m, by how many calculation points the measuring areas overlap. In the case of an measuring angle of 30′ and 6′, the measuring field for one measuring point overlaps with two or many more calculation points.

The phenomenon has a smaller influence on the average luminance, as calculated from many individual measured "points" that together overlap the whole measured area, than it has on luminance uniformities. Because of the large-sized measuring areas, the measured minimum will be higher than the minimum of a real point and the maximum will be lower than the maximum of a real point. The final result is that the measured uniformities, erroneously, appear to be much "better" than the calculated ones. The smaller the measuring angle, the smaller the difference.

CCD Luminance Meters High-quality, large-megabyte CCD luminance meters with high spatial resolution offer the solution to the measuring-area problem (Glenn et al. 2000; Moore et al. 2000; Rami and Lorge 2007; Bouroussis and Topalis 2009). Spatial measuring resolutions of well below $2'$ are possible. The perspective image of the road scene is projected on the CCD's pixel matrix. The signal of each pixel is proportional to the luminance of the corresponding road element. Depending on the meter's position and orientation relative to the road boundaries, the perspective image can be converted through software into a plane, non-perspective, image in which each pixel represents a small, same sized road area. From a single measurement the software subsequently calculates the average road-surface luminance and the road-surface luminance uniformities. Road-boundary detection can be facilitated by placing some markers on these boundaries.

Mobile Measurements Automatic boundary detection with CCD luminance meters is possible in cases where there is a clear distinction between the road and the road's surroundings. This is done by analysing luminance gradients in the picture (Bouroussis and Topalis 2009). This opens up the possibility for carrying out accurate luminance measurements from a moving vehicle with video CCD luminance meters. The problem here is getting a stable, constant direction of measurement from the moving vehicle on roads that are never completely even.

14.2.5.2 Glare Measurements

The common measure of disability glare, TI, can in principle be determined by separate measurement of its two component parts, the veiling luminance and the average road-surface luminance, from the formula:

$$TI = \frac{L_{veil}}{L_{av}^{0.8}}$$

The total veiling luminance caused by the whole lighting installation can be measured with the aid of a luminance meter fitted with a glare lens. The glare lens, placed in front of the luminance meter, weights the light passing through it in such a way that L_{veil} is measured direct with just a single reading (Fry et al. 1963). The average road-surface luminance is, of course, measured in the normal manner, without the glare lens attached. Unfortunately, today this lens is no longer commercially available.

Software for CCD luminance meters is being developed that allows for the determination of the veiling luminance by analysing the picture projected on the CCD matrix so as to obtain the luminances of the luminaires together with the individual positions of the luminaires (Zatari et al. 2004; Yamada and Kohko 2013). The veiling luminance then follows from the formula:

$$L_{veil} = 10 * \sum \frac{E_{eye,i}}{\theta_i^2} = 10 * \sum \frac{L_{luminaire,i}}{\theta_i^2} * \omega_i * \cos(\theta_i)$$

where:

$E_{eye,\,i}$ Illuminance on the eye or meter caused by i[th] luminaire or luminaire element (pixel)
θ_i Angle between light incidence from i[th] luminaire or luminaire element and viewing or measuring direction
$L_{luminaire,\,i}$ Luminance of the i[th] luminaire element in the direction of the meter
ω_i The solid angle of the i[th] luminaire element as seen from the meter

For discomfort glare, there is the glare control mark (G). However, due to the psychological nature of discomfort glare, the value of G cannot be derived from measurements.

14.2.5.3 External Influences

Stray light reaching the road surface direct from shop windows, traffic signs, vehicle lights, and even from the moon, as well as light reflected onto the surface from light-coloured clothing, walls of nearby buildings and so forth, can add considerably to the amount of light reaching the road surface from the lighting installation alone. The influence of stray light is, of course, particularly noticeable when seeking to measure minimum values. Suppose, for example, that the minimum illuminance given by the road-lighting installation alone at a point on the road surface is 0.5 lx. Stray light contributing only 0.05 lx will then already account for a 10 % discrepancy. Stray light that does not appreciably influence the illuminance measurement (light from an oncoming car, for example) can, due to its direction of incidence, have a marked effect on the magnitude of the luminance reading.

For measurements to be meaningful, the installation's supply voltage should be kept to its nominal value while the measurements are being made; only then will the nominal flux from the lamps be obtained. If control of the supply voltage is not possible, it should at least be monitored so that in the event of supply variations occurring, corresponding corrections to the light output can be made. For installations containing new discharge lamps, 100 h of operation should have elapsed before measurements are taken, in order to be sure that the lamps are stabilised.

Before luminance measurements are carried out it is important to check that the normal reflection properties of the road surface have not temporarily changed for one reason or another. Such changes can be caused by large accumulations of surface dirt (mud, oil, leaves, salt—employed to melt snow and ice—and so forth) or, in the case of bitumen-based surfaces during very hot weather, by partial melting or softening of the surface itself. Where it is the dry-surface luminance that is being measured, care must, of course, be taken to ensure that the surface is perfectly dry. An additional source of error or uncertainty will arise where the wet-surface luminance is being measured, since this surface condition is not accurately reproducible.

Finally, since field measurements are only valid for the conditions prevailing at the time of the survey, it is important to record a detailed description of the area surveyed and to make a note of all those factors that might conceivably influence the results: factors such as lamp type and age, luminaire and ballast type, supply voltage, state of maintenance (including date last cleaned), weather condition (temperature, humidity) exact location of the observation and measuring points and the type and serial number of the measuring instrument used.

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Part II
Light Pollution

Chapter 15
Purpose of Light-Pollution Restriction

Abstract Light spilled outside the area to be lighted is a visible sign of a bad lighting installation. It is most probably not cost-effective and is sure to waste energy with all the negative consequences for the environment, including CO_2 emissions. The light radiated outside the area to be lighted also has serious negative consequences for people, wildlife and vegetation. The purpose of restricting light pollution is to minimize or eliminate all these negative effects. The increased brightness of the environment is also annoying for residents and may lead to stress and health-related problems. It may also negatively influence the visual performance and comfort of road users. The sky glow resulting from light radiated into the sky can completely diminish the visibility of stars and other celestial bodies. The consequence of this is that professional and amateur astronomers cannot carry out their work. For all of us it means that we may be no longer able to see the stars. Animal life, too is affected by an increase of the brightness of the environment, and is manifested by changes in the behaviour and physiology of animals, with possible fatal consequences. Disturbance of the daily dark-light cycle, the lunar cycle and the seasonal cycle are some of the reasons for these changes. Plant life is also affected, so that vegetation may change or become extinct because of light pollution. This chapter elaborates on the various negative effects of light pollution and will help to provide an understanding of the importance of restricting such pollution.

15.1 Balance of Positive and Negative Effects

As we have seen in Part 1 of this book, night-time lighting can make a positive contribution to safety, security, and the quality of life. And this is essential for our society. However, lighting that lights not only the area intended but that spreads out uncontrolled into the surrounding areas and into the sky is an annoyance to society. The terms used to describe this negative aspect of lighting are spill light, obtrusive light, light trespass or, simply, light pollution. It may be a danger for road users and disturb residents, wildlife and the growth of vegetation. It may also disturb both professional and amateur astronomers in their research work and make it impossible for all of us to see the stars. We should also realize that sky glow is a visible sign of unprofessional lighting that wastes energy and contributes to CO_2 emissions and the associated climate change.

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The purpose of restricting light pollution is to minimize all the negative effects of lighting mentioned above. Professional, carefully-designed lighting should bring the light to only where it is really needed, only as much as is needed, and only when it is really needed. Only then can the right balance be achieved between the positive effects of lighting and the negative impacts of that lighting on the environment.

15.2 Disturbing Effects

15.2.1 Residents

Residents may be annoyed or disturbed by the increase in average brightness of their surroundings during the dark hours or by bright lights directly in their field of view, especially in or around their homes. Terms used to describe these phenomena are intrusive light or light trespass. The annoyance has not only a negative influence on quality of life but it may, in extreme cases, lead to stress that in turn may have a negative influence on health. Dynamic changes in the brightness and or colour of the light or flashing lights increase the annoyance and disturbance.

We have evolved under the natural 24-h rhythm (also called circadian rhythm) of bright light during the day and darkness during the night. This light-dark rhythm is an important mechanism for controlling our biological clock, which in turn, controls many biological processes of our body. In extreme situations of light pollution with high intrusive lighting levels, our biological clock may be disturbed, again with negative effects for our health (Navara and Nelson 2007; Lucas et al. 2013).

Some studies suggest that there is a connection between night-time lighting and an increased risk of breast cancer. Indeed, epidemiological evidence suggests that women who have worked for many years in the night-shift, have a moderately-increased risk of breast cancer (Schernhammer et al. 2001; Schernhammer 2006). It is supposed that the circadian system plays a role in breast cancer (Stevens 2005). However, bright light experienced during the night by night-workers is only one of many possible reasons for the increased risk (Figueiro et al. 2006). Also given the low levels of road lighting compared to lighting levels in interiors used by night workers, the connection between road lighting and cancer remains speculative (Figueiro et al. 2006; Brons et al. 2008). It should also be noted that lighting levels in living-rooms during the dark hours are much higher than road-lighting levels. Lighting levels created by light pollution are usually lower than road-lighting levels. Of course, sleeping in a bedroom with light-tight curtains is an effective countermeasure.

15.2.2 Motorised and Slow-Moving Traffic

The disturbing effect of light pollution on road users is mainly that of increased glare. If not sufficiently controlled, this may have a negative effect on both visual

Fig. 15.1 North American starry sky. (Photograph: Dave Crawford)

performance (disability glare) and comfort (discomfort glare). This can lead to dangerous situations, especially for motorised traffic. For slow-moving traffic, such as pedestrians moving around in the street (e.g. sightseeing, shopping, or just going somewhere), the discomfort glare is usually the more important aspect. Dynamic changes in the lighting, or flashing lights, increase the negative effects for both motorised and slow-moving traffic.

15.2.3 Astronomers

Light radiated into the sky is scattered in all directions by air molecules, and by water and dust particles. The scattering from the sky into downward directions produces a bright haze through which the visibility of stars and other celestial bodies is greatly reduced or made impossible. Because of this bright haze, or sky glow, which is almost-always present, many of us today are no longer aware of the amazing number of stars that can be seen in a real dark sky (Fig. 15.1). The cause of sky glow is not only direct light radiated upwards from lighting installations, but also the indirect light reflected upwards from the illuminated surfaces. Professional astronomers making use of observatories as well as the many amateur astronomers, are affected in their research by the negative effects of sky glow. Sky glow is in fact the reason that from within our cities stars have become virtually invisible—and even outside of the city limits, in the open country, only a few brighter stars can be seen with the naked eye. Cinzano et al. (2001) published "the first world atlas of the artificial night-sky brightness". From this survey it is evident that for about 25 % of the world population the sky is never dark enough to be able to see the Milky Way (Narisada and Schreuder 2004).

Light radiated near to or just above the horizon can, through forward scattering, still have a negative influence on an observatory at a distance of some 100 km. This is especially the case with the great amount of light originating from a large city. Figure 15.2 illustrates this by showing the average sky luminance (black dots) measured at different distances from some small, a medium, and a large city (ranging in population from 5000 to 2,000,000 inhabitants). As a comparison for the values shown in the figure: the sky luminance caused by natural background radiation varies between

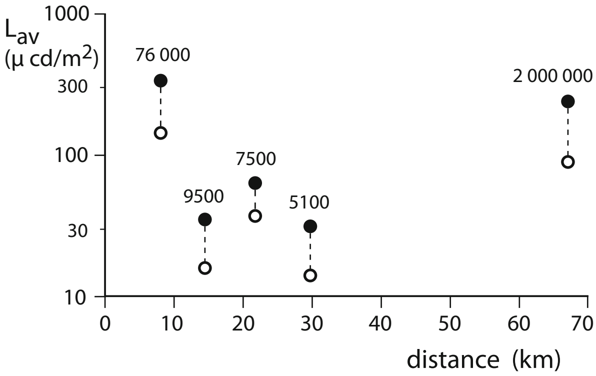

Fig. 15.2 Average sky luminances at different distances from different cities. *Black dots*: actual situation, *open dots*: theoretical situation after shielding all direct upward light. Parameter: city populations. (Figure after Duriscoe et al. 2014)

ca. 250 and 350 micro cd/m^2, depending on the geographical position, the solar activity and the sky area observed (Garstang 1986). Professional astronomers need the sky luminance due to artificial light to be clearly lower than the sky luminance caused by the natural background radiation (IAU/CIE 1980).

Figure 15.2 is based on a study of Duriscoe et al. (2014) in which the results of satellite observations were combined with CCD camera measurements at ground level. The model they developed also enabled the estimation of the sky luminances in the theoretical case where all luminaires in the cities concerned are shielded so as to restrict all direct upward light (without affecting the lighting level on the ground). The results of this estimation are given in Fig. 15.2 by means of the open dots. They show that shielding upward direct light from luminaires reduces sky glow considerably. In rural areas, a reduction of the sky glow of 40 % increases the number of stars visible with the naked eye by 300 % (Baddiley 2013).

Apart from the luminance level of the sky, the spectrum of the light source also plays a role in the severity of the sky-glow effect. Light sources with shorter wavelengths in their spectrum (blue and cool-white light) scatter more than do light sources with longer wavelengths (red and warm-white light) (Garstang 1986; Luginbuhl et al. 2013). The International Dark-sky Association (IDA) therefore suggests that light sources employed in a wide area around professional observatories should be limited to wavelengths larger than 500 nm (IDA 2010). Another light source recommended for the same purpose is that radiating monochromatic light, such as the low-pressure sodium lamp. By making observations through a telescope with a filter that blocks the relevant monochromatic wavelength, the sky glow produced by light from that light source is no longer disturbing.

15.2.4 Wildlife

Light pollution can have multiple negative, often fatal, effects on animals (Rich and Longcore 2006):

- their habitats may be disturbed, with as possible consequences: a decrease in successful mating, nesting and development of eggs and larvae; a decreased foraging success; and an increased risk of being preyed on by other animals;
- disorientation, often with disastrous consequences. For example, for migrating birds that get captured, off course, in bright areas such as cities, with little chance to survive; for sea turtle young that cannot find the ocean after being hatched on the beach or young salmon born in fresh-water rivers that cannot find their way to the sea and full-grown salmon that cannot re-enter these rivers from the sea at the end of their life to spawn in the upper reaches where they were born. And, finally, for insects and moths that are attracted by light and are killed by the lamps or by their supporting structures in the neighbourhood of the lights;
- disturbance of their bodily cycles, normally controlled by a changing light-dark experience such as the 24 h dark-light rhythm (diurnal or circadian rhythm), the lunar cycle and the seasonal cycle. All organisms have evolved to synchronize many of their activities according to these cycles, such as their sleeping, movement, migration, feeding, mating, breeding and hibernation times

The many nocturnal animals, with their large pupils and lenses, and retinas with few or no cones and a richness of rods, are especially affected. Of course, for some endangered species, protection from the negative effects of light pollution may be crucial.

These effects may be caused by the direct light of the lighting installation but also, indirectly, by the dome of light spread out over cities, caused by sky glow. Both the lighting level and the spectrum play a role in the severity of the negative effects. It seems that the effect of the spectrum is different for the different types of animals. There are a few studies, the outcome of which suggests that the effect of shorter, blue and green wavelengths is stronger than that of longer, yellow and red wavelengths as far as sea turtles and insects are concerned (Eisenbeis and Hassel 2000; Nelson 2002). For example, the German study of Eisenbeis and Hassel showed that just a single road-lighting luminaire containing a high pressure mercury lamp, killed an average of 150 insects per night, while a luminaire with a high-pressure sodium lamp killed an average of 60 insects over the same period. The ratios of insects caught with these different lamps are in line with those found in other studies (Rich and Longcore 2006). Laboratory studies and one field study into the effect of light on migrating birds show a completely different spectral effect: blue and green light have little or no disturbing effect on the migration of birds, while red and white light have a considerable disorientation effect (Wiltschko et al. 1993, 2000; Poot et al. 2008). The probable explanation here is that navigation of migrating birds involves both a visual and an in-built magnetic-compass mechanism, which are effected in different ways by light (Wiltschko and Wiltschko 2003).

Although an impressive number of studies are already available, for quantifying the effect of lighting level and spectrum of light on different animal species for the different threats listed above, many more studies, especially of the field type, are still needed. Figure 15.3 shows a photograph of an extensive ongoing field study on the impact of artificial light of different spectra on flora and fauna.

Fig. 15.3 At several locations in the Netherlands, natural habitat is experimentally illuminated, and the presence of many species is carefully monitored by the University of Wageningen and the Institute of Ecology of the Netherlands. (Photograph: Kamiel Spoelstra)

15.2.5 Vegetation

Plants are photoperiodic: that is to say, the light-dark cycle (diurnal cycle) has an influence on their physiology and guides their development. Four different families of photoreceptors (in the form of pigment proteins) have been identified in plants (Biggs and Huala 1999). Each of them has a different response to the quantity and to the spectrum of light. Some are sensitive to bluish light, others to reddish light. Different plants have different photoreceptors in different combinations, and therefore react differently to light.

Many laboratory investigations have been carried out into the effects of the quantity, spectrum, duration, periodicity and direction of artificial light for plant growth in greenhouses and more recently in daylight-tight containers. Unfortunately, very little research has as yet been done in the field on the long-term consequences of artificial light on plants (Rich and Longcore 2006). Vegetation in cities and other build-up areas has already adapted itself to the presence of artificial nighttime illumination. Species that cannot survive under such lighting are already extinct in this environment. The restriction of light pollution in order to safeguard natural vegetation is, of course, important for natural and national parks. For the purpose of specifying light pollution limits, these types of environments are classified as environmental lighting zone “E0” (see Sect. 17.1).

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Chapter 16
Light-Pollution Parameters

Abstract Designing light installations with a restricted amount of light pollution is not possible without a clear insight into which lighting parameters influence light pollution. These lighting parameters can be divided into those directly related to the light leaving the location being lighted, i.e. installation-bound parameters, and those directly related to the light arriving at the point of disturbance, i.e. disturbed-area-bound parameters. Some standards and recommendations use a mix of both parameter categories for the limitation of light pollution. In this section, the emphasis is on those lighting parameters used in specifying limits for light pollution by the International Lighting Commission CIE, and by the International Dark Sky Association IDA (in combination with the Illuminating Engineering Society of North America IESNA). They will be defined and explained. The limiting values themselves will be dealt with in a following section: "Standards and Recommendations".

The illustrations in this section are based on road-lighting installations, but all concepts described are in fact valid for all types of exterior lighting installations ranging from road lighting to residential-area lighting, decorative architectural lighting, industrial outdoor-area lighting and sports floodlighting.

It was not until the eighties of the last century that the subject of light pollution received general interest from the lighting community. At that moment there were hardly any recommendations and guidelines on the subject. Even the basic question of what are the lighting parameters with which light pollution or the restriction of light pollution can best be described was not yet answered. But, many different answers to this question were quickly being proposed and put into local recommendations and standards. Now harmonization is needed because it will facilitate the comparison of different lighting installations as far as the restriction of light pollution is concerned. This in turn will assist in the realization of lighting installations embodying the true restriction of light pollution. We will therefore concentrate on the light-pollution parameters specified by international organizations, i.e. by the International Lighting Commission, CIE and by the International Dark Sky Association, IDA (in combination with the Illuminating Engineering Society of North America, IESNA) (CIE 2013; IDA-IES 2011).

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16.1 Parameter Categories

The lighting parameters can be divided into those directly related to the light leaving the location being lighted, i.e. installation-bound parameters, and those directly related to the light arriving at the point of disturbance, i.e. disturbed area-bound parameters. CIE uses a mix of both parameter categories for the limitation of light pollution whereas IDA-IESNA uses solely parameters related to the light leaving the location. Using solely installation-bound parameters has the advantage that no information is needed concerning the location of areas where disturbance may arise. On the other hand, people who are disturbed by light pollution may want to check, from their own premises, whether or not a neighbouring lighting installation does indeed exceed the disturbance limits. In the case of disturbed-area-bound parameters, it is possible to design an installation in such a way that minimum disturbance in a possible extra-critical direction is at minimum.

A method for the restriction of all aspects of light pollution with the sole use of installation-bound parameters has been developed by Brons et al. (2008). Their OSP (Outdoor Site-lighting Performance) method uses a calculation box that encloses the lighting installation along its property borders. The limiting parameters used are the illuminances on the six planes of this, virtual, box. The IDA-IESNA recommendations, as will be described in Sect. 16.2.2, are partly based on this method.

16.2 Installation-Bound Parameters

16.2.1 Parameters used by CIE

16.2.1.1 Upward Light Ratio ULR

The parameters used for the limitation of upward light, and thus for the limitation of sky glow, are all directly related to the light leaving the area to be lit. The upward light ratio ULR is the proportion of the luminous flux of a luminaire or of all the luminaires of an installation that is emitted at and above the horizontal, with the luminaire(s) as mounted (tilted) in the installation (Fig. 16.1):

$$ULR = \frac{\varnothing_{lum\ up}}{\varnothing_{lum\ tot}}$$

ULR does not take into account the effect of light reflected upwards from the illuminated surfaces. This is because ULR is a luminaire related criterion instead of an installation related one.

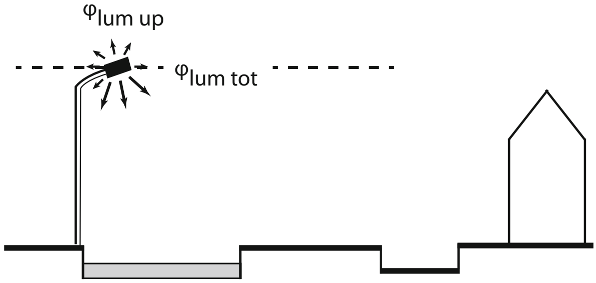

Fig. 16.1 The variables used in the upward light ratio ULR

16.2.1.2 Upper Flux Ratio UFR

In contrast to ULR, the upper flux ratio UFR does also take into account light reflected upwards from the installation. The importance of taking into account reflected light may be evident by considering an installation with luminaires that have in their installed position no direct upward light component viz. ULR = 0. Such a zero-ULR installation will nevertheless result in some degree of sky glow because of light reflected upwards from the horizontal and other surfaces. Soardo et al. (2008) in fact showed that an installation carefully designed to have strictly-limited direct upward light, may nevertheless result in a higher degree of sky glow than an installation with some less restricted direct upward light. This is because the luminaires of such an installation may be less efficient as far as the lighting of the road surface is concerned. Consequently, more light has to be radiated in the downward direction to fulfill the road-lighting specifications, hence more light is reflected upward from the horizontal and other surfaces. Such an installation is also less energy-friendly.

The upper flux ratio UFR, an installation related parameter that does take into account both direct upward light and indirect upward-reflected light, is defined as (see Fig. 16.2): the ratio between the luminous flux at and above the horizontal resulting from the actual lighting installation:

- directly from all the luminaires in their installed position,
- reflected from the surface area intended to be lighted,
- reflected from the surrounding surface area lighted because of spill light

and the flux above the horizontal in the hypothetical ideal situation where the luminaires have:

- no direct light above the horizontal,
- all their light is concentrated into the zone towards the surface area to be lighted,
- that area has exactly the required lighting level.

This definition means that the hypothetical ideal situation has an UFR value of 1. The larger the UFR value of a real installation, the further away it is from the ideal situation, and indeed the higher the sky glow will be. UFR can be calculated from the data of the lighting installation together with the geometric and reflectance data

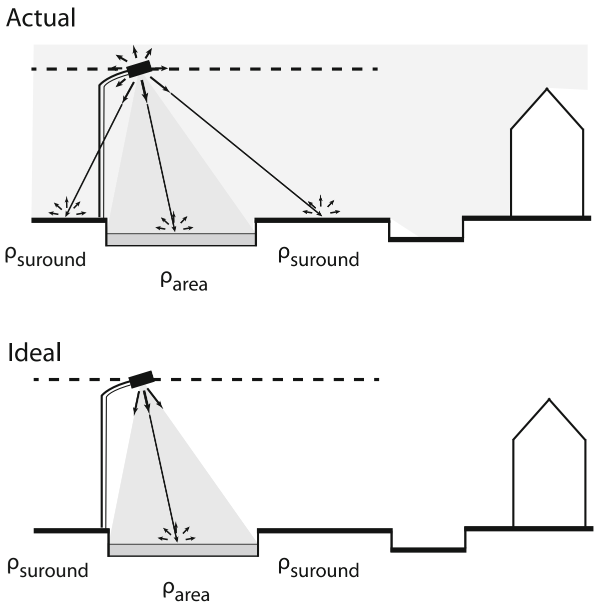

Fig. 16.2 The actual situation and the hypothetical ideal situation that are compared in the definition of upper flux ratio UFR

of the lighted area and its surroundings according to the formula (AFNOR 2011):

$$UFR = \frac{\mathrm{E}_{\mathrm{av,initial}}}{\mathrm{E}_{\mathrm{av,maint}}} \left\{ 1 + \frac{ULOR}{\rho_{area} * \mu} + \frac{\rho_{surrounds}}{\rho_{area}} \left(\frac{DLOR - \mu}{\mu} \right) \right\}$$

where:

$\mathrm{E}_{\mathrm{av,initial}}$ = The initial average illuminance of the area to be lit,
$\mathrm{E}_{\mathrm{av,maint}}$ = The required maintained illuminance of the area to be lit,
ULOR = Proportion of the upward flux to the total flux of the luminaires in their installed position,
DLOR = Proportion of the downward flux to the total flux of the luminaires in their installed position,
ρ_{area} = Reflectance of the area to be lit,
$\rho_{\mathrm{surrounds}}$ = Reflectance of the surrounding surfaces,
μ = Utilization factor of the installation related to the area to be lit.

In the case of road-lighting installations designed on the basis of luminances, the illuminance ratio in the formula has to be replaced by the luminance ratio. That the ratio of initial to required maintained lighting level plays a role in the value of UFR is in fact an impulse to design an installation as close as possible to the required lighting level: needless over-lighting automatically results in a higher and therefore worse value of UFR.

At first glance it may appear strange that the reflectance of the area to be lighted, ρ_{area}, is in the denominator of the formula. The higher the value of this reflectance, the

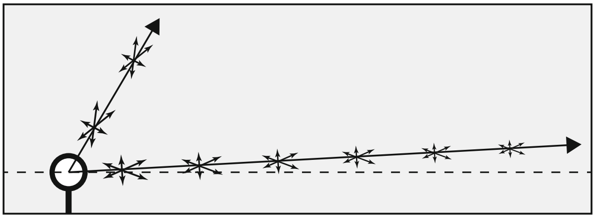

Fig. 16.3 Light radiated near to the horizontal scatters over a great distance

better is the UFR and indeed the lower sky glow will be, provided that the luminaires have direct upward light (i.e. ULOR $\neq 0$). This is because with a high reflectance of the area to be lighted, lamps with a lower luminous flux can be used in all the luminaires, meaning that there will be a lower direct upward light component from these luminaires. Of course, the reflectance of the surroundings of the area to be lighted should be as low as possible in order to restrict reflected light from these surrounds being reflected upwards. The quantity $\rho_{\text{surrounds}}$ is indeed in the numerator of the formula.

In the case of road lighting, the areas directly adjacent to the carriageway should often receive some light as well (Sect. 8.1.3 of Part 1). UFR can then be calculated with sufficient accuracy by taking for the reflectance of the area to be lit, the weighted average reflectance of carriageway and adjacent areas that should receive some light:

$$\rho_{area} = \frac{\rho_{carriageway} * w_{carriageway} + \rho_{adjacent} * w_{adjacent}}{w_{carriageway+adjacent}}$$

16.2.1.3 Luminous Intensities Near the Horizontal

Light radiated near the horizontal in a zone between 90° and some 110° travels forward over a much greater distance than does light radiated at higher angles of elevation (Fig. 16.3). Over this greater distance, scattered light is responsible for sky glow over a greater area. This can especially be a problem for observatories at great distances (up to some 100 km) from the lighting installation (Cinzano and Diaz Castro 2000; Luginbuhl 2013) . To limit this effect in a wide area around observatories, CIE recommends limits for the luminous intensities in the zone between 90° and 110° (Fig. 16.4):

$$I_{90-110}$$

16.2.2 *Parameters Used by IDA-IESNA*

16.2.2.1 Total Initial Luminaire Luminous Flux

Evidently, the less the amount of light is installed, the less light can leave the area to be lighted. For some situations, IDA-IESNA therefore specifies limits for the total

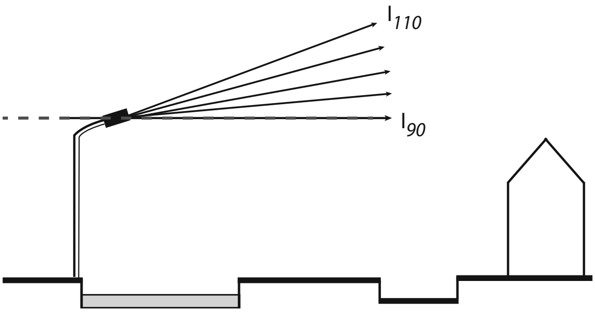

Fig. 16.4 Luminous intensities critical for sky glow at great distances

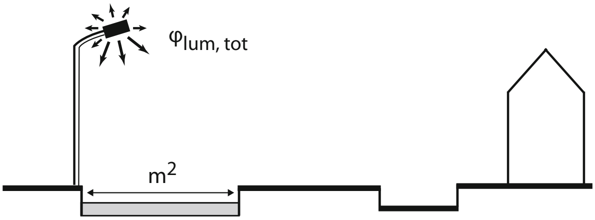

Fig. 16.5 Total permitted luminaire luminous flux as a measure to limit light pollution

initial luminous flux of all luminaires installed in an area or installed per area of surface (Fig. 16.5):

$$\varnothing_{lum\ tot} \text{ or } \frac{\varnothing_{lum\ tot}}{m^2}$$

16.2.2.2 Virtual Flux Ratio

A straightforward measure for the quantity of lumens leaving the area, as used for some situations by IDA-IESNA, is based on a virtual enclosure around the perimeter of the area to be lighted, with the top of the enclosure at least 10 m above the highest installed luminaire. The limit is then expressed as a maximum percentage of lumens on the inside surfaces of the enclosure compared with the total initial lumens provided by the installation. The lighting parameter, virtual flux ratio, is thus the ratio of the luminous flux on the inside surfaces to the total flux (Fig. 16.6):

$$\frac{\varnothing_{surf\ virt}}{\varnothing_{lum\ tot}}$$

16.2.2.3 Virtual Vertical Illuminance

The lighting parameter "virtual flux ratio", which is the flux on the inside surfaces divided by the total flux, defined above, is combined by IDA-IES with the parameter

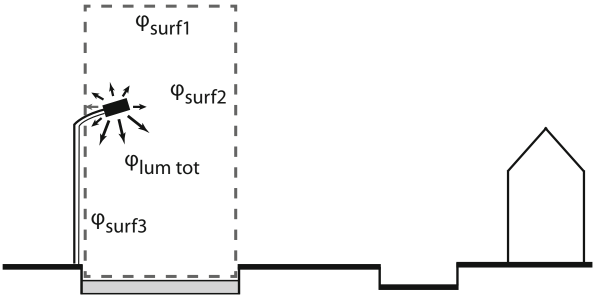

Fig. 16.6 Luminous flux $\Phi_{surf1} + \Phi_{surf2} + \Phi_{surf3}$ leaving the virtual surfaces surrounding the area to be lighted

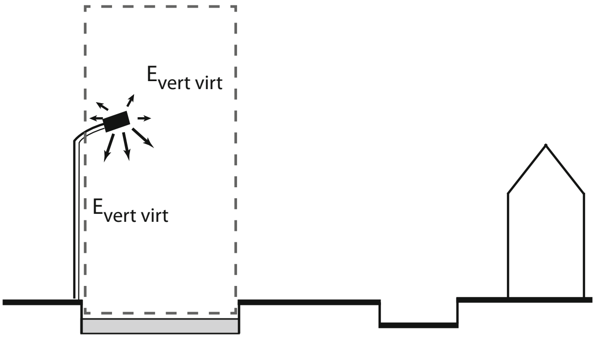

Fig. 16.7 Vertical illuminance on inside vertical surfaces of the virtual enclosure of the area to be lighted

"virtual vertical illuminance" at any point on the vertical inside surfaces of the same virtual enclosure (Fig. 16.7):

$$E_{vert\ virt}$$

Normally this parameter is used in combination with the parameter described in the previous Section: total luminous flux leaving the virtual surfaces surrounding the area to be lighted (and that is including the top surface).

16.2.2.4 BUG Luminaire Classification

IDA-IESNA uses the IES luminaire classification system, LCS, as described in Sect. 11.1.2, to classify the light-pollution characteristics of a luminaire (IES 2007). This so-called BUG luminaire classification system divides the light distribution of a luminaire[1] into three zones or solid angles (Fig. 16.8):

- the backward quarter sphere, denoted by the letter B, responsible for possible light trespass (light beyond the area to be lit),
- the upper hemisphere, denoted by the letter U, responsible for possible sky glow,

[1] The light distribution of a luminaire here is given for the standard mounting position of the luminaire. Adverse effects of tilting luminaires in an installation are therefore not taken into account in the BUG system.

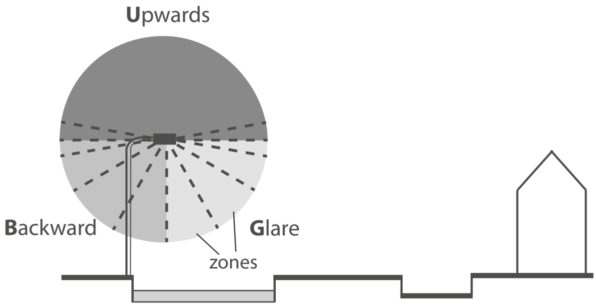

Fig. 16.8 The solid angles of the light distribution that are the basis for the BUG luminaire classification system

- the forward quarter sphere, responsible for the lighting of the area to be lit, but also for possible glare to road users outside the area, which is the reason that this zone is denoted by the letter G.

The BUG system is named after the above-mentioned abbreviation letters. Each zone is divided into solid-angle sub-zones. Depending on the total luminous flux radiated in each of the solid angles of a zone, the luminaire is classified as either B or U or G in a class ranging from 0 (good limitation) to 5 (bad limitation). Examples have been shown in Table 11.3 of Chap. 11. The higher the luminous flux in the higher elevation solid angles, the higher the class rating. For example, a luminaire with a BUG classification of 505 has very bad limitation as far as backward (light trespass) and glare is concerned, but emits hardly any upward light. A BUG classification of 245 denotes reasonable backward limitation of light, bad upward limitation, and very bad glare control. It is important to note that the luminous flux values that determine the BUG classes are in absolute values. This means that a lower lumen-package lamp in a luminaire gives a lower BUG rating.

16.3 Disturbed-Area-Bound Parameters

16.3.1 Parameters Used by CIE

16.3.1.1 Vertical Illuminance on Facades

Light that intrudes into the private living environment of people can be characterised by the vertical illuminance on the facades of properties outside the area being lighted. The limiting parameter, directly related to light arriving at the area of disturbance, is therefore (Fig. 16.9):

$$E_{vert\ property}$$

The relevant surfaces of the facades, such as windows or other openings, should be taken as the basis. The advantage of using this parameter for limiting intrusive light is that compliance can be checked at the property where possible disturbance occurs, or would occur if new property were to be constructed.

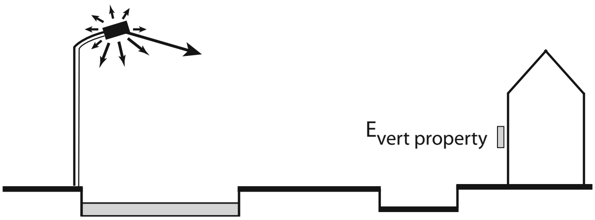

Fig. 16.9 Vertical illuminance on facades of neighbouring property

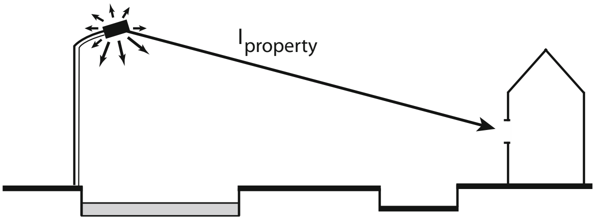

Fig. 16.10 Luminous intensity in the direction of neighbouring property

16.3.1.2 Luminous Intensity

Residents may be further disturbed by bright lights shining directly into their eyes at their property. This disturbance can be minimised by limiting the luminous intensity of luminaires in directions where views of bright parts of the luminaires are likely to be troublesome for residents in or around their property. Consequently, the limiting parameter here—again directly related to light arriving at the area of disturbance—is (Fig. 16.10):

$$I_{property}$$

Only viewing directions that are likely to be maintained for a longer time should be taken into account. Momentary and short-time viewing directions should be disregarded. With this parameter, compliance can also be checked at the property where possible disturbance occurs.

16.3.1.3 Facade Luminance

Over-lit bright facades of buildings can be disturbing to both residents and traffic. It is evident that the limiting lighting parameter here is the luminance of the façade itself (Fig. 16.11):

$$L_{facade}$$

Dynamically-changing light levels and colours, as employed in more and more decorative outdoor lighting installations using LEDs, may increase the disturbance to motorists, cyclists, pedestrians and residents. Flashing lights, as sometimes used in advertising signs, further increase the disturbance. Research is being conducted

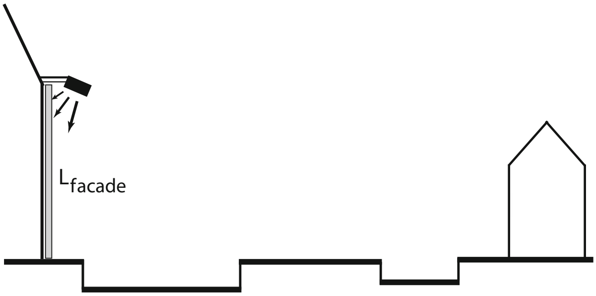

Fig. 16.11 Facade luminance as a measure to avoid over-lighting

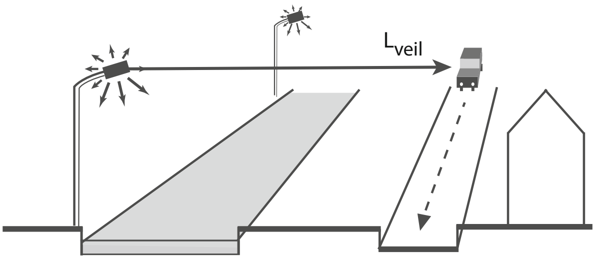

Fig. 16.12 Veiling luminance experienced by a motorist

into the best limiting parameters to be employed for this purpose (Hsieh et al. 2013; Hsu et al. 2013). It is evident that the luminance of the bright scene, the amplitude and frequency of the changes, and the position and size of the bright scene, play a role. Much more research is needed to enable designers to design sound decorative outdoor lighting installations making use of changing light levels and colours and to avoid problems with advertising LED signs.

16.3.1.4 Veiling Luminance

The disturbing effect of light pollution to road users is mainly that of increased glare on roads in the neighbourhood of the installation responsible for the pollution. The severity of this increase in glare can be expressed with the lighting parameter that is also used in road lighting for motorised traffic, viz. the veiling luminance:

$$L_{veil}$$

As explained in Sect. 3.1.3.1 of Part 1, light arriving at the eye from a glare source, or from the light-polluting area, scatters in the eye and produces a bright veil over the bright image of the scene viewed. This in turn deteriorates the vision of that scene. The veiling luminance characterizes the luminance of this disturbing veil. The relevant observer positions for the determination of the veiling luminance are on the path of travel on the adjacent roads where disturbance may occur, with viewing directions along that path towards the road ahead (Fig. 16.12).

Table 16.1 Light-limiting parameters as defined by CIE. (CIE 2013)

	ULR	UFR	I_{90-110}	$E_{vert,property}$	$I_{property}$	L_{facade}	L_{veil}
At area to be lighted	√	√	√	x	x	x	x
At location of disturbance	x	x	x	√	√	√	√
Luminaire(s) position as installed	√	√	√	√	√	√	√
Direct light only	√	x	√	√	√	√	√
Direct + reflected light	x	√	x	x	x	x	x
Critical zone around horizontal	x	x	√	x	x	x	x
Impulse for design to required lighting level	x	√	x	x	x	x	x

Table 16.2 Light-limiting parameters as defined by IDA and IESNA. (IDA-IES 2011)

	$\Phi_{lum,tot}$	$\Phi_{lum,tot}/m^2$	$\Phi_{surf,virt}/\Phi_{lum,tot}$	$E_{vert,virt}$	BUG
At area to be lighted	√	√	√	√	√
At location of disturbance	x	x	x	x	x
Luminaire(s) position as installed	x	x	√	√	x
Direct light	√	√	√	√	√
Direct + reflected light	x	x	x	x	x
Critical zone around horizontal	x	x	x	x	√
Impulse for design to required lighting level	√	√	x	x	x

16.4 Summary

16.4.1 CIE Parameters

Table 16.1 summarises the light-limiting parameters as defined by CIE, with some of their typical properties.

16.4.2 IDA-IESNA Parameters

Table 16.2 summarises the light-limiting parameters as defined by IDA-IESNA, with some of their typical properties.

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Chapter 17
Standards and Recommendations

Abstract In this chapter, the recommendations for the restriction of obtrusive light of the international lighting commission, CIE, will first be summarized. These recommendations form the basis for many national or regional standards for outdoor lighting in many parts of the world. The European Standards for the lighting of exterior working areas and for sports lighting have sections about the limitation of light pollution based entirely on the CIE recommendations. In North America, recommendations for the limitation of light pollution are jointly published by the International Dark-sky Association (IDA) and the Illuminating Engineering Society of North America (IESNA). These recommendations are summarized in the second part of this section.

The effect light pollution has, depends not only on the lighting values of the critical lighting parameters of the installation, but also on the location of the installation, the brightness of the surrounding area of that location and on the time in the evening or night. This chapter therefore starts with the definition of environmental zones, characterizing the location area, and the explanation of the principle of curfew in the context of the restriction of light pollution.

All values specified in the Standards and Recommendations dealt with here for the light-limiting parameters, concern the initial values given by the new installation, as these represent the worst-case situation as far as light pollution is concerned.

The focus in this chapter is on the methods that the various standards and recommendations use for specifying light pollution restriction. For copyright reasons, Tables of these Standards and Recommendations are reproduced only in part.

17.1 Environmental Zones and Curfew

The severity of the effect of light pollution depends on the location and brightness character of the area or district concerned and on the actual time in the evening or night. In the centre of a big, bright city the severity will be less than in a darker, residential environment; and it will be much less than in a natural environment that is inherently dark. Early in the evening the severity is less than later in the evening and much less than in the middle of the night. Concepts of lighting zones and curfew are often used to distinguish areas and times for the purpose of limiting light pollution.

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Table 17.1 Environmental lighting zones. (CIE 2013)

Zone	Lighting environment	Examples
E0	Intrinsically dark	Unesco starlight reserves, IDA dark-sky parks
E1	Dark	Relatively-uninhabited rural areas
E2	Low district brightness	Sparsely-inhabited rural areas
E3	Medium district brightness	Well-inhabited rural and urban areas
E4	High district brightness	Town and city centres, commercial areas

The CIE has developed a system for dividing areas into different environmental zones according to the typical brightness of their environment. This system is used in many international, national and local regulations, sometimes in a modified form to suit local circumstances. In the latest CIE recommendation, five different environmental zones (E0 – E4) are defined (CIE 2013). Table 17.1 gives the CIE definition of these five zones together with examples of areas for each zone. The Lighting-Zone system defined jointly by the International Dark Sky Association (IDA) and the Illuminating Engineering Society of North America (IESNA) also uses five different zones, which are labelled LZ0 – LZ4. They are similar to the environmental zones of the CIE.

Most regulations for the limitation of light pollution make use of the principle of curfew to take into account the effect of severity in relation to time in the evening or night. Before curfew, the regulations are more relaxed than after curfew, when they are more stringent. This enables, for example, sports lighting installations to be used before curfew but no longer after curfew. The same curfew principle is also often used in regulations governing decorative outdoor lighting installations. The before-and-after curfew lighting specifications are given in the light-pollution standards, but the exact timing of the curfew is usually not specified here. The timing of curfew is very much seen as a local responsibility and is usually given in municipality or other local governmental regulations. Of course, after-curfew regulations should not be specified for lighting that serves to promote safety or security – as, for example, road lighting.

17.2 CIE Guide

In 2003 CIE published the "Guide on the limitation of the effects of obtrusive light from outdoor lighting installations". In 2015 a completely updated version of this Guide will be published. The information given here is based on the 2013 draft (CIE 2013). The guide specifies maximum values for the light-pollution parameters, described in the previous chapter, for each of the five environmental zones (E0 – E4) defined in Table 17.1. For some parameters the values specified are different for pre-curfew and after-curfew hours. As an example, the values for environmental zones E0, E2 and E4 are given in Table 17.2.

Table 17.2 Maximum values of light-limiting parameters for the environmental lighting zones E0, E2 and E4. (CIE 2013)

Zone	Curfew	$E_{vert,property}$ (lx)	L_{facade} (cd/m^2)	ULR	UFR_{road}	$UFR_{amenity}$	UFR_{sports}	I_{90-110} (cd/klm)
E0	Pre Post	n. a. n. a.	0	0	n. a.	n. a.	n. a.	0.5
E2	Pre Post	5 1	5	2.5	5	6	2	
E4	Pre Post	25 5	25	15	12	35	15	

I_{90-110} requirement: near observatories
n.a. not applicable

Table 17.3 Maximum values of luminous intensity $I_{property}$ in critical directions towards neighbouring properties according to size of the luminaire (A in m^2) and the distance between luminaire and property (*d* in m), for the environmental zones E0, E2 and E4. (CIE 2013)

		$I_{property}$ (cd)				
Zone	Curfew	A = 0 – 0.002	A = 0.002 – 0.01	A = 0.01 – 0.03	A = 0.03 – 0.13	A = 0.13 – 0.50
E0	Pre Post	0 0	0 0	0 0	0 0	0 0
E2	Pre Post	*d* 0.3*d*	3*d* 0.6*d*	6*d* 1*d*	13*d* 3*d*	26*d* 5*d*
E4	Pre Post	1*d*	16*d* 3*d*	31*d* 6*d*	63*d* 13*d*	128*d* 26*d*

The limiting values of the luminous intensities in critical directions (e.g. towards neighbouring properties) are dependent on the size of the bright parts of the luminaires and upon the viewing distance (viz. the distance *d* between the luminaire and the property). The smaller the bright part of the luminaire (more compact luminaire) and the shorter the viewing distance, the higher will be the disturbance and thus the more stringent the limiting values required. As an example, the limiting values for $I_{property}$ are given, again for environmental zones E0, E2 and E4, in Table 17.3.

The limits for veiling luminance are required everywhere on both lighted and unlighted roads where motorised and slow-moving road users may be confronted with reduced visibility due to glare caused by light pollution from neighbouring lighting installations. If the road itself has a lighting installation, the disturbance caused by light pollution is smaller. The higher the lighting level of that road-lighting installation, the smaller the disturbance will be because of the accompanying higher adaptation state of the road users. The limits for veiling luminance are therefore given according to the road-lighting class M1 – M6, where M1 has higher lighting levels than the lower classes (see Part 1 Sect 9.1). These limiting values are given for road-lighting classes M1, M2, M5, M6 and for the situation with no road lighting,

Table 17.4 Maximum values of veiling luminance for some road lighting classes. (CIE 2013)

Road lighting class	L_{veil} (cd/m^2)
M1/M2	0.85
M5/M6	0.25
No road lighting	0.04

in Table 17.4. The values are based on an extra TI value of 15 % because of light pollution.

17.3 European Standards

The European standard for sports lighting (CEN 2007b) and the standard for the lighting of outdoor work areas (CEN 2007a) have sections specifically devoted to the limitation of obtrusive light that are fully based on the 2003 CIE Guide. These sections will probably be updated once the updated 2015 CIE Guide is available.

The European standard for road lighting has a section on obtrusive light that gives a qualitative description and refers for additional quantitative information to the 2003 CIE Guide.

17.4 North-American Recommendations

North America has no overall Standard or Guide specifically devoted to the limitation of light pollution caused by all the different types of outdoor lighting. IESNA published two technical memoranda on the subject of light pollution: Technical Memorandum "light trespass: research, results and recommendations" (IESNA 2011a) and, more specifically for roadway lighting, Technical Memorandum "addressing obtrusive light (urban sky glow and light trespass) in conjunction with roadway lighting" (IESNA 2011b). It summarises the methods advocated by the CIE and describes a simple non-technical method for measuring light trespass. As written in these memoranda: they only begin to address the issues and are limited in their scope. The 2014 American National Standard Practice for Road Lighting, ANSI/IES RP-8-14 does give a quantitative description of sky glow and light trespass but no quantitative recommendations (ANSI/IES 2014). IESNA recommends that the "Model Lighting Ordinance" (MLO) prepared jointly by the International Dark-Sky Association (IDA) and the Illuminating Engineering Society of North America (IESNA) (IDA-IES 2011) be used for non-highway public road lighting, viz. major, collector and local roads where pedestrians and cyclists are generally present. The ordinance is developed especially for local governing bodies to formulate regulations for the limitation of light trespass and sky glow from different types of (mostly non-public) lighting installations. For outdoor sports areas and the decorative or architectural

Table 17.5 Limiting requirements for the uplight from ornamental street lights according to lighting zone. (IDA-IES 2011)

Lighting zone	U rating
LZ0	U0
LZ1	U1
LZ2	U2
LZ3	U3
LZ4	U4

lighting of monuments, buildings and structures, the same ordinance gives more comprehensive regulations. The regulations of the ordinance are given for different lighting zones LZ0 – LZ4, which are very similar to the CIE environmental zones E0 – E4. The lighting parameters that the ordinance uses have already been described in Sect 16.2.2 and were summarised in Table 16.2.

17.4.1 IDA-IESNA Ordinance for Road Lighting

Since the MLO ordinance is a free publication without copyright, the full Table values are reproduced in this book where relevant. The ordinance states that all street lighting, with the exception of ornamental street lighting, shall have no light emitted above 90° (the horizontal). Ornamental street lights must meet the U-rating of the BUG luminaire classification system as specified in Table 17.5. Table 17.6 gives an indication of what these U ratings mean in terms of luminous flux radiated above the horizontal.

17.4.2 IDA-IESNA Ordinance for Sports, Area and Architectural Lighting

The ordinance requires a curfew time to be set for these types of lighting installations, after which the lighting has to comply with a maximum luminous flux limit and either a limit of the BUG rating or a limit of the lighting on the surfaces of a virtual enclosure around the area to be lighted.

Table 17.6 Maximum luminaire lumens for the different U-ratings of the BUG system (Here only the maximum-permitted lumen above the horizontal are shown. For the U ratings, the BUG rating system also specifies the maximum lumens for the area just below the horizontal). (IDA-IES 2011)

	Φ_{lum} (lumen)					
Solid angle	U0	U1	U2	U3	U4	U5
UH (above 100°)	0	10	100	500	1000	> 1000
UL (90 – 100°)	0	10	100	500	1000	> 1000

Table 17.7 Maximum lumen per square metre for sports, area and architectural lighting installations depending on the lighting zone. Values converted from lumen/ft^2 to lumen/m^2. (IDA-IES 2011)

Lighting zone	Φ_{lumtot}/m^2 (lumen/m^2)
LZ0	5.4
LZ1	13
LZ2	27
LZ3	54
LZ4	81

17.4.2.1 Limit of Luminous Flux

The maximum luminous flux of the total installation per area of the installation, $\Phi_{lum,tot}/m^2$ is dependent on the actual lighting zone as given in Table 17.7.

The ordinance allows for some specific genres of area and architectural installations, such as facade and outdoor sales-lot lighting, to have some additional luminous flux in addition to the values given in Table 17.7.

17.4.2.2 Limit of BUG Ratings

To limit back-light, up-light and glare, the BUG rating of the luminaires is used as the limiting parameter. The lower the BUG number, the better the limitation. The degree of limitation of back-light (B) and glare (G) is dependent on the distance of the property from the lighting installation: the smaller this distance, the higher the degree of limitation needed. Table 17.8 gives the limiting ratings. As can be seen from the table, the upward component (U) must always be zero.

17.4.2.3 Limit of Lighting on Surfaces of Virtual Enclosure

As an alternative to employing the BUG method, the ordinance gives the method of limiting the light falling on the surfaces of a virtual enclosure surrounding the area to be lighted. The associated limiting parameters (virtual flux ratio and virtual vertical

Table 17.8 Maximum allowable BUG ratings of luminaires according to lighting zone and distance from property. Distance (dist) is given in terms of mounting height, *h*. (IDA-IES 2011)

	BUG			
Lighting zone	dist > 2 h	dist < 2 h	dist < 1 h	dist < 0.5 h
LZ0	100	100	000	000
LZ1	301	200	100	000
LZ2	402	301	200	000
LZ3	503	401	301	100
LZ4	504	402	301	201

Table 17.9 Maximum allowable value of $E_{vert,virt}$ according to lighting zone. (IDA-IES 2011)

Lighting zone	$E_{vert,virt}$ (lx)
LZ0	0.5
LZ1	1
LZ2	3
LZ3	8
LZ4	15

illuminance, $\Phi_{surfvirt}$ and $E_{vertvirt}$) have been described in Sect 16.2.2 (see Figs. 16.6 and 16.7). The total luminous flux leaving the vertical surfaces and the top surface ($\Phi_{surfvirt}$) should be less than 15 % of the total luminous flux of all luminaires, Φ_{lumtot}. The maximum vertical illuminance at any point of the virtual vertical surfaces is given in Table 17.9.

17.5 Spectrum of Light

Light with shorter wavelengths (blue-greenish light) scatters more on the aerosol particles of the sky and therefore increases sky glow relative to that produced by yellowish-red light with its longer wavelengths. The spectral effect is different for different animal and plant species. For example, blue-rich light has a relatively great effect on sea turtles and insects, while blue and green light has little or no disturbing effect on the migration course of birds. Many more studies are needed in order to obtain a better insight in the influence of the spectrum on the different effects of light pollution. It is probably for this reason that the CIE Guide on light pollution and the IDA-IES MLO ordinance, dealt with in this chapter, do not give specifications for the spectrum of light.

It is more than likely that different spectra will have to be recommended for different locations with a different predominant disturbing effect. It also seems that metrics such as correlated colour temperature and S/P ratio are not really suitable enough for characterizing the effect of the spectrum on light pollution. In order to give some guidance, the International Dark-sky Association IDA, in a separate publication, suggests that the wavelengths of light sources employed in a wide area around professional observatories, should be limited to greater than 500 nm in order to restrict sky glow (IDA 2010).

References

ANSI/IES (2014) RP-8-14 Recommended practice for roadway lighting

CEN (2007a) Standard EN 12464-2 Lighting for work – -Part 2: Outdoor work places

CEN (2007b) Standard EN 12193 Light and lighting – -Sports lighting

CIE (2013) Draft Publication 150, Guide on the limitation of obtrusive light from outdoor lighting installations

IDA (2010) Visibility, environmental, and astronomical issues associated with blue-rich white outdoor lighting

IDA-IES (2011) Model lighting ordinance (MLO)

IESNA (2011a) Technical Memorandum on light trespass: research, results and recommendations. Reaffirmed 2011

IESNA (2011b) Technical Memorandum addressing obtrusive light (urban sky glow and light trespass) in conjunction with roadway lighting. Reaffirmed 2011

Chapter 18
Equipment and Design Aspects

Abstract The starting point when designing lighting installations that have a minimum of disturbing light pollution, is to ensure that only the minimum amount of light is provided that is needed to fulfill the function of the lighting installation. Dynamic control of the lighting installation enables the lighting to be adapted to different functional requirements according to the circumstances prevailing, such as variations in traffic density, weather and occupancy. This dynamic control should also include the ability to adapt the lighting to satisfy any curfew requirements. A further step, of course is, to design the lighting installation so as to produce the minimum of spill light. Here the physical shape of the lamp, and in certain situations also its spectral properties play an important role. The optical design of the luminaire determines its light distribution, and so is essential in obtaining the minimum amount of spill light. The choice of the reflectances of the surfaces of the area to be lighted and its surrounding areas may also have an influence on the actual amount of light pollution. All these aspects will be dealt with in this Chapter., together with guidance on determining the mounting height of luminaires and their aiming. The effect of employing LED lights embedded in the road surface for special conditions, is also described. Finally, the influence of any structures or trees surrounding lighting installations will be dealt with.

18.1 Equipment

18.1.1 Lamps

The smaller the area of the light-emitting surface of a lamp, the greater is the possibility to control the light distribution of the luminaire in which that lamp is housed, and thus the better the ability to control light pollution. Clear, or uncoated, lamps are therefore better than coated ones (for example: clear high-pressure sodium lamps instead of ovoid versions with the interior wall of the outer bulb coated with diffusing powder). LEDs, of course, have very small light-emitting surfaces, and this facilitates the creation of appropriate optical systems.

With those lamps having an outer bulb, a very small part of the light emitted is reflected from the inner surface of this bulb, and this part of the light is difficult to control. In the case of very-high-output metal halide lamps with a luminous flux

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of, say, 100–200,000 lm (1000–2000 W), the total amount of uncontrollable light emitted due to this phenomenon can become too great. To avoid this problem, special metal halide lamps have been developed. These lamps have a small gas discharge tube and no outer bulb. They are especially suitable for the lighting of outdoor sports fields and arenas.

The low-pressure sodium lamp has a large light-emitting surface, but thanks to its monochromatic light the lamp is preferred by professional astronomers for use in the neighbourhood of observatories. This is because the monochromatic light can easily be completely filtered out by employing a filter on the front of their telescopes. Near-monochromatic LED light sources with a similar spectrum offer the same advantage. Since light with relatively short wavelengths (bluish light) scatters more than does light with long wavelengths (see Sect. 17.5), lamps, with wavelengths restricted to more than 500 nm, are particularly favoured in areas of up to 100 km around observatories.

In Sect. 17.5 it was said that different animals and plants species react differently to different spectra. In nature areas it is therefore recommended to study which animals and or plants are most threatened and to apply a suitable spectrum accordingly. As has also been discussed in Sect. 17.5, much more research into the influence of the spectrum on wild life and vegetation is still needed.

18.1.2 Luminaires

Luminaires with sharp-cut-off light distributions offer the best possibilities for the realisation of installations free of light pollution. With reflectors it is easier to create such light distributions than with refractors. Sometimes mirror screens inside the luminaire are employed to create really-sharp cut offs. For applications where the individual aiming of luminaires is not required, those designed for horizontal mounting with a flat cover offer great advantages over luminaires that need to be tilted. The upward light ratio (ULR) value of such luminaires gives a good indication of the restriction of the light above the horizontal. Floodlight luminaires designed so that their normal mounting position is horizontal or near horizontal and which are yet able to emit a sharply-controlled, fan-shaped, beam at medium elevation angles (Fig. 18.1) can be suitable for the lighting of larger areas. Here too, their ULR values are a good indication of the ability to restrict light above the horizontal plane. Sometimes, the only way to control disturbing light to a sufficient degree is to fit the luminaires with external louvres or screens fitted to the luminaire (Fig. 18.2).

18.1.3 Road Surfaces

In sect. 16.2.1.2 it has been shown that a high-reflectance surface of the area to be lighted may help to restrict sky glow. This is because with a high reflectance, lamps

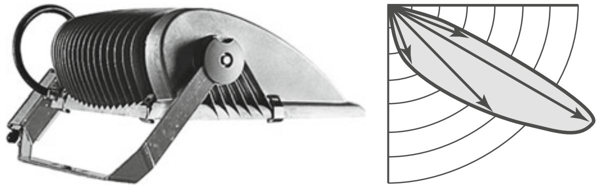

Fig. 18.1 Floodlight for near-horizontal mounting producing an asymmetrical, fan-shaped beam

Fig. 18.2 Examples of external screens or louvres for floodlights. The floodlight on the right has an internal mirror screen as well

with a lower luminous flux can be used in all the luminaires, and consequently these will exhibit a lower direct upward light component. This advantage is valid in the case of all luminaires that emit some direct upward light. Needless to say, the reflectance of the surroundings of the area to be lighted should be as low as possible so as to limit the amount of light reflected from these surrounds in the upward direction. The upward flux ratio (UFR) defined in the same Sect. 16.2.1.2, is the metric that allows us to analyse the situation with respect to different reflectances of the surfaces of the area.to be lighted and of the surrounding areas.

18.1.4 Lighting Control Systems

Lighting control systems should be employed to ensure that:

- the lighting is on only when needed,
- the lighting is always switched or dimmed to satisfy the lowest requirements prevailing in those situations where the required lighting changes take place according to time, traffic density, weather, or other circumstances.

Basically, a lighting control system consists of one or more of the following devices:

- input devices: such as switches, timers, photocells, traffic-flow and presence detectors and weather monitors,
- controlled luminaires: that can be switched or dimmed. In a programmable control system they should be (hardware or software) addressable,

- the control system itself,
- the control network: the link between the input devices and the luminaires being controlled, with (in the case of controlled systems) programmable controllers.

Section. 13.6 of Part 1 gives some more information about the control of road-lighting installations.

18.2 Design aspects

18.2.1 Design to Satisfy Functional Requirements

A first and very important step in minimizing light pollution is ensuring that the design accurately fulfils the functional requirements, without over-lighting the area to be lit. Automated control systems that continuously dim the lighting level to exactly the required level can be a great help in this respect. Taking lumen depreciation and dirt accumulation into account, the initial lighting level is in this way equal to the required level (see Part 1, Figs. 13 and 14). Lighting control systems as described in the previous Section should be employed to ensure that under changing conditions (e.g. traffic density, weather, degree of occupancy) no more than the minimum lighting level required under the prevailing conditions is provided. Of course, curfew restrictions should be strictly observed.

Some temporarily conditions of nature should perhaps receive priority over the normal functional requirements of lighting installations. An example can be the temporary switching off of decorative outdoor lighting during the migrating season of certain animal species.

18.2.2 Mounting Height and Aiming

As far as the mounting height of the luminaires is concerned, there are two conflicting arguments:

- The lower the mounting height, the greater the chance that the bright luminaires themselves will be hidden from sight by bushes, hedges, fences and buildings. However, the beams will then have to be aimed relatively close to the horizon in order to light the whole of the area, and this could in fact increase light pollution.
- The higher the mounting height, the more the luminaires can be angled downwards towards the area to be lighted. Provided luminaires with sharp, narrow beams are used, this will minimize upward and spill light (Fig. 18.3).

For decorative façade lighting, the solution in which the luminaires are aimed downwards from the top of the building or structure is, of course, preferable. However, extra care will then have to be taken to avoid glare to motorized traffic and pedestrians in the vicinity of the lighted facade.

Fig. 18.3 Limiting light pollution by the use of luminaires with sharp, narrow beams aimed downwards towards the field from medium-height poles

The light pollution parameters defined in Chap. 16 allow for the comparison of different designs as far as the different sorts of disturbance are concerned. This permits the optimum solution to be determined.

18.2.3 Embedded Light

Some areas in which there are endangered animal species may benefit from LED lights embedded in the road surface instead of conventional lighting from poles. Such embedded lights can only provide visual guidance; they cannot provide visibility of objects and obstacles to the road users. Tests in Florida on coastal roads adjacent to beaches where sea turtles nest have shown that such embedded lights are indeed much less disturbing to the turtles than is conventional lighting (Bertolotti and Salmon 2005). The embedded lights should have their main direction of light output in near-horizontal directions in order to limit the amount of upward light that could create disturbing sky glow. In the Netherlands, tests, including reactions of road users have been carried out with embedded lights controlled in response to the presence or absence of traffic (called active road marking), as an alternative to fixed road lighting at some specific areas, including nature areas with endangered animal species (NSVV 2014).

18.2.4 Spectrum of Light

The last part of Sect. 18.1.1 "Lamps" of this Chapter. provided information on the use of specific lamp spectra in relation to the restriction of specific disturbing effects of light pollution.

18.2.5 Screening by Structures and Trees

Structures such as facades of buildings may increase the negative effects of light pollution if they are of high-reflectance materials. Their surfaces may become disturbingly bright, for both humans and animals, because of spill light from neighbouring lighting installations. On the other hand, if their reflectance is low, they will absorb spill light and therefore reduce light pollution. In sports-stadium lighting the roofs of the stands may effectively screen any spill light from floodlights mounted under them. Such under-roof lighting is, from a light pollution restriction point of view, therefore preferred over mast lighting. In order to ensure sufficiently uniform and glare-free lighting on the playing field, the roofs must be sufficiently high.

Trees surrounding roads and other outdoor-lighting installations may serve as effective light screens, especially since the light radiated in the extra-disturbing near-horizontal directions is screened. Obviously, the location of the luminaires relative to the trees should be such that the trees do not screen the light directed towards the area to be lighted.

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Part III
Tunnel Lighting

Chapter 19
Purpose and Benefits of Tunnel Lighting

Abstract Although the accident risk per vehicle km in tunnels is smaller than on open roads, the human and economic consequences are more severe. Just as with open roads, tunnels require good lighting in order to keep the visual performance good enough. Compared with the night-time requirements of tunnel lighting, the visual performance requirements that must be satisfied during the hours of daylight are considerably more demanding. The lighting in a tunnel must be such that the adaptation problem caused by the difference in high daytime brightnesses outside the tunnel and the low luminances inside the tunnel, is minimized. Even with visual performance aspects satisfied, the tunnel entrance may still appear somewhat as a black hole which may have a negative effect on the sense of confidence of the motorist approaching and driving through the tunnel leading to a hesitant driving behavior. As will be described in more detail in this chapter, the basic purpose of tunnel lighting for motorised traffic is to enhance the motorist's visual performance and to maintain his sense of confidence.

Where cyclists and pedestrians in short tunnels and underpasses are concerned, the lighting should also help to promote personal security and discourage violence and vandalism.

Studies in different countries into the accident risk in tunnels show that the risk, per vehicle km, in tunnels is slightly lower than that on open roads (Amundsen and Ranes 2000; Brilon and Lemke 2000; Salvisberg et al. 2004; Nussbaumer 2007). Tunnel accident rates are highest in the entrance zones of tunnels (Amundsen and Engelbrektsen 2009; SWOV 2011). The majority of all these studies show that the consequences of accidents in tunnels are more severe than on those on open roads, both in terms of human and economic consequences. Catastrophic tunnel accidents strengthen the relevance of this conclusion (Leitner 2001; Voeltzel and Dix 2004).

Just as with the lighting of open roads, tunnels require good lighting in order to keep the visual performance of the motorists at a sufficiently high level. Here too, visual performance means the ability of a motorist to continuously select and process that part of the visual information presented to him that is necessary for the safe control of his vehicle. Compared with the night-time requirements of tunnel lighting, the visual performance requirements that must be satisfied during the hours of daylight are considerably more demanding. Visual performance by day is affected by the fact that when the human eye is adapted to high daytime brightnesses it is quite unable to function properly when suddenly confronted with relatively-low

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luminances in a tunnel entrance. The lighting in a tunnel must therefore be such that this adaptation problem is minimized, so that good visual performance is ensured during the whole distance from the brightness outside the tunnel entrance, through the darker tunnel interior, and on to the brightness outside the tunnel exit.

But even with good visual performance ensured, driving through a tunnel is considered by many motorists to be more demanding than driving along an open road. Some drivers feel insecure and uncertain and a few are downright anxious. Even with visual performance aspects satisfied, the tunnel entrance may still appear somewhat as a black hole; and there is less room to manoeuvre in the tunnel itself. This lack of confidence of the motorist approaching and driving through the tunnel may lead to a hesitant driving behaviour, including reducing speed and change of lateral position away from the tunnel walls (Martens and Kaptein 1998). Needless to say, such driving behaviour has a negative influence on traffic safety. Good tunnel lighting can help the motorist to maintain a high sense of confidence when approaching the tunnel entrance and driving into the tunnel.

In very long tunnels (to date, the longest road tunnel in the world is more than 24 km) the monotony that builds up during the drive through the tunnel may result in sleepiness and in distraction of the driver away from the carriageway. A tunnel simulation study has shown that lighting with some artistic elements in its design can help break the monotony (Flø and Jenssen 2007). It would be interesting to combine such studies with the measurement of the brain activity of the test drivers along the lines described in Sect. 3.10 of Part 1.

The basic purpose of tunnel lighting for motorised traffic can be summarised as:

- to enhance the motorist's visual performance,
- to maintain his sense of confidence.

Short tunnels and underpasses may also be used by slow-moving traffic, cyclists and pedestrians. Where cyclists and pedestrians are concerned, the lighting should help to promote not only visual performance and sense of confidence but also personal security whilst also discouraging violence and vandalism. As far as personal security is concerned, it is both:

- a feeling of security
- and actual security

that is important. As mentioned already in Chap. 1 of this book, perceived insecurity limits the mobility of especially young women and the elderly. A feeling of insecurity especially arises when an easy escape possibility is not there, or seems not to be there. Good lighting should thus already make the exit and the stretch beyond it clearly visible at the moment of someone entering the tunnel.

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Chapter 20
Visual Performance and Sense of Confidence

Abstract During the daytime, the eyes of a driver approaching a tunnel entrance are adapted to the high level of daytime luminances surrounding that entrance. In order to keep the level of visual performance and the sense of confidence of drivers high enough, the lighting level inside the tunnel should not decrease too quickly. The basic problem is the lack of full adaptation to the lower lighting levels in the tunnel. During the drive through the tunnel, adaptation gradually becomes more complete again. Consequently, the different zones in the tunnel, require different lighting. The lighting requirements for these zones, called the threshold zone, the transition zone, the interior zone and the exit zone, are based mainly on fundamental research carried out in the sixties and seventies of the last century. Much of this research will be described in this Chapter. The limited amount of more recent research available today, will, of course, be dealt with as well. From all this, it will become clear that lighting requirements have to be specified in terms of lighting level, uniformity, glare and flicker restriction. A distinction is made between long tunnels on the one hand and short tunnels and underpasses on the other. As will be shown, under certain conditions no daytime lighting is needed for short tunnels and underpasses.

In the event of a sudden technical failure in the electrical installation or an accident, special emergency lighting is of the utmost importance and its requirements will also be dealt with here.

20.1 Tunnel Zones

The lighting requirements of a tunnel vary strongly with the longitudinal position in the tunnel. For lighting-specification purposes, therefore, a tunnel is divided into different zones, with each zone requiring different lighting (Fig. 20.1). During daytime, the eyes of a driver approaching a tunnel entrance are adapted to the high level of daytime luminance. Consequently, if the luminance level inside the tunnel is much lower than that outside, no details of its interior or any objects in it will be visible from the outside, and the tunnel entrance will appear as a 'black hole' (Fig. 20.2). The zone on the open road before the tunnel entrance where the approaching motorist should be able to see into the tunnel is called the access zone (Fig. 20.1). The first of four zones in the tunnel itself requiring special lighting during the hours of daylight is called the threshold zone. The walls and road surface in this threshold zone form

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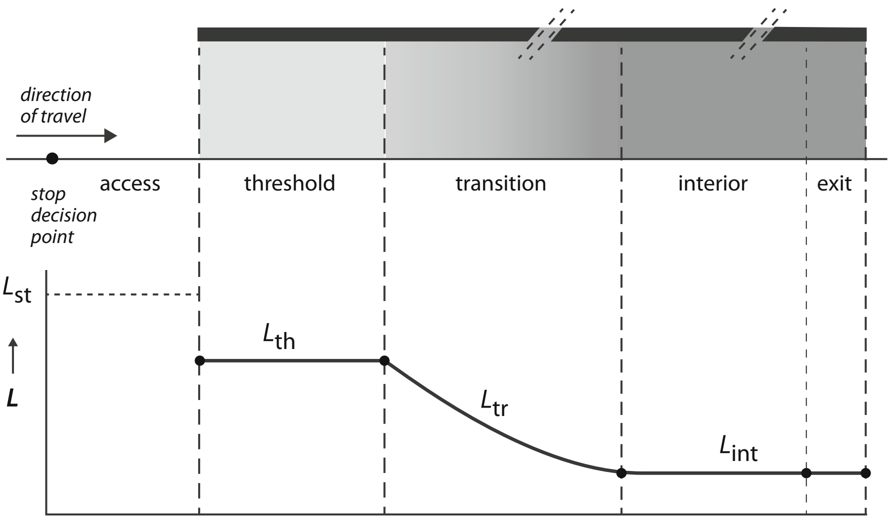
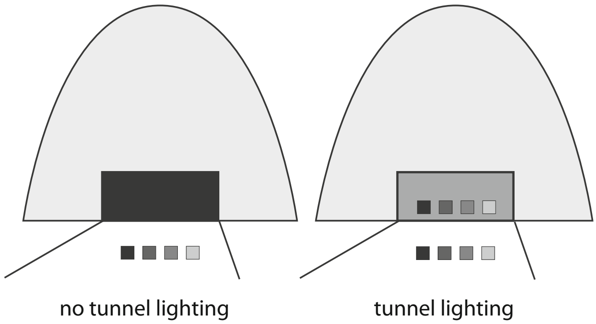


Fig. 20.1 Tunnel zones requiring different lighting

Fig. 20.2 During daytime a tunnel entrance without suitable lighting appears to an approaching driver as a black hole in which possible obstacles are not detectable



the background against which any obstacles are seen by the motorist, who is still outside the tunnel in the access zone.

After the relatively high lighting level required in the threshold zone, the lighting in the tunnel may be gradually reduced to a much lower level because the motorist's eyes gradually adapt during his drive through the tunnel. The zone in which this reduction takes place is called the transition zone. In long tunnels, the transition zone is followed by a zone in which the luminance level is kept constant. In this, the interior zone, adaptation is not necessarily complete and it is therefore necessary to arrange for a level of luminance that is somewhat higher compared with the level needed on an open road at night. While approaching the exit of the tunnel the adaptation level of the motorist gradually increases because the apparent size of the exit gradually increases. Since adaptation from low to high levels of luminance takes place practically instantaneously, and because obstacles in the exit stand out clearly against the bright exit, no extra adaptation lighting in the exit zone is needed during daytime.

The following sections will describe the lighting in the various tunnel zones in more detail from a point of view of visual performance and sense of confidence.

20.2 Threshold Zone

20.2.1 Daytime Luminances in the Access Zone

As already stated above, the daylight situation in front of the tunnel, viz. in the access zone, determines for an important part the lighting required in the threshold zone. Needless to say, the daylight level is not constant; it is continually changing with the time of day, season and weather conditions. A tunnel-lighting installation has to be designed so that safe traffic conditions are achieved under the highest lighting levels regularly occurring. The criterion is often the estimated daylighting level that is only exceeded for a certain percentage in a year (e.g. 2 %, which is for the 4000 annual daylight hours, 80 h per year). At all moments that the daylight level is lower, the electric lighting in the tunnel should be partly switched off or dimmed. Blaser and Dudli (1993) developed a method that allows the determination of the daytime luminance situation for different percentage criteria from the mean sunshine time distribution during the year for the region in question. Their method builds on the L_{20} concept that will be described in a following section.

Of course, it is not the illuminance level that determines the state of the approaching driver's eyes but the luminances in his field of view. These luminance values are dependent on the daylight illuminance in combination with the direction of view of the driver and the reflectance of the surfaces. Narisada and Yoshikawa (1974) found that drivers fixate for about 80 % of the time on the tunnel entrance itself, so that the direction of view can safely be taken as being towards the centre of the tunnel entrance. The position of the sun relative to the direction of view and thus the direction of travel, also has an influence. Table 20.1 gives an indication of luminance values for different driving directions of an approaching motorist corresponding to a daylight situation of around 100,000 lx horizontal illuminance. The low luminance value for dark paint illustrates the possibility to decrease the luminances in the field of view of the approaching driver and thus to lower the required lighting level in the tunnel. This can be achieved by painting the tunnel portal and its surrounding structures in a dark colour. Planting trees and shrubs above the tunnel entrance is another possibility. Sometimes, the construction of a large entrance canopy that shields part of the bright sky from view, can be effective as well. Figure 20.3 shows an example of this.

20.2.2 Symmetrical, Counter-Beam and Pro-Beam Lighting

Three fundamentally different tunnel-entrance lighting systems can be employed for the threshold zone: a symmetrical system, a counter-beam system and a pro-beam system. Which of these systems is employed has an influence on the level of

Table 20.1 Examples of luminance values (kcd/m^2) in the access zone roughly corresponding to 100,000 lx horizontal illuminance. These values are for the Northern hemisphere. For the Southern hemisphere, North and South should be interchanged. (Partly based on CIE 2004)

Driving direction	Sky	Road	Rocks	Buildings	Grass	Shrubs	Snow mountain	Snow flat	Dark paint
North	8	3	3	8	2	1	15	15	0.75
East and west	12	4	2	6	2	1	10	15	0.75
South	16	5	1	4	2	1	5	15	0.75

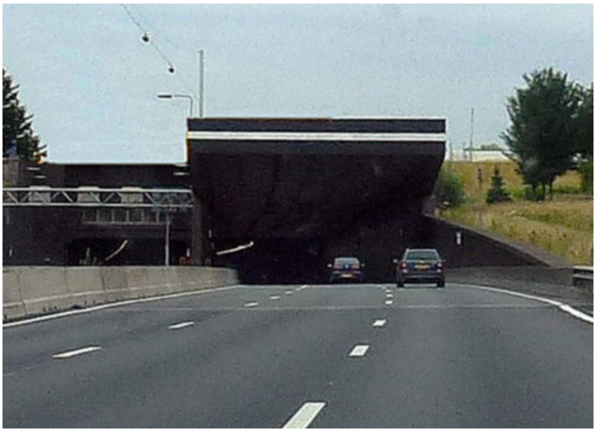


Fig. 20.3 Entrance canopy to shield off part of the bright sky

visual performance and the sense of confidence of the motorists, and thus on the lighting levels required. The three systems are characterised by the longitudinal light distribution of the luminaires employed (Fig. 20.4):

- symmetrical lighting systems throw their beams symmetrically in the forward and backwards directions,
- counter-beam lighting systems throw the main part of their beams in the direction against ("counter to") the direction of traffic flow,
- pro-beam systems throw the main part of the beam in the same direction as the traffic flow.

Symmetrical tunnel-lighting systems light both the road surface and obstacles on the road, very much as do normal road-lighting systems. Most, but not all, obstacles with different reflectances will be seen in negative contrast as silhouettes, just as with normal road lighting (Fig. 20.5 top left). The counter-beam system does provide lighting on the road surface, but very little on the surfaces of obstacles seen by the approaching motorist. Consequently, more of the objects are seen in silhouette with a larger (negative) contrast (Fig. 20.5 top right). As will be discussed in more detail in further sections, this means that the lighting level in the threshold zone with counter-beam systems can be lower, whilst still resulting in the same level of visual performance, but in a lower level of visual comfort and sense of confidence for the motorist (Fig. 20.5 bottom).

Fig. 20.4 Symmetrical, asymmetrical counter-beam and pro-beam tunnel-lighting systems

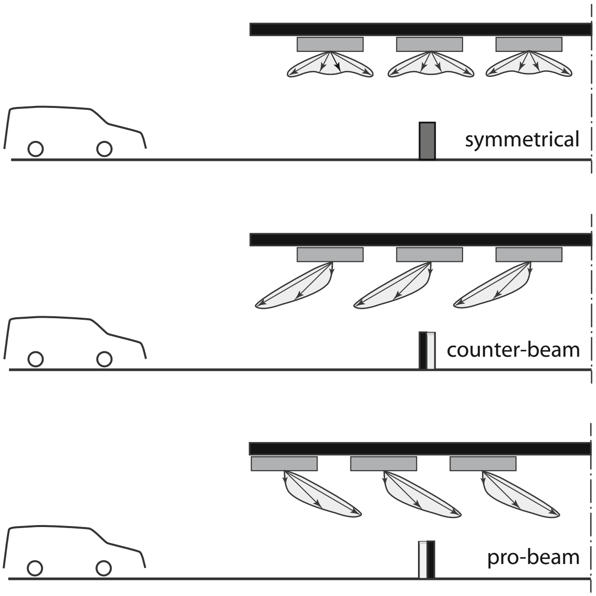
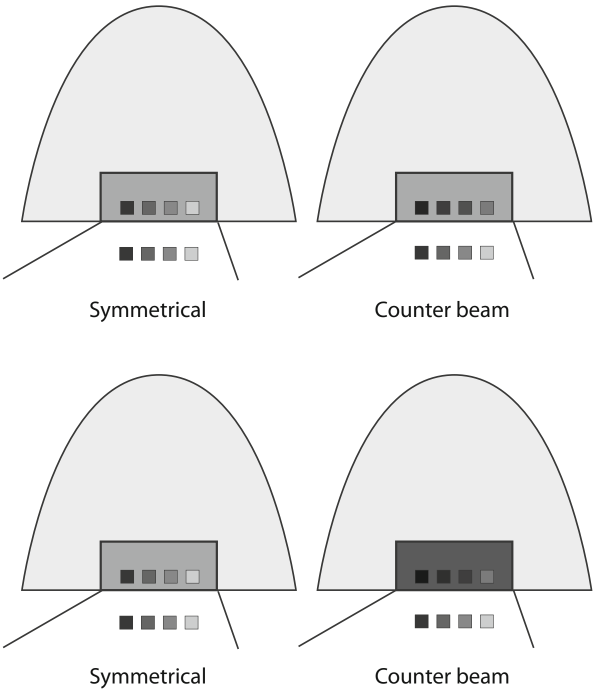


Fig. 20.5 Symmetrical and counter-beam systems. *Top* same lighting levels, counter-beam lighting results in improved negative contrasts. *Bottom* different lighting levels, comparable detectability of objects in the tunnel



Symmetrical and counter-beam systems can be classified according to the so-called "contrast revealing coefficient" (q_c), which is defined as:

$$q_c = L_{road}/E_{vert}$$

The better the limitation of the vertical illuminance (on the plane facing the oncoming motorists), the higher is the contrast-revealing coefficient. In many standards and recommendations for tunnel lighting, counter-beam systems are defined as systems with a contrast-revealing coefficient, q_c, equal to or higher than 0.6. A typical value of q_c for symmetrical systems is 0.2. Here it should be noted that these values do not normally take into account the indirect contribution to the vertical illuminance made by reflection of light from the road-surface area in front of an object. Lighter and more diffuse reflecting surfaces will increase this indirect contribution to the vertical illuminance and thus lower the contrast revealing coefficient, and indeed the effectiveness of a counter-beam system. Adrian and Gibbons (1993, 1999) introduced a provisional calculation system for the indirect contribution, but with limited validity. A generally-applicable system is not yet available.

As has been explained, a counter-beam system directs the maximum amount of light towards oncoming traffic. For this direction of light incidence a relatively large amount of light is reflected from the road surface towards the oncoming motorists. The road surface has a large luminance coefficient for this light incidence and viewing direction (See Chap. 12 of part 1). This effect increases the efficiency with which illuminance is converted into the required road-surface luminance: counter-beam installations thus have a high luminance yield. However, this efficiency advantage may sometimes be counterbalanced by the necessity of having to take special measures in the luminaires to prevent intolerable glare from their light directed towards the traffic.

The high luminance yield exhibited by counter-beam systems is not shared by pro-beam installations. This means that high horizontal illuminances and thus high luminous-flux luminaires are needed to supply the required luminances. This is the most important reason why, to date, pro-beam tunnel lighting installations are seldom employed. There is also the fact that with them, the visual guidance normally obtained by lines of bright luminaires along the tunnel ceiling or walls, would be weakened. A certain degree of brightness of the tunnel luminaires, can indeed help in guiding motorists into and through the tunnel (Narisada et al. 1977).

Recently, in Japan, thought-provoking research on pro-beam lighting installations has been carried out. This involved the visibility of the rear of preceding cars and of a set of small objects with different reflectances (Hirakawa et al. 2007; Ito et al. 2011). One test, in one and the same tunnel tube, compared an actual pro-beam lighting installation employing LEDs with a symmetrical installation employing low-pressure sodium lamps (Ito et al. 2013). The results showed that the subjective appraisal of the visibility of the rear of a preceding car was better for the pro-beam system. On the basis of revealing power calculations (see Sect. 3.2 of Part 1) for objects defined in Fig. 3.10 of this book, the conclusion was that the pro-beam system provides such high vertical illuminances that many objects are seen in positive contrast, so that the revealing power is comparable with the symmetrical tunnel lighting installation: 86.6 % for pro-beam against 87.0 % for symmetrical. However, it should be noted that with the long low-pressure sodium lamps the creation of pronounced light distributions in the longitudinal direction is not easy. Smaller light sources, such as tubular high-pressure sodium lamps or LEDs, would have provided a more effective symmetrical light distribution. Of course, there remains the lower luminance yield of pro-beam systems and the consequently higher energy consumption. The suggestion made by Ito et al. (2011) of halving the lighting level with the pro-beam installation, would, if realized, result in a low level of confidence for drivers approaching the tunnel: they would experience the tunnel entrance as a black hole with scarcely any visual guidance into the tunnel provided by bright luminaires.

20.2.3 Influence of Traffic Speed

There is an important link between the traffic speed for which the tunnel is designed and the value of the lighting levels that need to be provided in the tunnel. In this section it will be shown that the traffic speed has a direct influence on the lighting level required in the first part of the tunnel zone, the threshold zone. The higher the speed, the higher the lighting level has to be. It should be realized that this also has a consequence for the amount of light required in the other zones: with a higher threshold zone level, the transition lighting in the transition zone has to start at a higher level, and it takes longer before it can be reduced to the low interior lighting level. Quantitative details will be given in later sections.

20.2.3.1 Adaptation State

During his approach to a tunnel, the relatively-dark tunnel entrance and its surround, occupy an increasingly larger part of a driver's total field of view. As a consequence of this, the state of adaptation of the driver's eyes is gradually decreasing. However, at any given moment during the approach his state of adaptation is determined not only by the luminance distribution in his field of view but also, because of "time lag", partly by the luminance distribution experienced shortly before his approach to the tunnel entrance. On the basis of many different experiments (Schreuder 1964, 1971; Narisada 1972; Narisada and Yoshikawa 1974; CIE 1984), it has become clear that the luminance to be provided in the threshold zone of the tunnel is best determined on the basis of the luminances of the tunnel surroundings at the point where the motorist has to be able to perceive an object in the tunnel entrance. For an object standing in the mouth of the tunnel this moment is defined by the 'stop-decision point', this being the point outside the tunnel at which a driver has to begin braking in order to come to a standstill at the tunnel entrance. The higher the speed, the farther the stop-decision point from the tunnel entrance. At that point, the luminances in the surrounding field of view are greater, since the dark tunnel entrance then forms only a small part of the visual field. Consequently, with higher speeds, higher lighting levels in the threshold zone are required.

20.2.3.2 Atmospheric Scattering

A secondary reason for the influence that speed of approach has on the lighting levels needed in the threshold zone has to do with atmospheric light scatter. This takes place due to dust and other particles suspended in the air between the motorist and the tunnel entrance. The problem caused by this form of disturbing light scatter is familiar to those who have ever driven in fog: the light scattered from the moisture-laden air into the motorist's eyes hampers his visibility. Even with a relatively clear sky during daytime, the same phenomenon hampers the visibility of objects in the threshold zone for a driver outside the tunnel. With a higher approach speed, the layer of air between the driver at the stop decision point and the tunnel entrance is thicker and scattering therefore has more of a negative influence. This has to be compensated for by a higher lighting level in the tunnel.

20.2.3.3 Difficulty of Driving Task

Obviously, the driving task is more difficult at higher driving speeds. At the greater stopping distances associated with higher speeds, objects subtend a smaller angle. In order to be able to see an object under such high-speed conditions, the contrast of the object has to be higher, which in turn requires higher lighting levels.

20.2.4 Uniform Field-Luminance Concept

Schreuder was the first to carry out extensive research into tunnel lighting—in the 1960s of the last century (Schreuder 1964, 1967). This research generated basic knowledge regarding the luminance levels required in a tunnel entrance zone according to different daytime lighting levels and the visual-task parameters prevailing. His research is still often referred to today. He used a static laboratory set-up consisting basically of a large screen of completely-uniform luminance extending over the observer's entire field of vision. This represented the daytime lighting situation for a driver approaching the tunnel (Fig. 20.6).

A small square representing the threshold zone of the tunnel could be displayed on the screen for 0.1 of a second, with an object in its centre of varying size and contrast. The luminance of both the screen (adaptation luminance) and of the square (threshold luminance) were varied, and observers were asked whether or not detection of the object was possible. The results, later confirmed by others (Mäder and Fuchs 1966; Narisada and Yoshimura 1974), show that for outside adaptation luminances

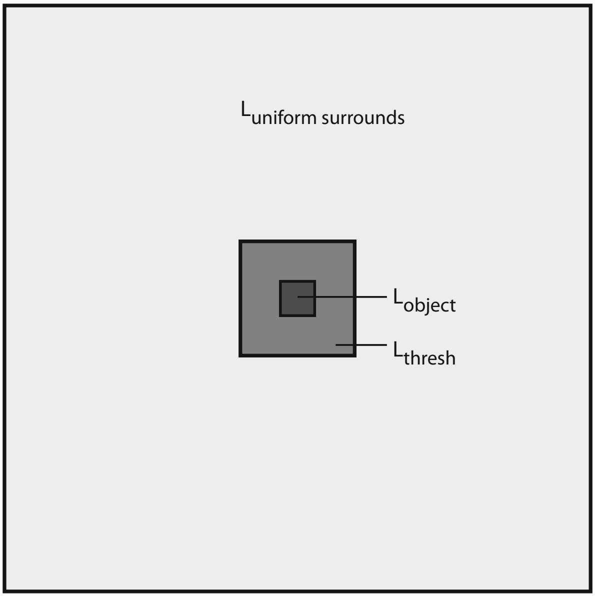


Fig. 20.6 Sketch of Schreuder's static laboratory set-up

greater than about 100 cd/m^2, the lighting level in the threshold zone should be equal to or greater than 0.10 times the uniform adaptation luminance for an object seen under an angle of 7 min of arc (20 × 20 cm, from a distance of 100 m) with a critical contrast of 0.20. If one assumes a more easily visible object with a critical contrast of 0.25, the corresponding ratio between required threshold luminance and uniform adaptation luminance is only 0.07 instead of 0.10: thus 30 % lower. This illustrates how important the influence of the choice of critical contrast is as a basis for determining tunnel lighting levels.

20.2.5 L_{20} Concept

The results of Schreuder' research are only valid for a uniform adaptation luminance. In practice, of course, the luminance of the surroundings of a tunnel entrance are by no means uniform. To overcome this practical problem, a concept has been introduced that enables the determination of the adaptation state of the approaching driver while taking into account the non-uniform surrounding luminances. This concept is called the L_{20} concept. L_{20} is the average luminance in a conical field of view subtending an angle of 20° at the eye of an observer at the stop-decision point and centred on a viewing direction towards the tunnel entrance (CIE 1973, 2004; Narisada et al. 1979; Van Bommel 1981). The examples of Fig. 20.7 show that the resulting L_{20} value is, of course, different for tunnels with different surrounding luminances. The L_{20} value of the tunnel on the left is 5100 cd/m^2 and on the right only 2400 cd/m^2.

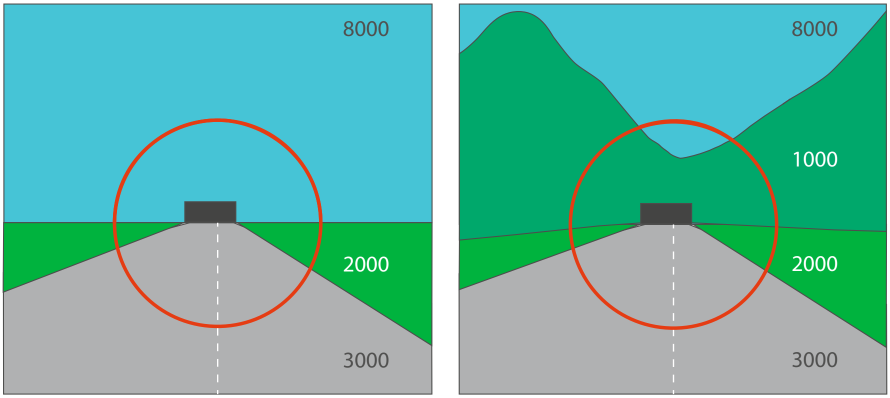


Fig. 20.7 The L_{20} concept. The *circle* represents the projected 20° cone from the stop-decision point. The average value in the circle (L_{20}) is 5100 cd/m^2 for the tunnel on the left and 2400 cd/m^2 for the tunnel on the right

For the same critical visual task as used by Schreuder (viz. object with contrast of 0.20 seen under an angle of arc of 7 min, presented for 0.1 s) the ratio between the threshold-zone luminance required and the value of L_{20} has to be (CIE 1990, 2004):

- $L_{th}/L_{20} > 0.06$ for symmetrical systems,
- $L_{th}/L_{20} > 0.05$ for counter-beam systems.

As mentioned above, the size of the critical object of 7 min corresponds to a 20×20 cm object seen from a distance of 100 m. Since 100 m is approximately the stopping distance at a speed of 80 km/h, the above requirements hold for driving speeds of up to 80 km/h. Higher driving speeds require higher ratios. This is because the critical object of 20×20 cm is then seen under a smaller angle because of the greater stopping distance. For example, for 120 km/h, again for the same critical object to be detectable, the ratio has to be:

- $L_{th}/L_{20} > 0.10$ for symmetrical systems,
- $L_{th}/L_{20} > 0.07$ for counter-beam systems.

The L_{20} concept is still sometimes used as a simple alternative to the more accurate but more complicated veiling-luminance concept that will be described in the following section.

20.2.6 Veiling-Luminance Concept

Luminances closer to the centre of the visual field, viz. closer to the tunnel entrance, contribute more to the adaptation state of the approaching driver than do luminances towards the outer field of view. This "position" effect of the surrounding luminances

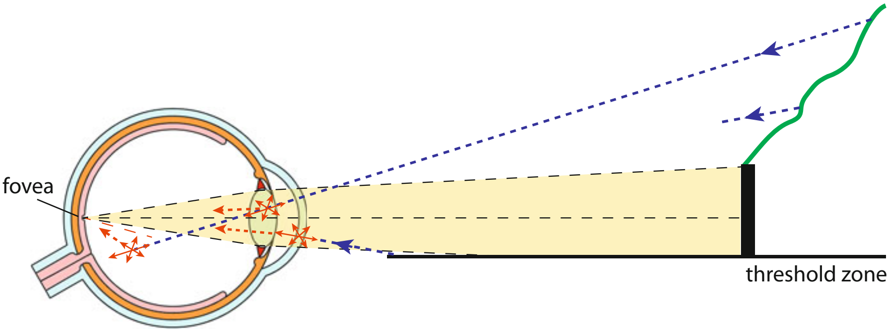


Fig. 20.8 Tunnel entrance surroundings as small glare sources, the light of which scatters in the eye towards the fovea where it overlaps with the sharp image obtained from the centre of the visual field. Drawing not to scale

is not taken into consideration in the L_{20} concept: all positions get the same weight while averaging over the cone of 20°. A concept that does take this position effect into account was proposed long ago (Adrian 1976, 1982) and now forms the basis for the latest international recommendations for tunnel lighting (CIE 2004). It considers the bright surroundings of the tunnel as many glare sources that reduce the perceived contrast of objects in the tunnel through light scatter within the eye (Fig. 20.8).

This process is exactly the same as that experienced by motorists on an open road during the night-time, from glaring road-lighting luminaires while looking towards the darker road ahead (see Sect. 3.1.3.1 of part 1). Light coming from the bright areas surrounding the tunnel entrance and entering the eyes of the oncoming driver, is partly scattered in the eye lens and eyeball and re-directed towards the fovea. This light creates a bright veil that overlaps with the sharp image obtained from the centre of the visual field, viz. the tunnel entrance and any objects within it. The value of the corresponding veiling luminance is dependent on the position of each bright area and can be expressed with exactly the same formula as that used for glare from road-lighting luminaires:

$$L_{seq} = \frac{10\ E_{eye,i}}{\theta_i^2}$$

where L_{seq} is the veiling luminance caused by the surrounding luminances and $E_{eye,i}$ is the illuminance on the eye caused by the ith luminance element (Fig. 20.9).

Since tunnel-lighting professionals normally use the expression "equivalent veiling luminance, L_{seq}" for the parameter "veiling luminance" we too will use that expression in the Tunnel-lighting part of this book[1].

The final effect of the veil is a reduction of the contrast of objects as perceived by the oncoming driver.

[1] L_{veil} as used in glare restriction for open road lighting is exactly the same parameter as L_{seq}, The "s" in the abbreviation L_{seq} stands for the German word for veil: "Schleier".

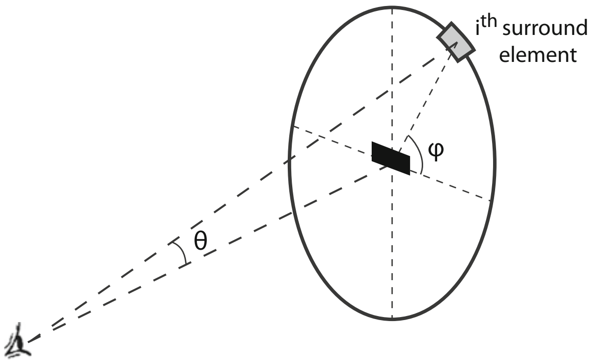


Fig. 20.9 Geometry for calculating veiling luminances L_{seq}

As discussed earlier, the scattering of bright daylight by the layer of atmosphere containing dust and dirt particles between the driver and the tunnel entrance, hampers the visibility of objects in the threshold zone. Part of the light that scatters within the cone of vision arrives directly at the fovea, where it overlaps with the sharp image of the tunnel entrance (Fig. 20.10). This can have an important further contrast-reducing effect. Part of the light that scatters outside the cone of vision into the direction of the eye can still reach the fovea because of light scatter within the eye. This secondary scattering effect of atmospheric light (in Fig. 20.10 drawn in black) is small and is usually neglected.

If bright daylight falls onto a car's windscreen, part of it will be scattered at the windscreen into the direction of the driver's eyes to produce a contrast-diminishing effect. Dirty windscreens increase the seriousness of this effect. Here, too, that part of the light that is scattered at the windscreen to enter the cone of vision is radiated towards the fovea, where it overlaps with the sharp image of the tunnel entrance to reduce the contrast of objects seen there (Fig. 20.11 red drawn scatters). The secondary scattering effect of scattered light from parts of the window outside the cone of vision (black drawn scatter) is small and is neglected.

The three different kinds of veiling luminance originating from:

- light scatter in the eye of light from the bright tunnel surrounds (L_{seq}),
- light scatter from the layer of air into the direction of the fovea (L_{atm}),
- light scatter from the windscreen into the direction of the fovea (L_{ws})

thus all have a contrast-reducing effect for objects in the threshold zone of a tunnel as seen by the approaching driver from the access zone.

The threshold zone luminance needed to acquire a certain minimum value of perceived contrast can be determined (CIE 2004). The formula is:

$$L_{th} = \left\{ \frac{\left(\tau_{ws} L_{atm} + L_{ws} + L_{seq}\right)}{\tau_{ws}} \right\} / \left\{ \frac{1}{C_{perc}} \left(\frac{\rho}{\pi q_c} - 1 \right) - 1 \right\}$$

where:

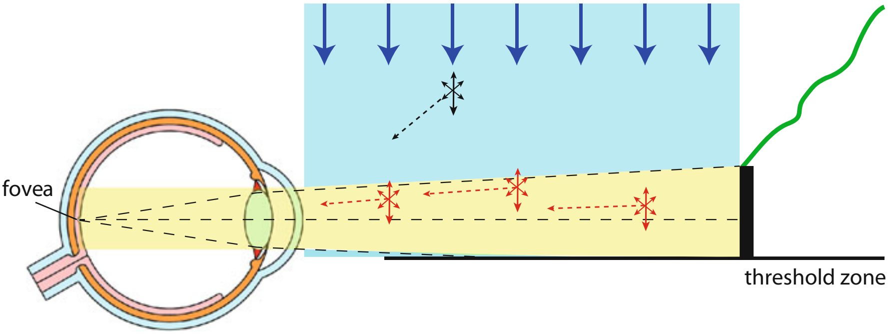


Fig. 20.10 Scattering of light (inside and outside the cone of vision, shown in *red* and *grey* respectively) from the atmospheric layer of air between the motorist's eye and the tunnel entrance towards the fovea of the motorist. Drawing not to scale

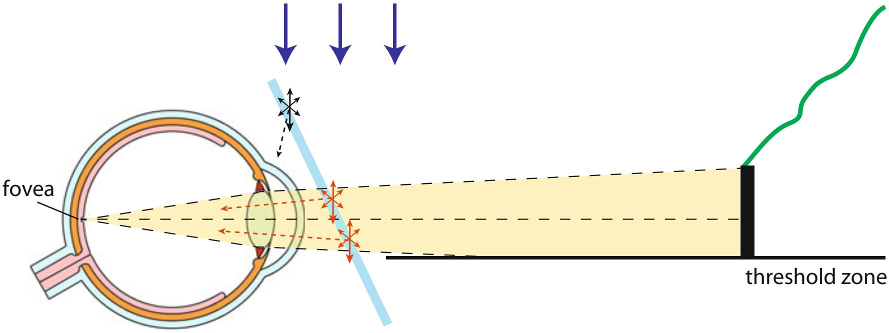


Fig. 20.11 Scattering of light from the windscreen of a car towards the fovea of the eye of a motorist. Drawing not too scale

C_{perc} = Minimum required perceived contrast
ρ = Reflectance of the critical object
q_c = Contrast-revealing coefficient of the lighting system (symmetrical or counter-beam)
τ_{ws} = Transmission of the windscreen

A typical value for the atmospheric veiling luminance (L_{atm}) is 200 cd/m^2 and for the windscreen veiling luminance (L_{ws}) 100 cd/m^2 (Padmos and Alferdinck 1983). These values correspond to high daylight levels of around 100,000 lx horizontal illuminance. In more polluted areas or with dirty windscreens these values will be larger. Windscreen transmission is typically some 0.80, which means that the amount of light from the surrounding luminances and from the layer of atmospheric air is reduced by the same factor. Figure 20.12 shows, for these typical values, the required threshold-zone luminance (L_{th}) as calculated for a value of critical perceived contrast of 0.28, as a function of the equivalent veiling luminance (L_{seq}). A value of 0.28 for the minimum perceived contrast is recommended by the CIE in its latest

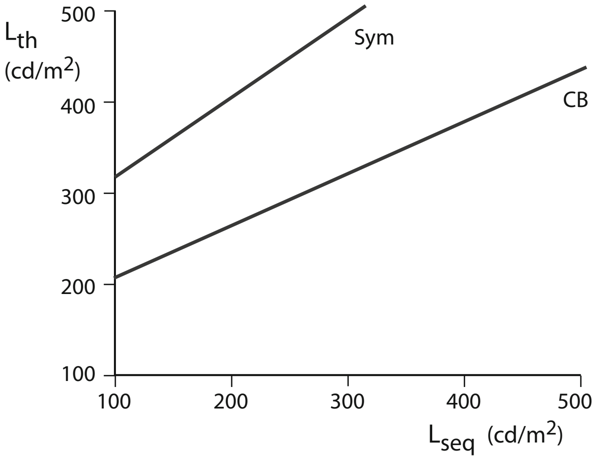


Fig. 20.12 The required threshold-zone luminance (L_{th}) as a function of the equivalent veiling luminance (L_{seq}) for a symmetrical (*Sym*) and a counter-beam (*CB*) system. L_{th} is calculated for a perceived contrast of 0.28. Reflectance (ρ) of object 0.20; L_{atm} 200 cd/m^2; L_{ws} 100 cd/m^2, and τ_{ws} 0.8

Recommendation (together with an object reflectance of 0.20) for use as a basis for the determination of the threshold-zone luminance (CIE 2004).

20.2.7 Length of Threshold Zone

Threshold-zone lighting serves to produce a background luminance against which an obstacle anywhere on the road surface within the zone will be clearly visible to a driver approaching the tunnel entrance. The threshold zone lighting should therefore extend into the tunnel over a distance equal to the safe-stopping distance. The eye-adaptation state of the approaching driver, although not immediately following the luminance changes, decreases to some extent during his drive from the stop-decision point to the tunnel entrance because the relatively dark tunnel entrance gradually constitutes a larger part of his visual field. The threshold-zone lighting in the more distant part of the threshold zone may therefore be gradually decreased. CIE (2004) permits of a linear decrease by some 60 % of its original value from half the stopping distance to the end of the zone.

20.2.8 Sense of Confidence

Even with the visual-performance aspects concerning objects in the tunnel, satisfied, the tunnel entrance may still appear rather like a black hole. In the access zone and in the tunnel itself there is less room to manoeuvre than on an open road. All this may have a negative effect on the sense of confidence of the motorist approaching the tunnel. Some drivers feel insecure and uncertain and a few are downright anxious. As

Table 20.2 Safety rating numbers (SRN) used for subjective tunnel entrance appraisals. (Adrian 1982)

SRN	Experienced sensation	Description
1	Black hole	Completely unacceptable
3	Inadequate	Entrance too dark, not sufficient for a safe entry
5	Fair	Lower limit of just-sufficient levels for safe entry
7	Good	Satisfactory, driver feels safe when entering
9	Excellent	Very good viewing conditions

has already been explained in the previous chapter, it may lead to a hesitant driving behaviour, such as unnecessary slowing down or even braking, and a change of lateral position away from the tunnel walls. Subjective appraisals of existing tunnels have, indeed, shown that different tunnel entrances and different surroundings are appraised rather differently by motorists approaching tunnels. Many of these appraisals were conducted without any obstacles in the tunnel, so that the sense of confidence was appraised without information on the actual effect on visual performance provided by the lighting.

Methodical research into this aspect for real-life tunnels is in practice rather difficult. It has, however, been done employing laboratory-scale simulations. The most extensive simulation study made use of two large photographic slides simulating one tunnel scene typical for a mountain tunnel and one for an urban tunnel (Adrian 1982). These slides were illuminated from behind by a light box to produce surrounding luminances up to the highest values occurring in practice and measured in terms of $L_{seq.}$ The tunnel entrance itself could be varied in luminance independently, and was measured as well: L_{th}. For a range of different L_{seq} and L_{th} values, observers were asked to assess the subjective safety of each situation with the aid of the appraisal scale, called the Safety Rating Numbers (SRN) scale, given in Table 20.2. These appraisals are also a good measure for the sense of confidence of drivers during their approach to a tunnel. Figure 20.13 shows the results of the appraisals.

From the figure it is evident that high threshold-zone levels of clearly more than 300 cd/m^2 are required to provide conditions that result in at least an appraisal "good" (SRN $\geq$ 7). To compare these results with the results on visual performance as dealt with earlier in this section, Fig. 20.14 superimposes the appraisal results onto the L_{th}-L_{seq} relationship of Fig. 20.13 that is based on visual performance. For the L_{seq} range varying from 100 to 300 cd/m^2, symmetrical lighting installations coincide with subjective appraisals "fair" to "good" (SRN 5–7) and counter-beam systems from "insufficient" to "just sufficient" (SRN 4–6). For approximately the same visual performance, the sense of confidence provided by counter-beam systems is thus clearly lower than that provided by symmetrical systems.

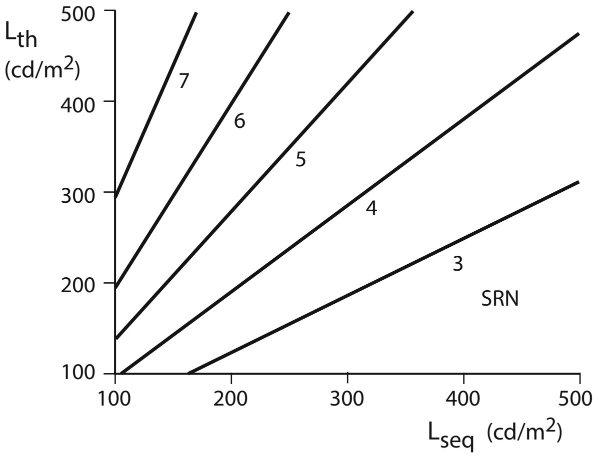


Fig. 20.13 Safety rating number SRN as a function of the threshold-zone luminance (L_{th}) and the veiling luminance of the surrounds (L_{seq}) (Adrian 1982)

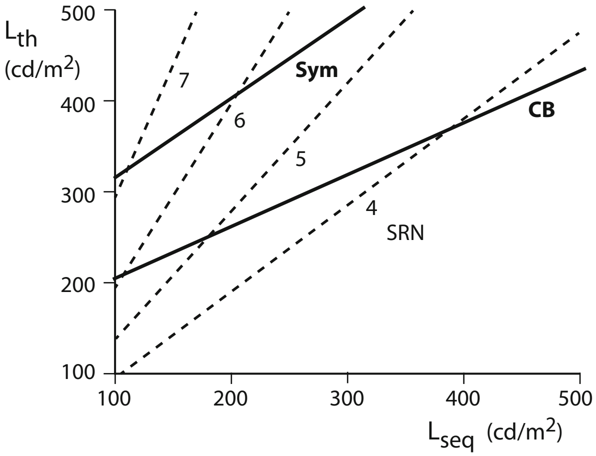


Fig. 20.14 Safety rating numbers (*SRN*) super-imposed on the L_{th}-L_{seq} relationship for a minimum perceived contrast of 0.28 as given in Fig. 20.13

20.3 Transition Zone

After the relatively high lighting levels required in the threshold zone, the lighting in the transition zone may be gradually reduced to a much lower level. The adaptation state of the approaching driver will not immediately follow the luminance changes, so only partial adaptation can be obtained. Therefore, if the decrease in the transition zone is too rapid, visibility and visual comfort will deteriorate. A principal negative effect associated with partial adaptation is the occurrence of after-images. These are weak images of visual scenes that have been seen a short time previously when the conditions were still much brighter. The after-image is seen in reversed contrast and colour (Fig. 20.15).

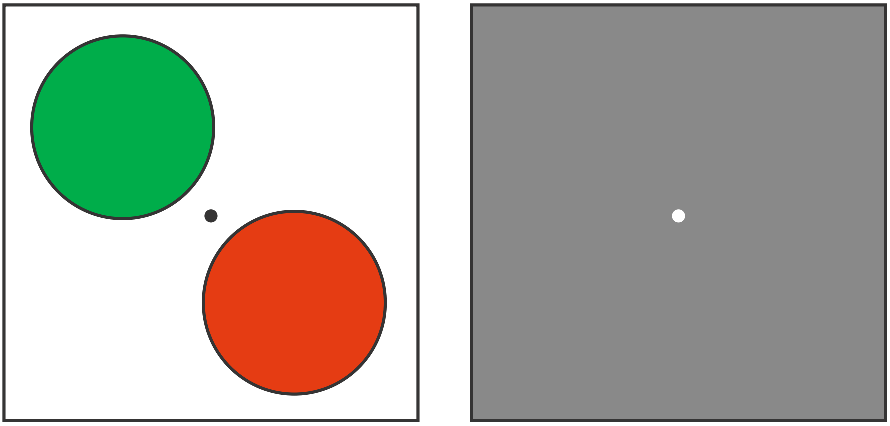
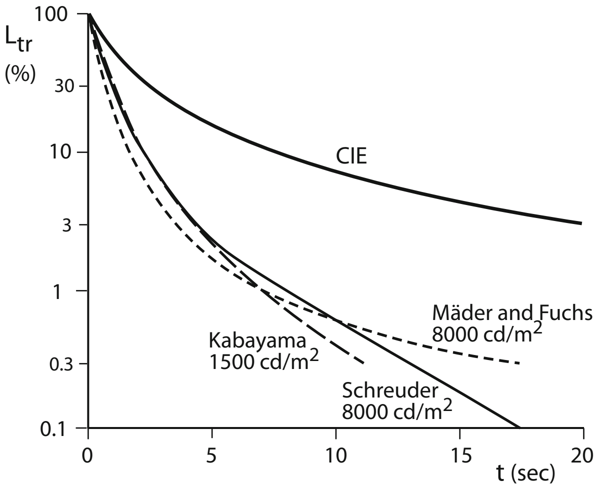


Fig. 20.15 An after-image may occur when, after concentrating for some 20 s on the bright picture (fixate the *black dot*), one subsequently concentrates on the darker *area* (fixate the *white dot*)

Fig. 20.16 Luminance reduction in terms of the transition-zone luminance, L_{tr}, of *CIE* and of different researchers with indication of the luminance starting point



Determination of the speed with which the luminances in the transition zone can be reduced without experiencing after-images and without losing sight of a critical object in that zone, has been carried out by Schreuder (1964). Kabayama (1963) and Mäder and Fuchs (1966) conducted similar investigations, but solely on the basis of visibility criteria. In these investigations luminance values for the starting point of the reduction varied widely. Figure 20.16 shows the results on a relative scale.

The permissible reduction is only slightly dependent on the starting luminance value, and the relative curves are in good agreement with each other. However, since these early investigations, experience with real tunnels has shown that when these reduction curves are applied in practice, a strong feeling of discomfort is experienced,

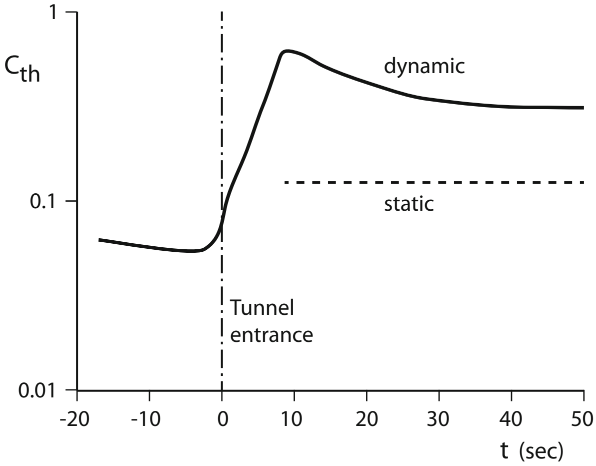


Fig. 20.17 Temporal adaptation defect: dynamic and static contrast threshold before and after entering a simulated tunnel with a luminance transition from 4000 to 1 and 5 cd/m^2. (Bourdy et al. 1987)

especially in the farthest parts of the transition zone: the sense of confidence is unacceptably low. This has probably to do with the only partial adaptation state of the drivers. With a tunnel simulator, Bourdy et al. (1987) determined the dynamic visibility threshold for two different small objects for two different luminance transition patterns, starting at 4000 cd/m^2 and ending at 5 and 1 cd/m^2 respectively. From these tests they estimated the temporal adaptation defect by comparing the dynamic contrast threshold with the static threshold (valid for a continuous constant luminance) as shown in Fig. 20.17. From the figure it can be seen that the adaptation state reaches a steady state only some 35 s after having passed the tunnel entrance, corresponding to 1 km at a driving speed of 100 km/h. Note that the steady-state threshold is still higher than that of the static situation.

CIE defined a luminance reduction curve for the transition zone that is based for an important part on unpublished assessments made by technical committee members in a large number of different tunnels. This curve is also shown in Fig. 12.16. Figure 20.18 shows the same CIE curve with extra horizontal axes where the time is transformed into distances for a given driving speed. The 100 % point corresponds to the luminance value at the end of the threshold zone. If a lighting system is used in which continuous dimming of the lamps is not feasible, the smooth curve can be stepwise approximated, provided the succeeding steps have transitions smaller than 3:1 and that no step takes the lighting level below that of the curve (Fig. 20.18 dashed lines).

20.4 Interior Zone

In long tunnels, the transition zone is followed by a zone in which the luminance level is kept constant because the driver's eyes are reasonably-well adapted. As we

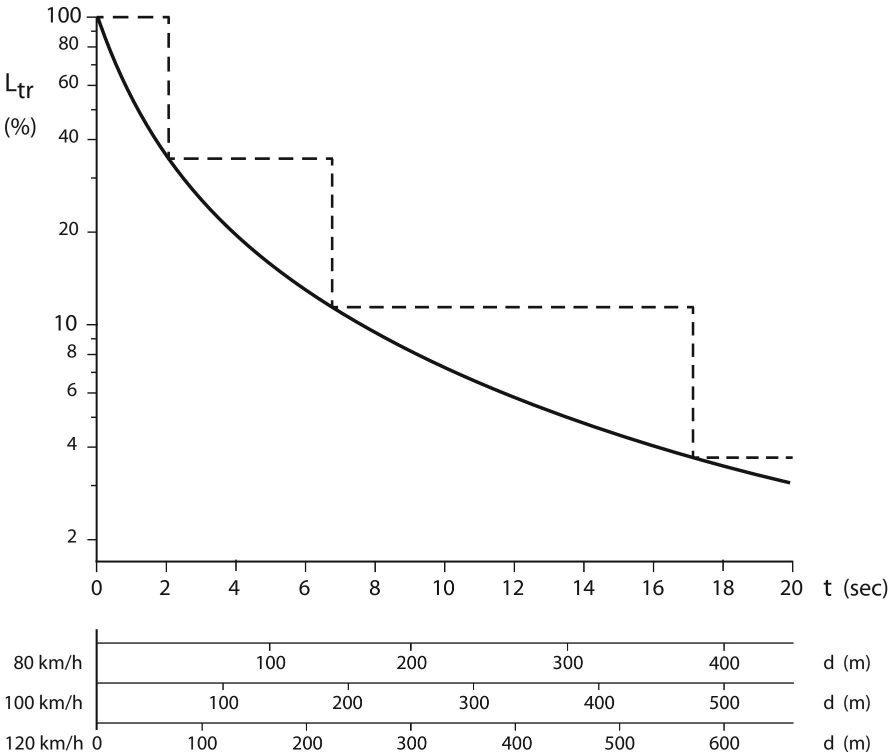


Fig. 20.18 CIE luminance-reduction curve showing the maximum permissible rate of decrease in the transition zone

have seen in the previous Section, in the beginning of this interior zone, adaptation is not yet complete and it is therefore necessary to arrange for a level of luminance that is fairly high compared with the level needed on an open road at night with a static adaptation. Even in very long tunnels where adaptation gradually becomes complete, the lighting level needs to be higher than that on an open road at night. The reason for this is that in a tunnel there is less space to correct an error and less space to avoid obstacles; and if an accident does occur, the consequences are likely to be more severe. Practical experience has shown that levels of 2 to 10 cd/m^2 are to be recommended for the interior zone, the lower levels being acceptable for tunnels with low traffic density and driving speed.

20.5 Exit Zone

The adaptation state of a driver approaching a tunnel exit gradually increases because the bright exit gradually increases in size during the approach. Since adaptation from low to high levels of luminance takes place practically instantaneously, and because obstacles in the exit zone will stand out clearly against the bright exit, no extra lighting in the exit zone is needed. To ensure adequate vision via the rear-view mirror the exit zone should have the same lighting level as the interior zone.

20.6 Uniformity and Glare Restriction

As with normal road lighting, it is the overall uniformity (U_o), the ratio of minimum to average road surface luminance, that influences visual performance, while the longitudinal uniformity (U_l), the ratio of minimum to maximum luminance on a line parallel to the road axis, in particular influences visual comfort (Sect. 4.2 of part 1). Of the range of U_o and U_l values recommended for normal road lighting, the higher values should be considered for the lighting of all tunnel zones, viz. U_o at least 0.4 and U_l at least 0.6. In tunnels, the walls up to 2 m can form the background of cars. The average luminance of these parts of the walls should therefore be at least 0.6 of the average road-surface luminance.

As is the case with a normal road-lighting installation, glare from the luminaires should be restricted to keep visual performance at an adequate level. The threshold increment (TI) concept for glare restriction as described in Sect. 3.1.3 of Part 1 should also be applied in all zones of the tunnel. The TI formula given in that Section holds for road-surface luminances smaller than 5 cd/m^2. For the higher luminances that we often have in tunnel lighting, the influence of the average road-surface luminance is slightly different, as given by the formula:

$$TI = \frac{L_{veil}}{L_{av}^{1,05}}$$

where L_{veil} is the veiling luminance caused by the luminaires in the tunnel.

The more stringent TI values that are employed in normal road lighting should preferably be satisfied in tunnel lighting, viz. a maximum value of TI of 10 %. In practice, however, this may be difficult, or even impossible to achieve, because the low ceilings of tunnels make for low luminaire mounting heights.

20.7 Flicker

Light sources mounted in interrupted rows along the roofs or walls of a tunnel may produce a discomforting and distracting flicker experience in the eyes of a driver passing through it, so diminishing his feeling of confidence. The flicker is caused both by the light from the sources themselves, which appear and disappear at the edge of the driver's field of view, and by reflections of the sources glimpsed in shiny surfaces, e.g. the bonnet of the driver's own vehicle and the rear of any vehicle he may be following. The extent to which a driver is troubled by such flicker is largely dependent upon the following factors:

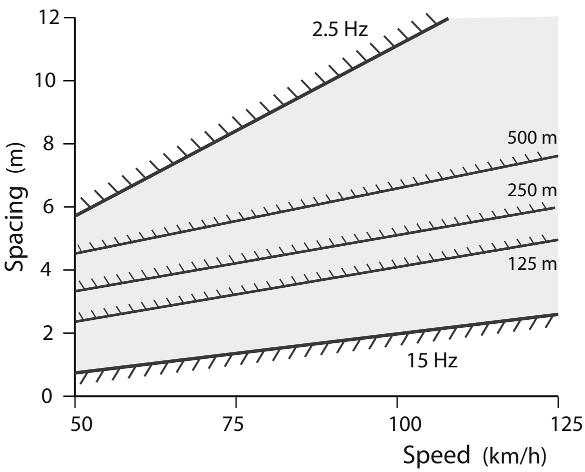


Fig. 20.19 Forbidden luminaire spacing (*shaded areas*) as a function of driving speed to avoid troublesome flicker. Effect of total exposure time characterised by tunnel length based on Walthert (1977)

- the number of flickers occurring per second (flicker frequency),
- the total duration of the flicker, i.e. the total time spent in a flickering environment,
- the photometric properties of the luminaire, especially its peak luminance value and the sharpness of its light distribution.

From laboratory tests in models with light sources moving on a belt towards observers to simulate a moving driver, it became clear that flicker is not disturbing under normal tunnel-lighting conditions so long as the flicker frequency is less than 2.5 Hz (pulses per second) or greater than 15 Hz (Jantzen 1960; Schreuder 1964; Walthert 1977). The disturbance is greatest for the frequency range 5–10 Hz. Flicker frequency is dependent upon the speed of travel through the tunnel and the spacing of the luminaires. The total exposure time to flicker has an influence on the range of frequencies over which the effect will prove troublesome: the shorter the exposure time (viz. the shorter the tunnel), the smaller the range of disturbing frequencies becomes (Walthert 1977). The relation between luminaire spacing and speed needed to avoid the forbidden range of frequencies is given in Fig. 20.19.

In the interior zone, with its permissibly-low lighting level, such a small number of luminaires are often needed that they are spaced some metres apart. As indicated in Fig. 20.20 top, this may easily give frequencies resulting in disturbing flicker for many driving speeds. By positioning the luminaires in groups of three, for example, the flicker problem is avoided for most driving speeds (Fig. 20.20 bottom). At the same time. the spacing-to-height ratio (s/h) is small enough to provide sufficient luminance uniformity on the road.

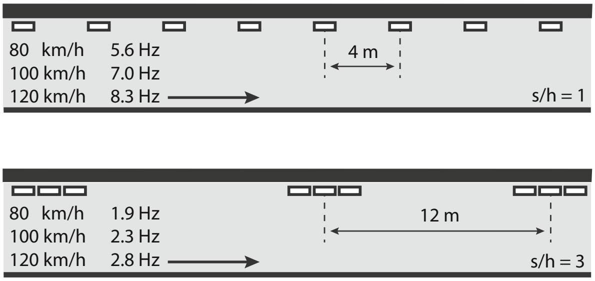


Fig. 20.20 Grouping of luminaires in the interior zone avoids flicker problems

20.8 Night-Time Lighting

As has already been mentioned several times, a tunnel is more dangerous than an open road because in it there is less room available to manoeuvre. Also, motorists often feel less confident when approaching and driving through the tunnel. At night, therefore, the luminance level in the tunnel (both on the road surface and on the lower two metres of the walls) should be no less than that required on the adjacent sections of open road: preferably one step higher (see Sect. 9.1.1 of Part 1). In cases where the adjacent open roads have no lighting, the lighting in the tunnel should be at least 1 cd/m^2. At night, the danger of the black-hole effect occurring at the tunnel exit is present if the open-road leading from the tunnel exit is not lighted. In order to avoid this problem and facilitate adaptation, transition lighting along the open stretch of the road is required. The lighting should cover a stretch of 200 to 300 m and should, in the case of lighting levels in the tunnel greater than 2 cd/m^2, gradually decrease in level, in steps of not greater than 3:1.

Of course, the night-time tunnel lighting should also meet the same uniformity, glare and flicker-restriction requirements as those recommended for the daytime tunnel lighting.

20.9 Emergency Lighting

Stand-by lighting is needed in the event of a sudden technical failure in the electrical installation normally providing the tunnel lighting. Here the task of the emergency lighting is to enable motorised traffic to safely drive to the exit of the tunnel. For this purpose a stand-by, no-break power supply is required that automatically provides uninterrupted electrical power from banks of batteries. This emergency power provision should supply power to a small number of the luminaires providing the normal night-time lighting so as to achieve at least 10 lx average illuminance on the road surface, with a minimum of 2 lx at each individual point on the surface. The duration required of the stand-by emergency supply is dependent upon the length of the tunnel. It goes without saying that proper signalling before the tunnel (to stop traffic entering) and in the tunnel should accompany this emergency lighting.

In the event of an accident in the tunnel that also affects the proper operation of the normal tunnel lighting, emergency lighting is needed. This lighting should give guidance and visibility to enable motorised traffic to leave the tunnel as quickly and as safely as possible. It should also enable people leaving their vehicles to evacuate the tunnel on foot through the tunnel exit or through emergency exits. Emergency lighting for this purpose is often subject to explicit regional and national legal requirements which should be followed. Therefore, only some general guidelines will be given here, which are mainly based on a CIE Guide (CIE 2010). Of course, as with stand-by lighting, the emergency lighting should be uninterruptible. For guidance of motorised traffic to the exit, the same lighting as described above under stand-by lighting conditions is required in case of a sudden power failure. To make emergency lay-bys easily detectable their horizontal lighting level should always be a factor three higher than that on the adjacent carriageway. Having the lay-bys lighted with a visually-different type of lighting system, helps in their detection. In that case a lighting level of only twice that on the adjacent road is needed. For fleeing pedestrians it is important that the stand-by emergency lighting as described above is supplemented with evacuation-route guidance lights. These should be positioned at both sides of the tunnel at a height of less than 1 m to preserve visibility in the case of smoke, and spaced at a distance of less than some 10 m apart. The emergency exits and their immediate surrounds (up to some 2 m from the borders of the exit) should stand out clearly and need therefore a lighting level three to five times the average illuminance level of the adjacent walls. This lighting should also be on during normal operation of the tunnel so as to familiarize all users of the tunnel with the location and situation of the emergency exits. Only in the case of an emergency should green emergency marker lights (preferably flashing), be on, around the exit doors.

20.10 Short Tunnels and Underpasses

20.10.1 Short Tunnels for Motorised Traffic

A tunnel is generally not in need of daytime lighting if the bright exit occupies a quite large part of the field of view when seen from a distance equal to the stopping distance of the motorist (Fig. 20.21). Obstacles in such a tunnel or underpass are silhouetted against this bright exit. If, however, the dark frame round the bright exit is too large, obstacles will become invisible in the absence of extra daytime lighting.

Whether or not obstacles are silhouetted clearly enough against the bright exit depends on the following factors:

- the geometry of the tunnel or underpass, especially the length of the tunnel and whether there are curves and or dips in the tunnel or on the tunnel approach road,
- the distance from which the tunnel is viewed; the greater that distance, is the smaller the dark frame,

Fig. 20.21 A short tunnel with the typical dark frame round the bright centre

- the degree of daylight penetration into the tunnel. Tunnels in open areas with no tall buildings or trees surrounding the tunnel exit have good daylight penetration, whereas exits facing the north have poor daylight penetration compared to other directions. High-reflectance tunnel walls improve daylight penetration,
- the type of possible obstacles; larger cars are, of course, more easily silhouetted against the bright exit than are smaller pedestrians and cyclists. The latter may become easily invisible against the dark frame.

A measure for the geometric and observation distance aspect is the so-called Look-Through Percentage, LTP, defined as the perspective area of the bright exit relative to that of the entrance (Schreuder 1998). In a formula (Fig. 20.22):

$$LTP = 100 * \frac{area\ EFGH}{area\ ABCD}$$

The ceiling area is not taken into account, since obstacles are normally not large enough to be seen against the ceiling as background. Daylight penetrating the tunnel may brighten a small stretch of road surface and walls at the entrance and exit. The depth of the dark frame is therefore shortened: at the entrance with some 5 m and at

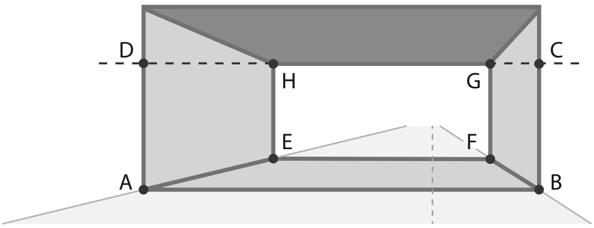


Fig. 20.22 Perspective view of bright exit (*EFGH*) and entrance (*ABCD*) used in the Look-Through Percentage LTP

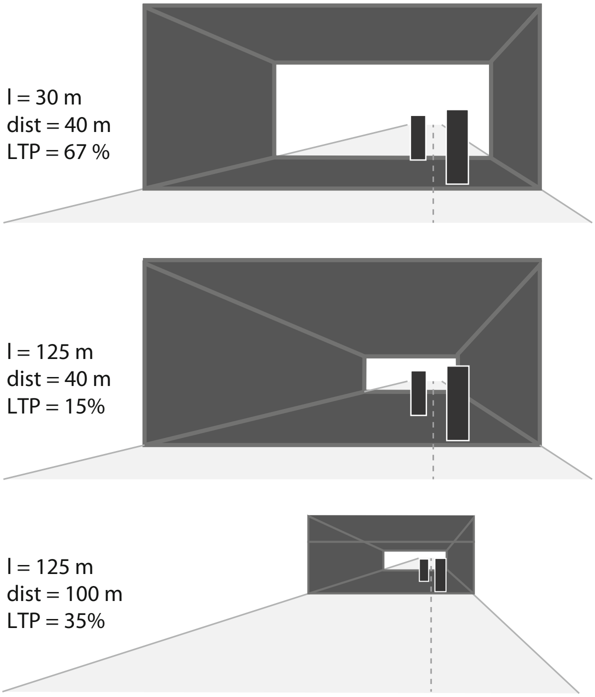


Fig. 20.23 Perspective sketches showing the degree of silhouetting of objects (pedestrians 0.5 x 1.8 m) for different tunnel lengths and viewing distances

the exit with some 10 m. LTP can be used as a criterion to check whether or not a short tunnel or underpass needs daytime lighting:

LTP < 20 : daytime electric lighting required,
LTP > 50 : no daytime electric lighting required.

Whether or not electric lighting is required during the daytime for LTP values in the intermediate 20–50 % range depends on the actual amount of daylight penetration and the types of in-tunnel obstacles that may be expected. Perspective sketches help in analysing the degree of silhouetting of different objects (Fig. 20.23). In this intermediate LTP case, full threshold zone lighting is required there where the analysis shows inadequate silhouetting of critical objects.

20.10.2 Underpasses for Pedestrians and Cyclists Only

Given the relatively-slow speed of pedestrians and cyclists, the delay in adaptation when entering a relatively dark underpass during the hours of daylight is not usually a problem as far as their ability to see possible obstacles is concerned. The lighting levels needed here during the hours of darkness will thus suffice for the daytime situation. However, the security aspect should receive extra attention. Many pedestrians and cyclists feel scared in underpasses and are indeed vulnerable to threats or attacks. An underpass with bright walls and bright exit areas will enable these users to be visually aware of their surroundings, so contributing to a feeling of security. At the same time, this will discourage those with hostile intentions, because they will know that they are easily visible. The apparent brightnesses in an underpass are negatively influenced by the delay in adaptation of the pedestrian or cyclist passing through it. Practical experience has shown that luminances of some 20 cd/m^2 are the minimum needed to create the apparent brightness required. This means that for walls of high reflectance (larger than some 0.60) and for exit areas, an illuminance of some 100 lx is called for. Especially important are those sections of the walls that coincide with the end of the normal viewing lines of pedestrians and cyclists on their way through the tunnel or underpass.

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Chapter 21
Standards and Recommendations

Abstract Many of the research results described in the previous Section have been translated into practical recommendations for tunnel lighting. Often these recommendations are also based on assessments made by committee members in many different existing tunnels with widely different lighting installations. In this Section, first the recommendations for tunnel lighting of the international lighting commission (CIE) will be dealt with. They concern both long tunnels for motorized traffic and short tunnels and underpasses for either motorised traffic or for slow-moving traffic such as pedestrians and cyclists. The CIE recommendation is often referred to in national or local tunnel-lighting recommendations all over the world. An example of this is the North American Standard for tunnel lighting, which will also be described here and which is based partly on former and partly on the most recent CIE recommendation. The focus is on the methods that the standard and recommendation use for specifying tunnel lighting. For the detailed contents reference is made to the relevant publications themselves.

All values specified concern maintained values. These are lighting values that need to be met during the entire lifetime of an installation. The design value of the new installation needs to be determined by taking into account an appropriate maintenance factor to allow for depreciation of the lamps and luminaires (see Sect. 13.5 "Maintenance" of Part 1). For copyright reasons, the Standards and Recommendations are reproduced only in part.

21.1 CIE Recommendation

The latest CIE recommendation for tunnel lighting was published in 2004 and is called "Guide for the lighting of road tunnels and underpasses" (CIE 2004).

21.1.1 Threshold Zone

For the highest lighting level to be installed in the threshold zone the CIE proposes the use of the daylight situation occurring during at least 75 daytime h/year as a basis. For determining the lighting in the threshold zone for that situation, CIE prescribes

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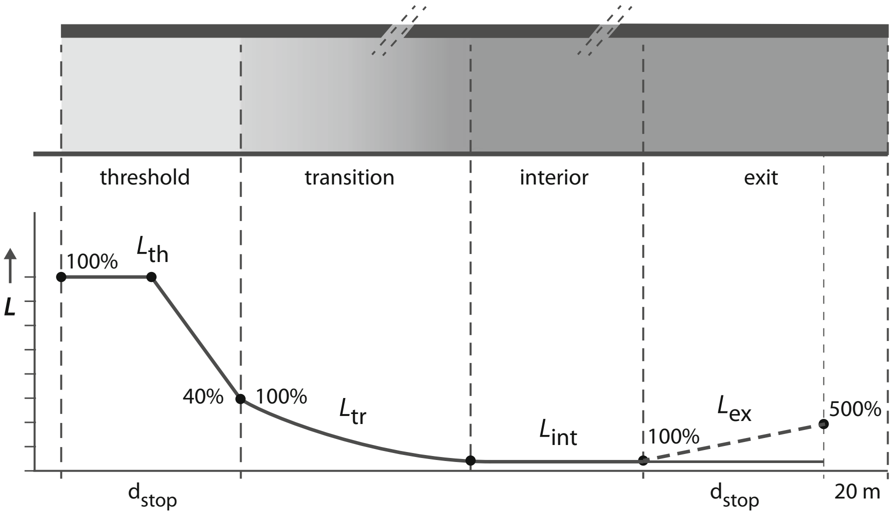

Fig. 21.1 According to CIE (2004), luminance in the threshold zone may decrease linearly from half the stopping distance onwards to 40 %. This 40 % point is subsequently the start of the 100 % point of the transition curve

the "perceived contrast method", which is the method described in Sect. 20.2.6 as the "veiling-luminance concept". The veiling luminances due to scattering in the eye of light from the bright tunnel surroundings, due to scattering in the atmosphere, and due to scattering in the windscreen together determine the lighting required in threshold zone. The formula to calculate this required threshold-zone luminance value from these parameters has already been given in Sect. 20.2.6 under the heading "veiling luminance concept". In this formula, the CIE recommended value for minimum required perceived contrast, C_{perc}, is taken as 0.28 with an object reflectance value (ρ) of 0.20. Again according to CIE, the contrast-revealing coefficient (q_c) is 0.2 for symmetrical and 0.6 for counter-beam systems.

The required length of the threshold zone is equal to the safe-stopping distance. Over the first half of this distance the luminance has to be constant, but from half the stopping distance onwards, the lighting level may linearly decrease to a value, at the end of the threshold zone, of 40 % of the value at the beginning of the threshold zone (Fig. 21.1). Note that graphs of lighting level are often given on a logarithmic scale where the linear line of the linear scale looks curved. The gradual decrease may, in the case of a lighting system with which continuous dimming is not feasible, be done in steps, provided that the luminance levels do not fall below the values corresponding to the gradual linear decrease.

21.1.2 Transition Zone

The reduction of the luminance in the transition zone follows the curve given in Fig. 20.18 of Chap. 20. The 100 % point of this curve coincides with the 40 % point at the end of the threshold zone (Fig. 21.1). In the case of a lighting system with which continuous dimming is not feasible, the smooth curve can be replaced, by a stepped one with levels that never fall below the curve. The maximum difference between each step should be less than a factor of 3, while the last step should be smaller than twice the interior-zone luminance.

21.1.3 Interior Zone

The required lighting level in the interior zone is dependent on the stopping distance (and therefore on the driving speed for which the tunnel is designed) and on the traffic flow. For high-speed tunnels (stopping distance 160 m) and heavy traffic flow, the required lighting level is 10 cd/m^2, while for low-speed tunnels (stopping distance 60 m) and low traffic flow, it is 3 cd/m^2. For very long tunnels (longer than a distance covered in 30 s, e.g. for 100 km/h, some 850 m), the lighting level can, after this distance, be reduced to 4.5 and 1 cd/m^2 respectively.

21.1.4 Exit Zone

Normally, the required lighting level in the exit zone is the same as that in the adjacent interior zone. In situations where additional hazards are expected near the exit of the tunnel, and in very long tunnels, the luminance in the exit zone should increase linearly over a distance equal to the stopping distance to a level of five times that of the adjacent interior zone up to a distance of 20 m from the exit portal (dashed line in Fig. 21.1).

21.1.5 Uniformity and Glare Restriction

The values required for the overall and longitudinal uniformity, U_o and U_l respectively, are the same as required by CIE for open roads during the night time, viz. 0.4 and 0.6 respectively. The average luminance of the walls up to a height of 2 m should be at least 0.6 of the average road-surface luminance.

As far as glare is concerned, CIE requires that the threshold increment value (as described in Sect. 3.1.3 of Part 1) be less than 15 % in all tunnel zones, both during daytime and at night time. For lighting levels greater than 5 cd/m^2, the formula for the calculation of TI is slightly different from the standard formula:

$$TI = 95\left(\frac{L_v}{{L_{av}}^{1,05}}\right)$$

21.1.6 Restriction of Flicker

According to the CIE recommendation, the flicker frequency range between 4 and 11 Hz should be avoided when its duration is longer than 20 s. Comparing this requirement with Fig. 20.19 of Chap. 20 would seem to show that this CIE requirement is not strict enough.

21.1.7 Switching Steps

The adjustment of the lighting levels in the tunnel to the changing outdoor lighting situation can be done through continuous dimming or by switching in steps. The difference between consecutive switching steps should, according to CIE be less than a factor 3.

21.1.8 Night-Time Lighting

If the tunnel is on a section of illuminated road, the quality of the night-time tunnel lighting should be at least the same, in terms of level, uniformity and glare restriction, as that of the road lighting on the open road. The uniformity of the night-time tunnel lighting should never be less than that during daytime.

If the tunnel is on a section of unlit road, the average road-surface luminance in the tunnel should be at least 1 cd/m^2, the overall uniformity U_o at least 0.4 and the longitudinal uniformity U_l at least 0.6.

21.1.9 Short Tunnels

CIE requires that all tunnels longer than 125 m should be treated as long tunnels. For tunnels shorter than 125 m the lighting requirements are dependent on:

- the length of the tunnel,
- whether or not the exit is fully visible from the stopping distance in front of the tunnel,
- whether daylight penetration is good or poor,

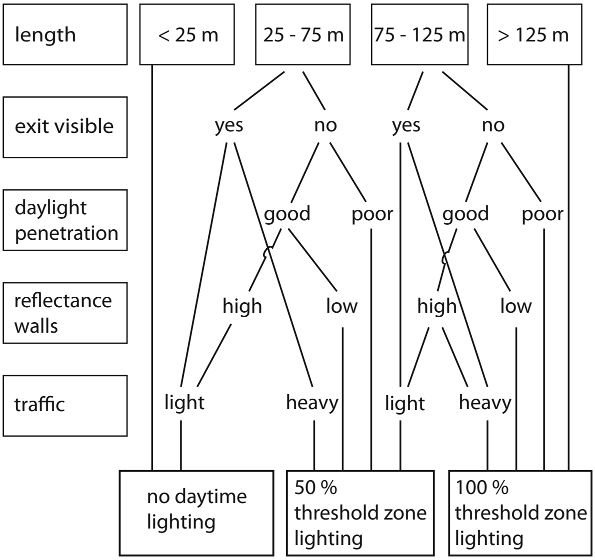

Fig. 21.2 Daytime lighting requirement for short tunnels. (CIE 2004)

- whether the wall reflectance is high (> 0.4) or low (< 0.2),
- whether or not traffic is heavy or includes cyclists or pedestrians.

The requirement for the lighting in accordance with these requirements varies from "no daytime lighting required" or "fifty per cent of normal threshold-zone lighting level required" to "normal threshold zone lighting level required". The normal threshold zone lighting here is that required for long tunnels. Figure 21.2 indicates which combination of the above factors leads to which lighting requirement.

21.2 European Report

The European Committee for Standardization (CEN) has not yet published a Standard on tunnel lighting. In 2003 CEN published a report that covers some common aspects of tunnel lighting and describes some different methods currently in use or under consideration in some European countries (CEN 2003). Most methods discussed are based on research dealt with already in Chap. 20 of this book. No single method is recommended in the report. Since it is not the intention here to discuss national Standards and Recommendations no further details of the CEN report will be given here.

21.3 North American Standard

The American tunnel lighting Standard was laid down in 2011 in Document RP-22-11 of ANSI/IES (American National Standards Institute and Illuminating Society of North America respectively) (ANSI/IES 2011)).

21.3.1 Threshold Zone

The report gives a method for a preliminary estimate of the threshold-zone lighting and a more advanced one for the final determination of the threshold zone. The preliminary method is based on a set of eight sketches of different tunnel scenes, adapted from CIE (CIE 1990). Threshold zone lighting levels are given for each of the eight tunnel scenes according to traffic speed. By comparing an actual tunnel scene with the eight sketches, the most similar sketch thus gives a first estimate of the threshold zone lighting level required.

The more advanced method that has to be used for the final determination of the threshold zone is based on the determination of the veiling luminance, L_{seq}, due to scattering in the eye of light from the bright tunnel surroundings (see Sect. 20.2.6 under "veiling-luminance concept"). The required threshold zone lighting for the resulting L_{seq} value is based on a method described, in an Annex of the former CIE Recommendation for tunnel lighting (CIE 1990). The resulting ratio is in the ANSI/IES Standard given as:

$$\frac{L_{th}}{L_{seq}} = 1.41$$

No difference is made for different lighting systems (symmetrical versus counter beam). The L_{seq} method as used by ANSI/IES does not take into account the effect of atmospheric and windscreen scattering as described in Sect. 20.2.6 under "veiling luminance concept" and as also used in the latest CIE recommendations (CIE 2004). However the ANSI/IES Standard describes this latest CIE method in its Annex B. This Annex concludes with:

> There is much discussion regarding the amount of (apparent) contrast required and transmission factors for the atmosphere and the windshield. Tunnel lighting experts are now trying to determine the best values for these variables and once established will help to better quantify the needed amount of illumination for tunnels.

In the meantime the values used in CIE 2004 have been confirmed in the tunnel lighting practice.

The threshold zone length must be equal to the safe stopping distance measured from the point in front of the tunnel at which the tunnel entrance occupies the entire field of view of the approaching driver. For a tunnel portal height of 4 m and a windscreen screening angle of 22–25° from the roof of the car, this point, called in the Standard "the adaptation point", is 5–7 m in front of the tunnel entrance. As in the CIE recommendation, the lighting level in the first half of the threshold zone has to be constant but over the second half the lighting level may be reduced linearly to 40 % at the end of the threshold zone.

21.3.2 Transition Zone

Exactly as in the CIE Recommendation, the reduction of the luminance in the transition zone follows the curve given in Fig. 20.18. The 100 % point of this curve, again like in CIE, coincides with the 40 % point at the end of the threshold zone. The reduction can be done in steps, provided that the step values never fall below those of the curve. The step lengths should not be less than that corresponding to 2 s driving time.

21.3.3 Interior Zone

The lighting level required in the interior zone is dependent on the traffic speed and traffic flow: again similar to the CIE Recommendation. The values vary from 10 cd/m^2 for high speeds and heavy traffic flow to 3 cd/m^2 for low speeds and light traffic flow: the same range as in CIE.

21.3.4 Exit Zone

No special requirements are specified in the American Standard for the tunnel exit.

21.3.5 Uniformity and Glare Restriction

The luminance uniformity for road surface and walls is specified in terms of average-to-minimum luminance (the reciprocal of CIE's overall uniformity U_o) as better than 2:1, and for the maximum-to-minimum luminance as better than 3.5:1. Contrary to CIE, the latter does not use the maximum and minimum values on a longitudinal line, but the absolute maximum and minimum luminance values wherever they occur.

The glare-restriction requirement is given in terms of the veiling-luminance ratio, L_v/L_{av}, as also used by ANSI/IESNA for open roads during the night time. The value should be less than 0.3, as is also required for freeways and expressways during the night-time.

21.3.6 Restriction of Flicker

The restriction of disturbing flicker is specified exactly the same as in CIE: the frequency range between 4 and 11 Hz should be avoided when the duration is greater than 20 s. As has been stated already when discussing the CIE recommendation, comparing this requirement with Fig. 20.19 of Chap. 20, shows that this requirement does not seem to be strict enough.

21.3.7 Switching Steps

The adjustment of the lighting levels in the tunnel to changing outdoor lighting situations can be done by means of continuous dimming or by switching in steps. The American Standard does not give a quantitative limitation for the difference in consecutive steps but a qualitative one in terms of, "the step difference should be moderated in level and time".

21.3.8 Night-Time Lighting

In tunnels with one-way traffic per tube the night-time average luminance should be at least 2.5 cd/m^2. In tunnels with two-way traffic per tube the average luminance in the tunnel during the night time should be equal to the levels specified for the interior zone for daytime use.

21.3.9 Short Tunnels

Exactly what geometric, surrounding, and traffic factors constitute a short tunnel and what lighting is required for different short tunnels is taken from the 2004 CIE Recommendation. Where CIE uses a decision-tree figure for this purpose (Fig. 21.2), the American Standard has converted this figure into a table with the same values.

References

ANSI/IES (2011) RP22-11, Tunnel lighting
CEN (2003) Report CR 14380, Lighting applications-tunnel lighting
CIE (1990) Publication 88:1990, Guide for the lighting of road tunnels and underpasses
CIE (2004) Publication 88:2004, Guide for the lighting of road tunnels and underpasses

Chapter 22
Equipment and Design Aspects

Abstract For the high lighting levels in the threshold zone, pronounced light distributions in the longitudinal direction are needed, which calls for the use of compact lamps. Tubular high-pressure sodium lamps and LEDs are therefore the lamp types most suitable for the lighting of the threshold zone. For the tunnel zones, where lower lighting levels are needed, viz. the transition and the interior zone, long linear light sources are more advantageous. Many tunnels therefore make use of tubular fluorescent lamps for these zones. However, thanks to the high efficacy and long life of LEDs, these types today offer often a more efficient solution. The most important properties of these lamps and of the luminaires in which they can be used, will be dealt with in this chapter. Daylight screens mounted in front of the tunnel that filter the daylight, can sometimes be an alternative to electric daytime lighting of the threshold zone. Such screening equipment will also be discussed in this chapter.

The importance of appropriate reflection properties of both the road surface and the lower parts of the walls will also be considered.

Also in this chapter, those design aspects that specifically relate to tunnel lighting design will be discussed. This concerns not only guidance for the lighting arrangements, but also for a proper control and maintenance of the installation. The tools to determine the values of L_{20} and L_{seq}, needed to define the required lighting levels of the threshold and consecutive tunnel zones, are also described.

22.1 Lamps and Gear

Figure 22.1 groups those lamps used for tunnel lighting according to the technology involved. Table 22.1 gives a survey of the values of the more important properties of these lamps. The values given are representative for the wattage versions commonly employed in tunnel lighting. Where relevant, the values of the properties include the effect of the electrical gear (Table 22.1).

For the high lighting levels in the threshold zone, lamps with both a high luminous efficacy and a high lumen output are required. This makes the high-pressure sodium lamp suitable for the lighting of the threshold zone. It has a somewhat lower efficacy than that of the low-pressure sodium lamp, but its luminous flux is higher and the lamp is more compact, so permitting of a pronounced, sharp-beam light distribution from a smaller luminaire. This combination of properties means that fewer luminaires

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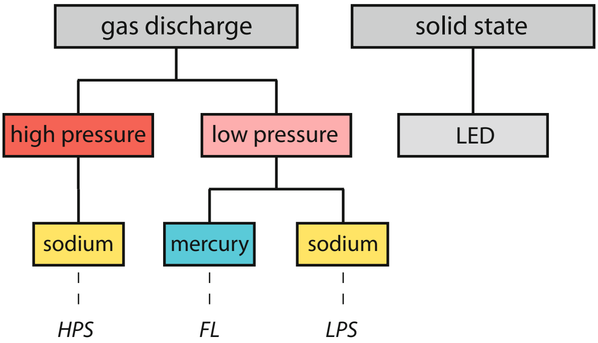


Fig. 22.1 Grouping of gas-discharge and solid-state light sources according to technology

are needed and less space in the tunnel ceiling is occupied. The same is possible with a compact array of white LEDs. Here an added advantage is the extremely-long lifetime of the light source. LEDs were initially introduced in tunnel lighting for use in the interior zone. With the further rise in both efficacy and lumen output of LEDs, they are now also suitable for the high-level lighting required in the threshold zone.

For the tunnel zones where lower lighting levels and thus fewer luminaires are needed, viz. the transition, and interior zones, long linear light sources are more suitable. These allow for continuous or near-continuous rows of light with which it is relatively easy to throw the light across the tunnel. They also help to improve visual guidance and they minimize flicker problems. The low-pressure sodium lamp, in spite of its long, linear shape, is nevertheless not suitable for use in the interior zone because its lumen output is too high for the low lighting levels required. This is

Table 22.1 Survey of characteristics of commercially-available light sources employed in tunnel lighting: luminous efficacy (lm/W), correlated colour temperature T_k, colour rendering index R_a, lifetime in hours (based on 20 % mortality)

Lamp type	lm/W	Lumen range (klumen)	T_k	R_a	Lifetime	Shape
High-pressure sodium (tubular) HPS	120–140	15–150	2000	25	20,000	Compact
Tubular fluorescent FL	70–90	3–6	4000	80	15–20,000	Long linear
Low-pressure sodium LPS	150–190	8–32	1700	0	15,000	Long linear
LED (white) single LED	80–150	< 1	3000–5000	60–90	35–50,000	Point source
LED (white) multitude LEDs	80–150	1–15	3000–5000	60–90	35–50,000	Compact or long linear

Fig. 22.2 Example of a longitudinal LED tunnel-lighting luminaire

why many tunnels make use of tubular fluorescent lamps for the interior zone. Solid-state LED light sources combine a high efficacy and extremely long life and can also be produced in long linear versions by mounting multiple LED points in a long flat or round shape (Fig. 22.2). LEDs permits the development of flat luminaire shapes so that the lighting will call for less space in the tunnel. The installation costs with such compact luminaires are reduced as well. Thanks to solid-state technology, the LED is also a robust solution that can withstand a tunnel's hostile environment with greater resistance to shock and vibration than can conventional solutions. LEDs can be instantly switched and easily dimmed to accurately suit varying daylight and night-time conditions. This means that overlighting is avoided and energy consumption is reduced. Also, the extremely long life of LEDs reduces both initial and maintenance costs.

Gas-discharge and solid-state lamps cannot function properly when they are operated directly from the mains-supply voltage. They need control gear to ensure that the lamp can be started (gas-discharge lamps); that it can be operated stably over a longer period; and, if the lamp type permits of it, that it can be dimmed. The control devices needed are called igniters, ballasts and dimmers. The electrical control gear employed with solid-state lamps is usually referred to as a driver. Section 10.4 of Part 1 gave detailed information on electrical gear.

22.2 Luminaires

The general aspects of outdoor luminaires are dealt with in Chap. 11 of Part 1 of this book. Here we shall describe specific aspects of tunnel-lighting luminaires.

Tunnel-lighting luminaires can be divided into two groups according to their light distribution in a vertical plane parallel to the tunnel axis: symmetrical and asymmetrical luminaires. Those in the latter group are employed when counter-beam

Fig. 22.3 Open non-sunlight daylight screens

or pro-beam systems are chosen for use in the threshold zone (see Fig. 20.4). For asymmetrical luminaires, especially, to be sufficiently compact, small light sources are required: sources such as the tubular high-pressure sodium lamps and high-lumen package LEDs. For most of the transition zone and for the interior zone, symmetrical luminaires are employed.

Tunnel-lighting luminaires are either wall mounted or ceiling mounted. Because of the limited space available in tunnels, the height of the luminaire is especially critical. Whatever type of mounting and light distribution is chosen, the luminaire and its light distribution have to be fine-tuned for the actual tunnel width and tunnel height in question. Furthermore, different types of lamps and thus different luminaires are often needed for the different tunnel zones. Modular luminaire designs that allow for flexibility in lamp and optics combinations in one and the same housing are therefore useful.

Tunnel-lighting luminaires should be easy to clean, robust, and proof against corrosion from soiling. Their water resistance should be at least as specified by the classification “jet proof” i.e. IP65.

22.3 Daylight Screens

An alternative to the electric daytime lighting of the threshold zone is to employ a canopy in front of the tunnel with daylight screens that filter the daylight to the level normally required for this zone. The electric lighting in the first part of the tunnel itself then need only satisfy the lower lighting-level requirements of the transition zone. Such screens can, of course, save considerable electrical energy, but they have some disadvantages as well. Closed screens of translucent material cannot be cleaned often enough and well enough to provide a sufficiently-constant light transmission. This is why only open screens, which usually consist of a light-weight aluminium structure, are employed (Fig. 22.3). Open screens are usually of light-weight aluminium structure.

In principal, such screens can be designed such that, for the locally-occurring sunlight directions, direct sunlight is prevented from striking the road, so preventing the creation of disturbing dark-and-bright patterns on the road surface underneath the screens. However, these so-called sun-tight screens are now scarcely ever employed because their transmission quickly deteriorates due to the accumulation of dirt on the many diffusely-reflecting surfaces, and they are difficult to clean. So this leaves the open, non-sun-tight, daylight screens with their associated disadvantage of producing dark-bright patterns on the road in front of the driver as illustrated in Fig. 22.3. To reduce this problem to some extent it is recommended that the screens be so designed that the dark-bright pattern falls mainly across the road, as in the example of Fig. 22.3, and not along the road, where it would create also a severe flicker problem. The light transmission percentage of screens varies with varying sky conditions. It is therefore important that the average lighting level under the screens be continuously measured and the results used to control the electric lighting in the first part of the actual tunnel.

22.4 Road and Wall Surface

The reflectance of both the road surface and the lower parts of the walls should be high. Their luminance is determined by the amount of light directed towards them from the lamps and luminaires and reflected by them in the direction of the motorist. Higher reflectances thus means that less light is required to provide the required luminances. For the road surface an average luminance coefficient, Q_0, of at least 0.1 is recommended. Furthermore, the road surface should not reflect too diffusely. Such a road surface minimises backwards reflection towards small objects and the lower parts of larger objects, so that the silhouette effect, for symmetrical systems and especially for counter-beam systems, is not disturbed too much. As was described in Sect. 20.2.2 this backwards reflection from the road surface in fact lowers the contrast-revealing coefficient, q_c.

The walls of the tunnel have to be bright: not only because they form the background for larger objects in the tunnel but, if bright enough, also act as visual guidance for motorists both outside and inside the tunnel. Reflectances of 0.60–0.70 are recommended. In order to maintain the high reflectance, such tunnel walls should have a surface finish that facilitates cleaning.

22.5 Design Aspects

Common aspects of designing lighting installations based on the luminances of the road surface are dealt with in Chap. 13 of Part 1. In the present section those aspects that specifically relate to tunnel lighting design will be discussed.

The foremost and probably also the most important task in designing a tunnel-lighting installation is the determination of the highest lighting level to be installed in the threshold zone of the tunnel. The highest lighting levels to be installed in all the following zones will depend on this threshold-zone level. Tools will be described that are needed to facilitate the determination of this level in practice for tunnels that are already in place as well as for tunnels still in the design or construction phase.

Guidelines on the arrangement of the luminaires, on lighting control in response to varying daylight situations, and the all-important subject of maintenance will be given in a further part of this section.

22.5.1 *Tools for the Determination of L_{20} and L_{seq}*

As has been discussed in detail in Sect. 20.2, different concepts have been developed to determine the required threshold-zone luminance level corresponding to the brightest daylight situation occurring at least 75 h annually (75 h being recommended by CIE).

The two most important concepts are the L_{20} and L_{seq} concepts. In the case of existing tunnels, the values of L_{20} or L_{seq} can be measured on site with appropriate measuring equipment. However, it is difficult, if not impossible, to measure at the moment when the "75 h daylight situation" happens to occur. It is therefore more realistic to determine the values of L_{20} or L_{seq} based on photographs or, in the case of tunnels yet to be constructed, on perspective drawings of the tunnel as seen by the approaching motorist from a safe stopping distance in front of the tunnel. The luminance values of the different surfaces surrounding the tunnel entrance occurring at the moment of the "75 h daylight situation" can, for example, be obtained from Sect. 20.2.1 "Daylight Luminances in the Access Zone" (Table 20.1). This then forms the basis for the determination of both L_{20} and L_{seq}.

22.5.1.1 Determination of L_{20}

A 20° circle is drawn on the tunnel photograph or drawing, scaled from the perspective of the safe stopping distance. The known height of the tunnel entrance can be the basis for sizing the 20° circle. An example of the result is shown in Fig. 22.4. From the photograph or drawing the percentage (p) in the 20° circle of the sky, of the road surface and of the different types of surrounding surfaces is determined. L_{20} follows from the formula:

$$L_{20} = p_{sky} * L_{sky} + p_{road} * L_{road} + p_{grass} * L_{grass} + p_{mountain} * L_{mountain}$$

The values of the sky, road, grass and mountain luminances can then be taken from Table 20.1.

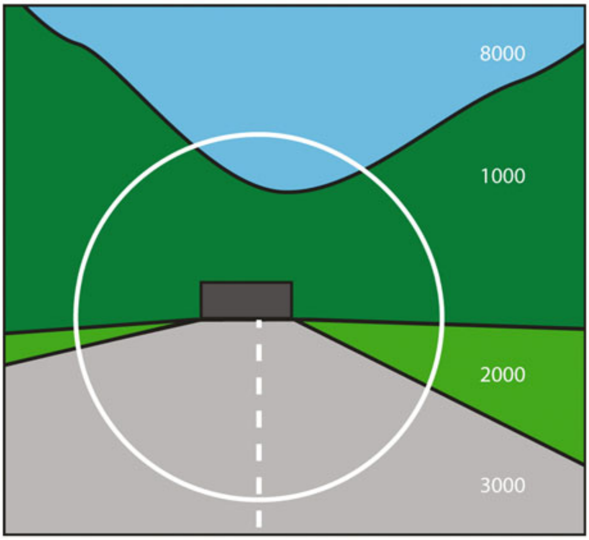


Fig. 22.4 Perspective drawing of a tunnel entrance with 20° circle projected from the safe stopping distance

22.5.1.2 Determination of L_{seq}

The recommended concept of CIE for the determination of the threshold-zone level is the L_{seq} concept. The photograph or perspective drawing of the tunnel entrance surround as seen from the safe stopping distance, described in the previous section for L_{20} use, can also be used for the determination of $L_{seq.}$ A polar diagram has been developed (Adrian 1987), and is published by CIE (CIE 2004), that can be superimposed on the tunnel photograph or drawing. It divides the tunnel drawing or photograph into segments and concentric circle parts (Fig. 22.5). The sizes of the consecutive circle parts have been determined such that, for equal luminances, each area produces the same veiling luminance. It is now easy to determine in each part the percentages of the actually-occurring luminances and so form the average luminance for that segment. The total veiling luminance L_{seq} caused by all segments is then obtained by summing the contributions from all segments:

$$L_{seq} = 5{,}1.\ 10^{-4} \sum L_{segment\ i}$$

Again, the luminances of the different segments such as sky, road, grass and mountain, can be taken from Table 20.1. This is a simple process which can relatively quickly be executed with the use of a spreadsheet.

22.5.2 *Lighting Arrangement*

With symmetrical tunnel-lighting installations the light comes from one or more rows of luminaires, depending on the lighting levels needed. These are usually

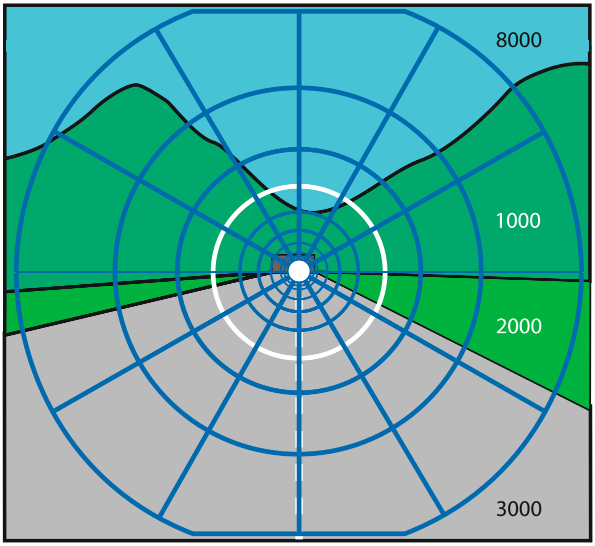


Fig. 22.5 Perspective drawing of a tunnel entrance as seen from the safe stopping distance with polar diagram with segments producing equal veiling luminances. *White circle* coincides with 20° circle

concentrated above the centre of the carriageway or above each of the carriageways (Fig. 22.6 top). In such central arrangement, which is always employed for counter-beam systems, the luminous-intensity distribution across the road is symmetrical or slightly asymmetrical. However, it may be that the height of the ceiling is insufficient to permit of a central arrangement or that the ceiling void is needed for ventilation purposes. In such cases, the ceiling-mounted side arrangement is the next best choice (Fig. 22.6 middle). Here, the luminous intensity distribution across the road has to be more asymmetrical in order to provide sufficient luminance in the middle part of the tunnel. The side arrangement can be some 25–50 % less efficient in terms of road-surface luminance yield (cd/m^2 per lumen installed per metre length of tunnel) than the central arrangement. Counter-beam systems in a side arrangement have a still lower efficiency and are therefore not normally employed. When, for reasons of space, a wall-mounted arrangement is the only solution (Fig. 22.6 bottom), strongly-asymmetrical luminous-intensity distributions across the tunnel are required. The efficiency is consequently being lowered even further. With the wall-mounted arrangement it is difficult to provide sufficient luminance low down on the tunnel walls. Continuous light tubes on both sides of the tunnel have the advantage that they provide a feeling of width, which is positive for the sense of confidence of the drivers. Maintenance operations require only one lane to be blocked.

In the threshold and transition zones the lighting levels required are so high that the luminaires are usually mounted in a continuous or near-continuous row. In the interior zone, where relatively low lighting levels are required, the luminaires can often be spaced at greater distances. The designer should then take care that for normally-occurring driving speeds the luminaire spacing does not result in disturbing flicker, as discussed in Sect. 20.7. As has also been explained in that section, the grouping

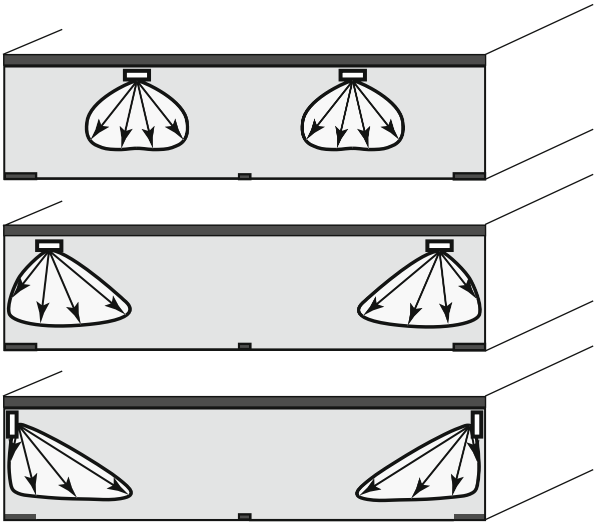


Fig. 22.6 Lighting arrangements and corresponding light distributions

of some three or four luminaires can often solve potential flicker problems in the interior zone.

22.5.3 Daylight Variation and Lighting Control

As has already been discussed, a tunnel-lighting installation should be laid out to satisfy the lighting requirements relevant to the highest daylight levels regularly prevailing. This means, of course, that when daylight levels are lower, the tunnel lighting has to be switched or dimmed to a lower level. In many older tunnels, this is done in response to signals received from photocells, which monitor the daylight illuminance level at the entrance. However, this can sometimes lead to tunnel lighting that does not satisfy the visibility and sense of confidence requirements.

The luminance in the threshold zone of a tunnel must at all times be an appropriate specified percentage of the value of L_{20} or L_{seq}, or at least of some quantity closely related to it. For this purpose luminance meters have to be employed, one at each tunnel entrance, mounted as close as possible to the stop-decision point and facing in the direction of the tunnel entrance. From the continuously-measured values that these meters send back, the luminances required in the threshold zone at each moment are determined. A control system then provides the required lighting steps in the various tunnel zones. If the installation allows for dimming, the luminance levels determined in this way are obtained by continuous dimming. It is then possible, with a more advanced control system, to keep the actual required ratio of L_{th}/L_{20} or L_{th}/L_{seq} constant. For this to be possible, an additional luminance meter in the threshold zone (and sometimes in other zones as well) measures the actual luminance obtained from the electric lighting. If the installation is switched in a stepwise manner, the reduction to lower levels and the increase to higher levels is made in steps of no greater than 3:1 and 1:3 respectively. This is in order to avoid too large and too sudden changes in the lighting, which could startle drivers at the moment of switching. Some five to six such switching steps are required to go from the highest level to the night-time level.

The requirements for uniformity, glare and flicker restriction, as given in previous sections, should be met for all switching steps.

22.5.4 Maintenance

A great deal of dust and grime, including leaking fuel and oil, is brought into a tunnel by the traffic passing through it. And there is no rain to help wash away all this dirt. In addition, the exhaust fumes of the vehicles contain quantities of unburnt carbon particles. All this may reduce visibility in the tunnel and will certainly produce soiling of the luminaires, daylight screens and light-reflecting surfaces (e.g. road surface and walls). This can bring about a rapid deterioration in the various luminances and so add further to the worsening of the visibility.

All the maintenance aspects for outdoor lighting that have been dealt with in Sect. 13.5 of Part 1, are also very relevant for tunnel lighting. But cleaning has to be more frequent for tunnel lighting than for normal, open-road lighting. As to the method of cleaning the luminaires, washing them with a mechanical scrubber yields better results than does water-jet cleaning alone. Quite a number of tunnels are cleaned by special vehicles designed solely for this purpose. It need hardly be added, that the luminaires should be easy to clean, robust (mechanical scrubbers can be vigorous in operation), and proof against corrosion from soiling. Their water resistance should at least be as specified by the classification "jet proof" i.e. IP65. The tunnel walls should have a surface finish that facilitates cleaning.

The photometers mounted in the access zone, and sometimes also in other tunnel zones that control the lighting, have to be checked and cleaned as well.

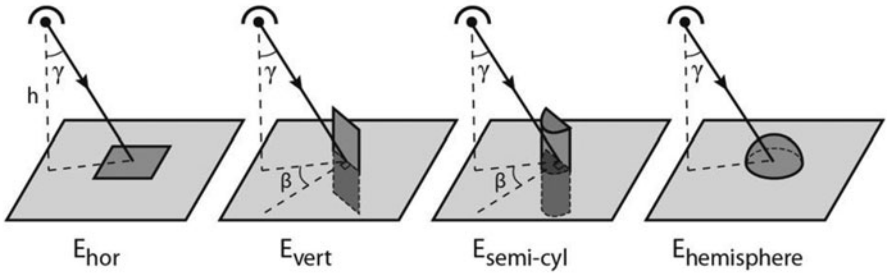
References

AdrianW (1987) Adaptation luminance when approaching a tunnel in daytime. Light Res Technol 19(3):73–79

CIE (2004) Publication 88:2004, Guide for the lighting of road tunnels and underpasses

Appendix

Appendix A Illuminance Formulas



*Horizontal illuminance, E*hor

$$E_{hor} = \frac{I}{h^2} \times cos^3\gamma$$

*Vertical illuminance, E*vert

$$E_{vert} = \frac{I}{h^2} \times sin\gamma \times cos^2\gamma \times cos\beta$$

*Semi-cylindrical illuminance, E*semi−cyl

$$E_{semi-cyl} = \frac{I}{\pi \times h^2} \times sin\gamma \times cos^2\gamma \times (1 + cos\beta)$$

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Hemisperical illuminance, $E_{\text{hemisphere}}$

$$E_{hemisphere} = \frac{I}{4 \times h^2} \times cos^2\gamma \times (1 + cos\gamma)$$

Appendix B Visibility Formulas

Contrast Threshold

According to Adrian, reference: (Adrian 1989) of Chap. 3.

Contrast Threshold, C_{th}

$$C_{th} = \frac{2.6}{L_b} \times \left\{ \left(\frac{b}{\alpha} \right) + c \right\}^2 \times F_{cp} \times AF \times T_{obs}$$

where:

L_b	= background luminance (cd/m^2)
α	= visual angle under which object is seen (min)
F_{cp}	= contrast polarity factor
AF	= age factor
T_{obs}	= observation time factor
b and c	= intermediate calculation functions[1]

for $L_b \geq 0.6$:

$$b = \log\left(4.2841 \times L_b^{0.1556}\right) + 0.1684 \times L_b^{0.5867}$$

$$c = 0.05946 \times L_b^{0.466}$$

for $0.0042 < L_b < 0.6$:

$$b = 10^{-0.072 + 0.3372 \times \log(L_b) + 0.0866 \times \{\log(L_b)\}^2}$$

$$c = 10^{-1.256 + 0.319 \times \log(L_b)}$$

[1] In the calculation function b, the first value, 4.2841, has been changed slightly from Adrian's original value of 4.1925 in order to have for $L_b = 0.6$ a same b-value for both b-formulas. The new value is the same as that specified by ANSI/IES.

Contrast Polarity Factor, F_{cp}

$$F_{cp} = 1 - \frac{d \times \alpha^{-e}}{2.4 \times C_{th,poscontrast} \times L_b}$$

where:

α = visual angle under which object is seen (min)
d and e = intermediate calculation functions

for $L_b \geq 0.1$:

$$d = 10^{-10^{-[0.125 \times \{\log(L_b)\}^2 + 0.0245]}}$$

$$e = 0.6 * L_b^{-0.1488}$$

Age Factor, AF

AF = 1 for age = 23
for 23 < age ≤ 64:

$$AF = \frac{(age - 19)^2}{2160} + 0.99$$

for 64 < age ≤ 75:

$$AF = \frac{(age - 56.6)^2}{116.3} + 1.43$$

Observation Time Factor, T_{obs}

$$T_{obs} = \frac{f + t}{t}$$

where:

t = observation time (sec)
T_{obs} = 1 for t = 2
f = intermediate calculation function

$$f = \frac{(g^2 + h^2)^{0.5}}{2.1}$$

where:

g and h = intermediate calculation functions

$$g = 0.36 - 0.0972 \times \frac{\{\log(\alpha) + 0.523\}^2}{\{\log(\alpha) + 0.523\}^2 - 2.513 \times \{\log(\alpha) + 0.523\} + 2.7895}$$

$$h = 0.355 - 0.1217 \times \frac{\{\log(L_b) + 6\}^2}{\{\log(L_b) + 6\}^2 - 10.4 \times \{\log(L_b) + 6\} + 52.28}$$

Visibility Level

Visibility Level, VL

$$VL = \frac{C_{actual}}{C_{th}} = \frac{\Delta L_{actual}}{\Delta L_{th}}$$

where:

C_{th} = threshold contrast
ΔL = luminance difference between object and background

Small Target Visibility, STV

According to ANSI/IES, reference (ANSI/IES 2000) of Chap. 3.

$$STV = -10 \times log\left[\frac{\sum 10^{\{-0.1 \times ABS(VL)\}}}{n}\right]$$

where:

VL = visibility level of a grid point
ABS = absolute value
n = number of grid points

Relative Visual Performance

According to Rea and Ouellette, reference (Rea and Ouellette 1991) of Chap. 3.

Go through step 1–7 to calculate relative visual performance RVT. The actual meaning of the parameters to be calculated in the different steps are given in reference (Rea and Ouellette 1991) of Chap. 3. Here we treat these parameters just as intermediate calculation functions.

- Step1

$$I_{R'} = P * L_A * \pi * r^2$$

where:

L_A = adaptation luminance in cd/m^2 (with glare: add veiling luminance, L_v)

$$r = 2.39 - \{1.22 * \tanh(0.3 * \log L_A)\}$$

$$P = 1 - 0.017 * (a - 20)$$

where:

a = age of observer for 20–65 years

- Step 2

$$C'_{t,d} = \varepsilon * 10^{(-1.364-0.179*A-0.813*L+0,226*A^2-0.0772*L^2+0.169*A*L)}$$

where:

$$A = logtanh(20000 * \omega)$$

$$L = loglog\left(10 * \frac{I_{R'}}{\pi}\right)$$

$$\varepsilon = 1 + (0.00251) * (a - 20)$$

where:

ω = area of the object in steradians

- Step 3

$$K = 10^{(-1.763-0.175*A^*-0.0310*L^*+0.112*A^{*2}+0.171*L^{*2}+0.0622*A^**L^*)}$$

$$A^* = logtanh(5000 * \omega)$$

$$L^* = logtanh\left(0.04 * \frac{I_{R'}}{\pi}\right)$$

- Step 4

$$R_{max} = 0.000196 * log I_{R'} + 0.0027$$

- Step 5

$$RT = \frac{\Delta C_d^{0.97} + K^{0.97}}{\Delta C_d^{0.97} * R_{max}}$$

$$\Delta C_d = C_v - C'_{t,d}; \Delta C_d > 0$$

$$C_v = \frac{|L_B - L_T|}{L_B} = \frac{|E_v * \rho/\pi - L_T|}{L_B}$$

with glare:

$$C_v = C_v * \frac{L_B}{L_B + L_v}$$

where:

L_B = background luminance in cd/m^2
L_T = target (object) luminance in cd/m^2
L_v = veiling luminance in cd/m^2
E_v = vertical illuminance on object in lux
P = reflectance factor of object

- Step 6

$$\Delta T_{vis} = 305.4 - RT$$

- Step 7

$$RVP = 0.998 * \left(\frac{\Delta T_{vis} + 800}{777} \right)$$

$$RVP < 0 \rightarrow RVP = 0 \; RVP > 1 \rightarrow RVP = 1$$

Appendix C Calculation of Q_0 from R-tables

Each R-value is multiplied by the corresponding weighting factor, given in the Table below, and by tan γ. The resulting values are added and the sum scaled by dividing by $9.936.10^7$. The scaling factor is needed because R-tables are standardized to be valid for a Q_0 value of 1, the actual Q_0 value being given as a separate value belonging to the R-table. So, for road surface luminance calculations the actual Q_0 value of the road surface has to be applied as a multiplying factor.

β (°) / tanγ	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0.00	8	8	32	22	40	20	40	30	40	25	45	120	60	120	60	120	60	120	60	60
0.25	32	32	128	88	160	80	160	80	160	100	180	480	240	480	240	480	240	480	240	240
0.50	16	16	64	44	80	40	80	40	80	50	90	240	120	240	120	240	120	240	120	120
0.75	32	32	128	88	160	80	160	80	160	100	180	480	240	480	240	480	240	480	240	240
1.00	16	16	64	44	80	40	80	40	80	50	90	240	120	240	120	240	120	240	120	120
1.25	32	32	128	88	160	80	160	80	160	100	180	480	240	480	240	480	240	480	240	240
1.50	16	16	64	44	80	40	80	40	80	50	90	240	120	240	120	240	120	240	120	120
1.75	32	32	128	88	160	80	160	80	160	100	180	480	240	480	240	480	240	480	240	240
2.00	24	24	96	66	120	60	120	60	120	75	135	360	180	360	180	360	180	360	180	180
2.50	64	64	256	176	320	160	320	160	320	200	360	960	480	960	480	969	480	960	480	480
3.00	32	32	128	88	160	80	160	80	160	100	180	480	240	480	240	480	240	480	240	240
3.50	64	64	256	176	320	160	320	160	320	200	120	270	33	0	-30	690	480	960	480	480
4.00	32	32	128	88	160	80	160	80	160	100	60	0	0	0	-75	-30	255	510	222	120
4.50	64	64	256	176	320	160	320	160	320	155	75	0	0	0	0	0	135	372	33	0
5.00	32	32	128	88	160	80	160	105	125	5	-15	0	0	0	0	0	0	33	0	0
5.50	64	64	256	176	320	160	320	170	90	0										
6.00	32	32	128	88	160	80	160	40	0											
6.50	64	64	256	176	320	160	275	35												
7.00	32	32	128	88	160	105	80	-25												
7.50	64	64	256	176	320	170	90													
8.00	32	32	128	88	160	85	45													
8.50	64	64	256	176	320	80	0													
9.00	32	32	128	88	160	40														
9.50	64	64	256	176	320	80														
10.00	32	32	128	88	115	-5														
10.50	64	64	256	176	230	-10														
11.00	32	32	128	113	80	-25														
11.50	64	64	256	186	90															
12.00	16	16	64	69	45															

Weighting factors for the calculation of Q_0 from R-tables as given in CIE Publication 44:2001

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