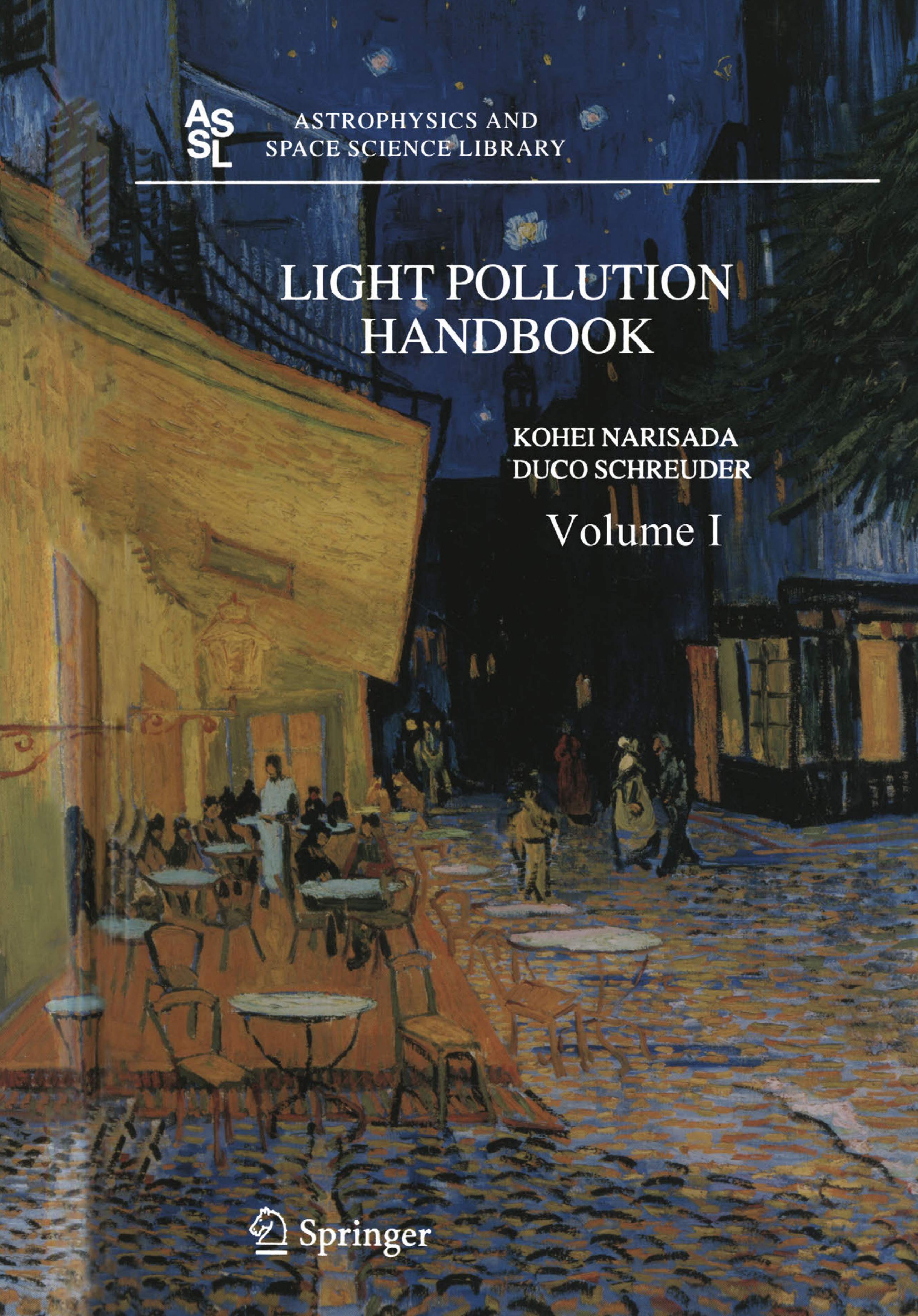

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LIGHT POLLUTION HANDBOOK

KOHEI NARISADA
DUCO SCHREUDER

Volume I

Springer

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VOLUME 322

LIGHT POLLUTION HANDBOOK

by

KOHEI NARISADA

and

DUCO SCHREUDER

Springer

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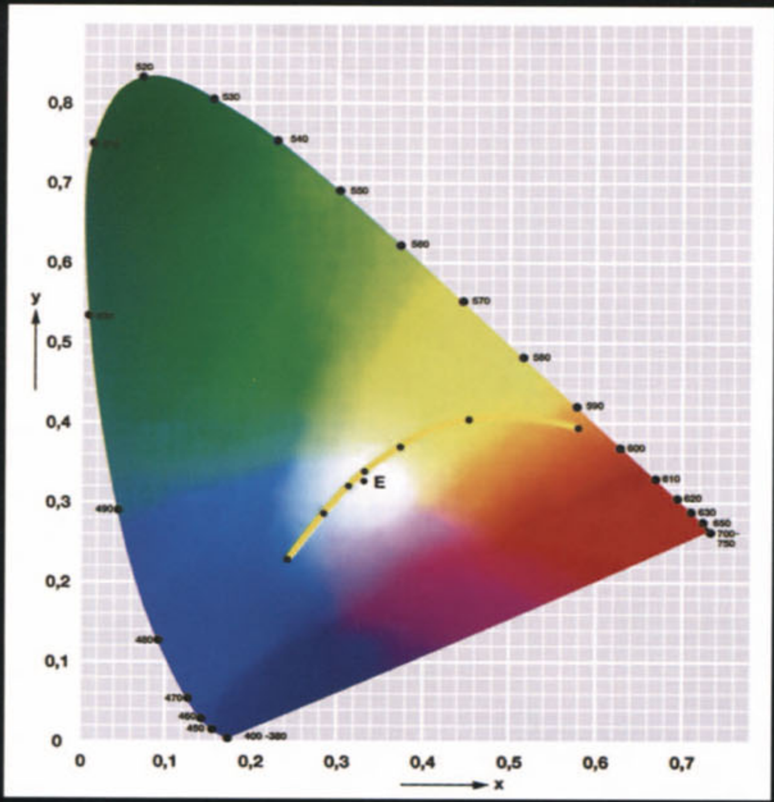

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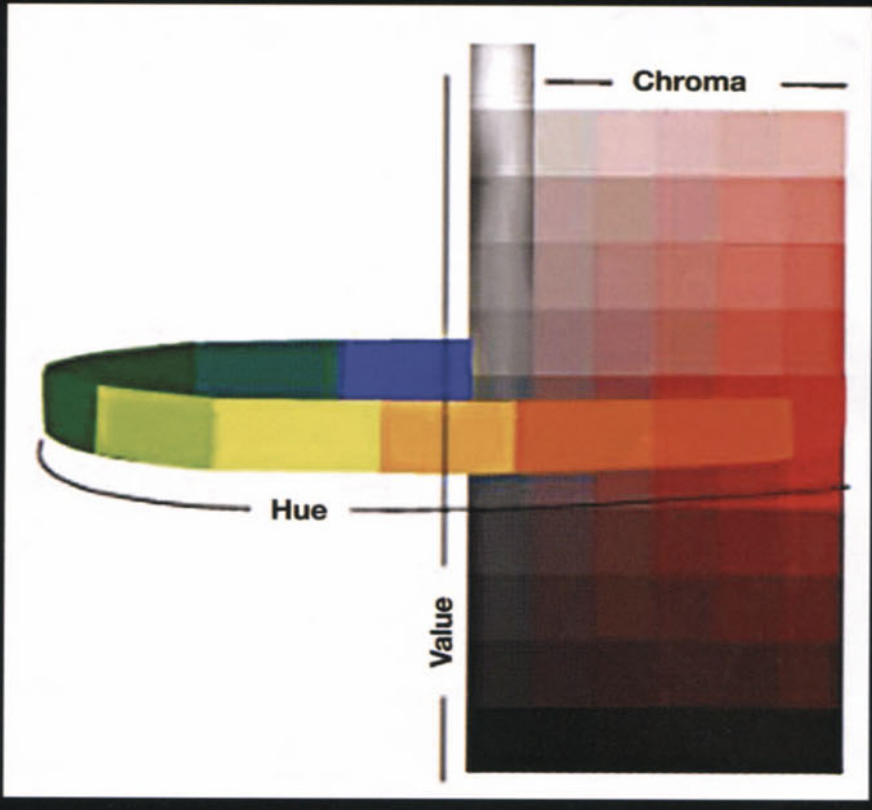

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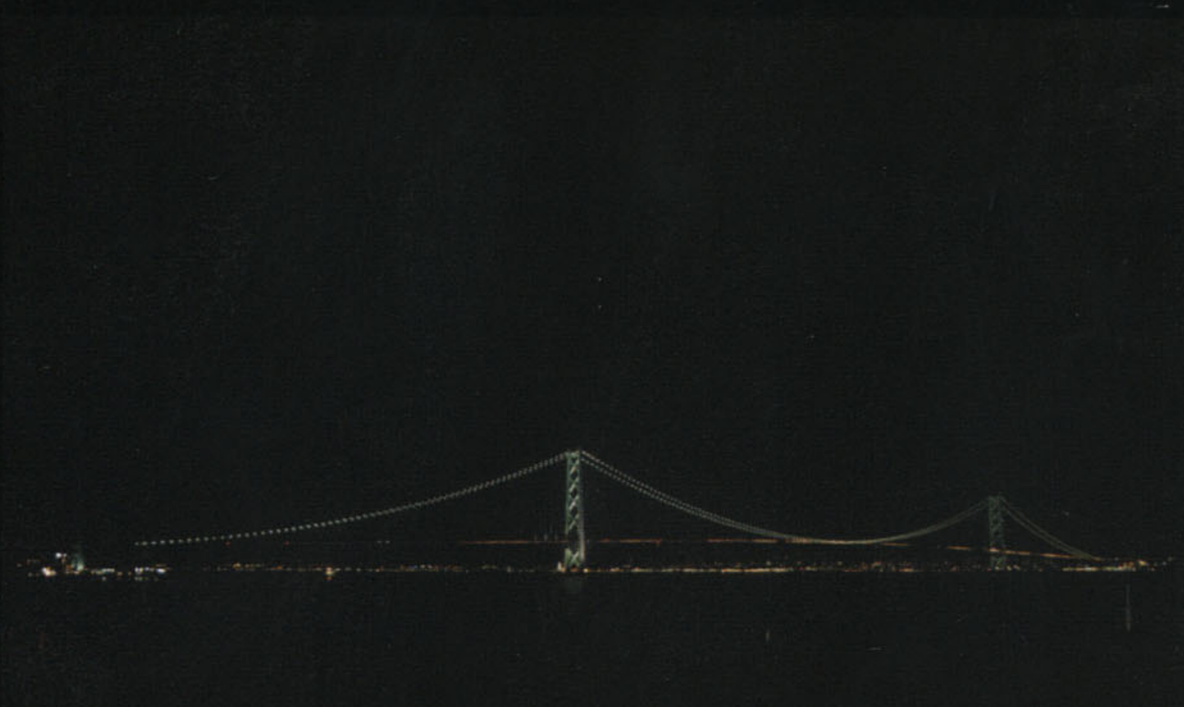
Road lighting with CIE cut-off lanterns

Outdoor lighting of Shirakawago village, Japan. A World Cultural Asset

Decorative lighting for the historical port of Moji, Japan



Illumination for Akashi-Kaiko bridge, Japan.
With 3911 m the longest suspension bridge in the world

Preface

This book deals with light pollution and about the ways to reduce it. Light pollution is one of the negative side-effects of artificial outdoor lighting. The term light pollution is an unhappy one, but as no better alternative seems to exist, it will be used throughout this book.
The function of all outdoor lighting is to enhance the visibility or the aesthetics in the nighttime environment. The light should come where it is needed. If not, it is spilled, causing economic and environmental losses as well as disturbance and discomfort. The overall effects are termed 'light pollution'; a major form of light pollution is the glow extending over the night sky.
Sky glow is discussed in many astronomical textbooks and in many popular brochures. The present book is primarily aimed at those responsible for outdoor lighting installations. Thus, an engineering approach has been chosen. The level of the book is that of 'college' or 'University level'. The book is organized in two parts. The first seven chapters cover the areas of general interest, and conclude with recommendations. The second part deals with the scientific and engineering elaboration of the first part. A number of examples are included that refer to specific outdoor lighting installations and projects that are directly related to the reduction of light pollution. Finally, some information is given about the authors.

(a) About light pollution

This book deals with light pollution. It is understood that light pollution is one of the negative side-effects of outdoor lighting. As is explained in several chapters of this book, outdoor lighting is essential for our type of society to survive. The side-effects are real. It is one of the objectives of this book, to show that they can be reduced by technical and organizational methods, so that the disturbance caused by light pollution can be lessened.

A point that must be made clear right from the beginning, is the use of the term 'light pollution'. To begin with, the term is actually a mishap, probably originating from the similarity in words with 'air pollution' and 'water pollution'. In these cases, it is the air or the water that gets dirty. Light cannot, in the same way, get dirty. As is explained in several chapters of this book, light is not only beneficial, but it is essential for all life on Earth. As mentioned already, there are negative side-effects. Whether the side-effects must be regarded as 'pollution', however, depends on the concepts of nature, the environment and of the 'human condition' that are favoured.

(b) About the book

This book deals with light pollution in a very general sense. Its nature of a 'handbook' implies that most effects of light pollution will be discussed. Some details are not discussed; they will be indicated later in this section. The emphasis is on those aspects of light pollution that interfere with astronomical observations. As will be explained later-on, astronomers are a major victim-group of light pollution.

As is explained earlier, light pollution is one of the negative side-effects of artificial outdoor lighting. The outset is that all outdoor lighting is functional, its function being the enhancement of the visibility or of the aesthetics in the night-time environment. Light pollution represents a loss as regards electric energy. Good lighting design ensures that the light comes where it is needed, and does not fall elsewhere. If not, the light is 'spilled'. It may cause considerable economic and environmental losses. Furthermore, spill light from outdoor lighting installations often causes disturbance and discomfort for those that have nothing to do with the lighting. The light invades into the private sphere of people. This is 'intrusive light' or 'light trespass'. The overall effects are termed 'light pollution', with the proviso made in the foregoing part of this section.

One of the most conspicuous forms of light pollution is the 'sky glow' that extends over all near and distant sources of light pollution. Sky glow is the result of light that is projected upwards, and then scattered back to the surface of the Earth. Part of the light that is emitted by the light sources is directed straight up. Another contribution to the sky glow results from light that, after having been 'used', has been reflected upwards.

Sky glow is discussed in detail in a number of excellent textbooks that are listed in sec. 15.2a. These textbooks are almost exclusively written by and for experts, in most cases professional or advanced amateur astronomers. They are, however, hardly useful for the general public, for policy makers, and for the authorities that are responsible to uphold the quality of life. Apart from these textbooks, one can encounter a wide variety of articles, brochures and pamphlets that describe in great detail the adverse effects of sky glow and of light pollution in general. Several of these publications ar listed in the following sections of this book.

The present book tries to fill the gap that exists between the astronomical textbooks and the popular brochures. It is aimed at all people directly involved – full time or part time – in outdoor lighting, people that come in contact with light pollution. It gives details of the different aspects that are relevant in dealing with the problems related to light pollution, its cause, and its reduction. The main audience of the handbook is the authorities that are responsible for the design, installation and maintenance of outdoor lighting installations, with a special reference to the resuction of light pollution effects. It is also aimed at the managers of astronomical observatories and at the authorities and decision makers responsible for the organization and maintenance of the public space. Also, it will serve a good purpose in education, particularly in graduate or postgraduate curricula for scientists, engineers, economists, and law students.

Thus, an engineering approach has been chosen, implying that the book aims at practical and economically feasible solutions for problems that are stated in scientific terms. The main characteristic of the engineering approach is that an optimum solution is looked for – often an attempt to reach a compromise between what different aspects would ideally require. As will be clear in several sections of this book, subjective elements may play some role in reaching the optimum. In this way, the engineering approach differs from the approach that aims at maximization – an approach that is often used in studies related to the natural sciences. Both the engineering approach and the natural-sciences approach are, however, based on scientifically valid data.

The level of the book corresponds to this audience. The level might be characterised as 'college level' – or University level for European audiences. Details that are time-sensitive or controversial are not put on the foreground, to ensure that the book is not out of date too soon and that it remains readable for readers of different outlooks. This does not mean that it is strictly objective; the personal opinions and preferences of the authors may be gleaned when looking closely at the text.

The book is to a large extent based on the investigations that have been made by the authors themselves. This means that there is an emphasis on the results of studies that were made in Japan and in the Netherlands respectively. This preference is supported by the fact that in the area of outdoor lighting, Japan and the Netherlands have always made large contributions. One of the reasons for this is that these countries are the home of several of the most important lighting industries in the world. It goes without saying that in many respects the contribution of other countries is just as important. When conceiving the book, great care is made to present the material in a fashion that guarantee a world-wide use for the book.

The different aspects of light pollution and of sky glow are dealt with in different degrees of detail, so as the subject requests. Mathematical arguments are restricted to a minimum. As far as feasible, reference is made to more detailed studies. Also, the wide subject of light scatter in the atmosphere is not dealt with. Neither are the technical details of outdoor lighting design, nor the details of legislation and regulation. These subjects are very relevant, but it was felt that they are too specialized for a more general readership. Nither are cost aspects dealt with in detail. This refers to the costs of light pollution and the costs of the implementation of light pollution countermeasures. The reason is three-fold. First, the costs of light pollution are only in part of a monetary nature. Second, costs estimates vary very much in time. Precise indications would make the handbook obsolete in a short time. And third, probably the most important, cost aspects vary very much between different areas in the world. So is energy, including electric energy, much cheaper in the US than in almost all other countries of the world. When the costs are compared to the

GNP of a country, the differences are much larger. As an example, we might compare the USA with Tanzania, one of the poorest countries in the word. In the USA, the per capita GPN is US$ 24 750, in Tanzania US$ 90 (1993 data). With a price of electric energy per MWh of 5 and 10 US$ respectively, the US citizen has to work 0,323 hours for one MWh, whereas the Tanzanian must work 89 hours for that – well over two weeks. Because there is so little ground for an easily comparison, cost considerations are dealt with only in summary in this handbook. A comprehensive bibliography is included at the end of each chapter of the book. This approach is reflected in the structure of the book.

As regards optical astronomy, light pollution is not its only disturbance. Important sources of man-made interference with astronomical observations are passing aircraft, contrails (the vapour trails left by passing aircraft), satellites and space debris. Furthermore, vibrations and dust – e.g. from nearby mining activities – may have adverse effects. In earthquake-sensitive areas, geophysical disturbances may pose serious difficulties. These disturbances are not dealt with in this book. For obvious reasons, radio astronomy and the many disturbances like interference by radio and television broadcasts by electromagnetic disturbances in general, are not dealt with either. We will, however, give some references that may serve the interested reader. To begin with, it did almost become a tradition that conferences on interference of astronomical observations discuss as the three main items: light pollution, radio interference, and space debris. The proceedings of such conferences give a considerable amount of further information. See for these aspects Cohen & Sullivan, eds. (2001); Crawford, ed. (1991); Isobe & Hirayama, eds. (1998); Kovalevsky, ed. (1992); McNally, ed. (1994); Schwarz, ed. (2003).

Passing aircraft and contrails are discussed in some detail in Pedersen (2001). The lights of the aircrafts themselves may damage CCD receivers (Kovalevsky, 1992, sec. 6.5), whereas the heat from the aircraft exhaust may reduce the 'seeing' (Pedersen, 2001, p. 174). After the passage of the aircraft, condensation trails ('contrails') may form that interfere with astronomical observation. Contrails are understood to increase the overall cloudiness world-wide by 0,1% and in Europe by 0,5%. In general, they do not seem to be a serious threat for astronomical observations, but it seems that under special meteorological circumstances, their influence is much bigger (Anon., 2002). It is estimated that in most parts of Western Europe, more than 1 to 2% of the noon-time sky is covered by 'young' persistent contrails, whereas the larger part of continental USA is covered for over 2% (Pedersen, 2001, figure 1, based on data from Mannstein et al., 1999). It is therefore recommended to select sites for observatories far away from air routes (Pedersen, 2001, p. 177).

Geophysical disturbances have been discussed in some detail in Anon. (1984). See also Barlier & Kovalevsky (1992). The matter is very topical in view of the fact that some of the major observatories in the world, like e.g. Cerro Paranal in Chile and Mauna Kea in Hawaii, are built on more or less active volcanoes, where the region is by nature earthquake-sensitive.

(c) The organization of the book

The book is organized in two main parts. The first part covers the areas of general interest. It includes a general discussion of the problems of light pollution and a survey of the remedial measures. It also gives recommendations. It is aimed at al people directly involved – full time or part time – in light pollution, the main audience being be the authorities and decision makers responsible for the organization and maintenance of the public space. This part ends with recommendations that are aimed at minimizing the negative aspects of light pollution.

The second part, from Chapter 8 onwards, deals with the scientific and engineering elaboration of the material covered in broad lines in the first part. There is some overlap between the two parts. The second part is aimed at professional scientists and engineers, such as the managers of astronomical observatories, the designers of lighting equipment, and the installateurs of lighting installations. Mathematical arguments are restricted to a minimum. Both first and second part may serve for graduate or postgraduate curricula for scientists, engineers, economists, and law students.

Two points must be clarified. The first regards the language of the book. The authors did all they reasonably could do to ensure that the meaning is made clear to the reader; although they tried to do this in UK-English, it should be realised that some Japanese-English and Dutch-English crept in, in spite of the efforts of Mr Stephen Harris, who checked the language. The authors wish to apologize if this leads to some obscurity.

The second point refers to the problem of the decimal sign. The authors used the ISO-standard for writing numbers, which means that the 'comma' is used for the decimal sign and a space between powers of one thousand. This agrees to the international ISO Standard ISO 31-0:1992 'Quantities and units – Part 0: General principles'. In section 3.3.2 of that standard, it is stated: "The decimal sign is a comma on the line. If the magnitude of the number is less than unity, the decimal sign should be preceded by a zero" (ISO, 1992, p. 11). This ISO-standard is followed by the great majority of scientific organizations and standardizing organizations worldwide, more in particular by CIE and CEN. In view of the fact that this book is aimed at a world-wide readership, and also to help to promote the use of international standards, this system was adopted in this book, in spite of the fact that IAU and some countries like UK and USA do otherwise.

(d) About the authors

Kohei NARISADA was born on 28 November 1929 in Kyoto. He obtained his degree in electrical engineering at Doshisha University, Kyoto, Japan. On joining Matsushita Electric in 1953, he was involved in lighting design at the Lighting Division. In 1962, he transferred to the newly established Lighting Research Laboratory and was involved in investigations concerning road and tunnel lighting. Between 1976 and 1989, he was head of the Lighting Research Laboratory. In 1976, he obtained a doctor degree (Engineering) at Kyoto University on tunnel entrance lighting. Between 1987 and 1991 he was the president of Japanese National Committee of CIE. After his retirement from the company in 1989, he became a professor of the Psychology Department at Chukyo University, Nagoya, Japan and was teaching visual perception in relation to road lighting. In 2003, he retired from the University. He is the honorary member of the Illuminating Engineering Institute of Japan, and a Chartered Engineer of CIBSE, UK. He became involved in international activities of Technical Committees of CIE on road and tunnel lighting in 1967. Since then, he is the member of a number of CIE technical committees on road and tunnel lighting, the chairman of the sub-committee on tunnel lighting. He is also a member of CIE technical committee dealing with the countermeasures for light pollution. Since 1979, he served a term as a member of the CIE Action Committee; he has been the Director of Division 7 and between 1991 and 1999 he was a Vice President of CIE. He is the co-author of several books and a great many scientific and technical papers.

Duco Anton SCHREUDER was born 1931 in Rotterdam, the Netherlands. In 1949 he graduated from the classical secondary school in Breda. After his national service from 1952 to 1954 as an officer in the Meteorological Service of the Dutch Royal Air Force, he took a masters degree in applied physics from the Delft University in 1958. In 1964, he was awarded a Doctorate of Technology from the Eindhoven University. In 1972 he took a masters degree in philosophy (specialization psychology) at the Haarlem International Institute. From 1958 to 1968 he was a research scientist at the Lighting Laboratories of Philips in Eindhoven. From 1968 to 1993 he was a Senior Researcher with SWOV Institute for Road Safety Research in Leidschendam. Since 1993 he is an independent consultant in the general fields of lighting and safety. Dr Schreuder is the author and co-author of several books and well over 300 scientific publications. He was and is the Chairman or member of a large number of national and international institutions and working groups, particularly in the Commission Internationale de l'Eclairage CIE, in the Comité Européen de Normalisation CEN, and in the Organization for Economic Cooperation and Development OECD.

The authors first met in the early 1960's, when their work on tunnel lighting lead in a natural way to an exchange of ideas and later to close cooperation. This cooperation was extended to most areas of outdoor lighting, focussing the last decade on matters of light pollution and of the interference by light of astronomical observation. The present book is a fruit of this decade-long cooperation of the two authors.

(e) Abbreviations

In this book, a number of abbreviations are used. Most of them are listed here, although many are explained in the text where they show up. The translations given here are indicative only. Most are not authorised; they are given only for matters of information.

ALCoR	Astronomical Light Control Region
Anon	'Anonymous', Author not known, or not indicated
ASP	Astronomical Society of the Pacific, San Francisco, USA
AVV	Adviesdienst Verkeer en Vervoer, Rijkswaterstaat (Transport Research Centre, Ministry of Transport, Public Works and Water Management). Rotterdam, the Netherlands
BAA	British Astronomical Association, London, UK
CBS	Centraal Bureau voor de Statistiek (Central Statistical Bureau). The Hague, the Netherlands
CCD	Charge-coupled Device
CEN	Comité Européen de Normalisation. Brussels, Belgium
CIBSE	Chartered Institute of Building Services Engineers. London, UK
CIE	Commission Internationale de l'Eclairage. Paris, France; now Vienna, Austria
COSPAR	Committee on Space Research
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek (Centre for regulation and research in soil, water and road engineering and traffic engineering). Ede, the Netherlands
DIN	Deutsches Institut für Normung e.V. (German Standards Institution)
DMSP	Defense Meteorological Satellite Program
DSC	Duco Schreuder Consultancies. Leidschendam, the Netherlands
DWW	Dienst Weg- en Waterbouw, Ministerie van Verkeer en Waterstaat (Department of road and waterway construction, Ministry of Transport, Public Works and Water Management), Delft, the Netherlands
EC	European Commission. Brussels, Belgium
EN	European Norm
GCRI	General Colour Rendering Index
HID-lamp	High Intensity Discharge lamp
IAU	International Astronomical Union. Paris, France
ICSU	Council for Science – formerly International Council of Scientific Unions
IDA	International Dark-Sky Association. Tucson, Arizona, USA
IDN	International Dark Sky Association Holland. Utrecht, The Netherlands
IEC	International Electrotechnical Commission
IES	The Illuminating Engineering Society of North America. New York, USA
IEIJ	Illuminating Engineering Institute of Japan. Tokyo, Japan
ILE	The Institution of Lighting Engineers. Rugby, UK
IPCC	Intergovernmental Panel on Climate Change
IRF	International Road Federation. Geneva, Switzerland
ISO	International Standards Organization
IUCN	International Union for Conservation of Nature and Natural Resources
IZF/TNO	Instituut voor Zintuigphysiologie TNO (Institute for Perception TNO). Soesterberg, the Netherlands (now TM/TNO)
JCIE	Japanese National Committee of CIE
LITG	Lichttechnische Gesellschaft (Association for illuminating engineering). Berlin, Germany
LNV	Ministerie van Landbouw, Natuurbeheer en Visserij (Ministry of Agriculture, Nature Policy and Fishery) Den Haag, the Netherlands
NSVV	Nederlandse Stichting voor Verlichtingskunde (Illuminating Engineering Society of The Netherlands). Arnhem, the Netherlands
NOVEM	Nederlandse Maatschappij voor Energie en Milieu bv (Society for energy and the environment of the Netherlands). Sittard, The Netherlands
OECD	Organization for Economic Cooperation and Development. Paris, France
OLS	Optical Linescan System

PAOVV Orgaan voor postacademisch onderwijs in de vervoerswetenschappen en de verkeerskunde. (Organisation for post-graduate studies in transportation sciences and traffic engineering). Rijswijk/Delft, the Netherlands
PrEN European Pre-Norm
RHT retinohypothalamic nerve tract
SANCI South African National Committee on Illumination
SCOPE Scientific Committee on the Problems of the Environment
SCOSTEP Scientific Committee on Solar Terrestrial Environment Problems
SCRI Special Colour Rendering Index R_i for an individual colour
SCW Studiecentrum Wegenbouw (Study Centre for Road Construction SCW). Arnhem, the Netherlands (now CROW)
SCN suprachiasmic nucleus
SVT Stichting Studiecentrum Verkeerstechniek (Study Centre for Traffic Engineering) Driebergen, the Netherlands (now CROW)
SWOV Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Institute for Road Safety Research). Leidschendam, the Netherlands
TRB Transportation Research Board. Washington, DC, USA
TRRL Transport and Road Research Laboratory. Crowthorne, Berks., UK (now TRL)
UNESCO United Nations Educational, Scientific and Cultural Organization
V&W Ministerie van Verkeer en Waterstaat (Ministry of Transport, Public Works and Water Management). Den Haag, the Netherlands
VNM Vereniging Natuurmonumenten – formerly Vereniging tot Behoud van Natuurmonumenten (the Society for the Preservation of Nature Monuments). 's Graveland, The Netherlands
VROM Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (Ministry of Public Housing, Land Planology and Environmental Policy). Den Haag, the Netherlands
WHO World Health Organization. Geneva, Switzerland
WVC Ministerie van Welzijn, Volksgezondheid en Cultuur (Ministry of Well-being, Public Health and Culture)
WWF World Wildlife Fund

(f) Acknowledgements

For a number of subjects, advise is asked from experts in different areas that fall outside the expertise of the authors. The two authors are, however, fully responsible for the contents of the book. In this respect, the authors want to extent their sincere thanks to many persons or institutions who were generous with their advise and comments. Many, but not all, are listed here, in alphabetical order.

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1 Preamble

There is only one Earth. Thus, we need to study carefully the 'environment'. There are three current thoughts about the environment that do lead to different sets of priorities as regards measures to conserve the environment. They may be defined as the materialistic, the naturalistic, and the cosmic principles. Also, some concept of humanity is needed. When discussing light pollution, some confusion is likely to arise when one considers the place of light and dark in the frame of human history and human culture. At the one hand, most religions and most philosophical systems stress the fact that Light is the incarnation of God, of Good, of Virtue, whereas Dark is the incarnation of the Devil, of Evil, of Sin.
When, as a result of the 24-hour economy and its ensuing night time outdoor lighting, the starry night is lost, there is much more at stake. For a human being to be conscious of the inherent unity of, and within the cosmos, the starry night is essential. There are few other ways to experience this unity and the place of humanity in it.
Light pollution represents a loss as regards electric energy. It is not easy, however, to estimate the amount of money nor the amount of energy that is involved in light pollution. Basically, there are two ways to avoid or at least to reduce the light pollution: avoid the light, or reduce the disturbance. Cost estimates and the implementation of countermeasures is discussed briefly. Finally, the goal and the structure of a number of international organizations is discussed.

1.1 There is only one Earth

1.1.1 The philosophy of the environment

(a) *The concept 'environment'*

The concept 'the environment' is used in many different ways; there is, however, no consensus in this. One seems to assume that everybody knows what it is all about. More specific, most people seem to agree that there is something fundamentally wrong about the environment, without real knowledge what is wrong, why this is a serious matter, and what must be done about it. To clarify things, some philosophical considerations are needed. At the end, a definition of the concept 'environment' will be given that can be used in the further context of this study.

There are three current thoughts about the environment that do lead to different sets of priorities as regards measures to conserve the environment. They may be defined as the materialistic, the naturalistic, and the cosmic principles.

(b) The materialistic principle

The materialistic principle focusses on the human species in the centre. Environmental considerations refer to the human condition, the threat of it, and the human causes of this threat. Human existence it in danger:

- when it is poisoned;
- when it is disturbed;
- when resources are depleted.

This principle is adhered to by different ideologies, amongst them socialism and Christianity – be it on different grounds. According to socialism, the material well-being of humanity is the only legitimate goal of any governmental activity, whereas in Christianity, Man is appointed as a guardian of nature; nature in its turn is only there to serve mankind.

Human existence is characterized by its materialistic aspects. This is the explicit aim of the policy of several governments, amongst them the government of the Netherlands, when its goal is defined to maintain 'sustainable society'. The time span is limited to about 15 years – the life span of politicians in most democracies.

In this context, light pollution must be fought against because it hinders the well-being of human beings.

(c) The naturalistic principle

Nature has a central place in the naturalistic principle. Usually, nature is considered as being inherently good: 'natural' and 'good' are regarded as synonyms. It is no problem when the natural equilibrium of things is disturbed by natural causes as they also are part of nature. Natural disasters like earthquakes or meteorite impacts may influence nature but they are 'just' part of the evolutionary process. Many state that evolution by means of natural causes is the beginning and the end of all scientific considerations, irrespective of severe, justified criticism towards this extreme Darwinism.

Humans are, in this way of thinking, not part of nature any more. As soon as human activity influences nature, it is considered as a negative impact on the environment. Not only does this mean that all animal and plant species must survive, it also is extended to the landscape – man-made landscapes included. The naturalistic principle is not free from inconsistencies. It may be noted that this view is not shared by the culture-optimists: in Europe, in the 18th and 19th centuries, it was a commonly thought that Man had a duty to refine the Creation. A similar thought may be found in Japanese garden architecture.

As regards light pollution, the picture is clear: light pollution from artificial light is an environmental infringement and must consequently be combatted, whereas obstructions in astronomical observations by the Moon – or by clouds for that matter – are 'natural' causes against which one must not rebel.

(d) The cosmic principle

The cosmic principle has a lot in common with the other two principles. Also in this case, nature has a central place but it is taken into account that human beings are part of nature as well. That includes the specific way of human acting and behaviour. The central notion of the cosmic principle is harmony. This implies that the human being not only acts as a user – or even an enemy – of nature but that there is harmony between humans and nature; nature both inside and outside the human being.

This approach leads to a number of ethical dilemmas. On the one hand it is not considered as acceptable to root out plants and animals; on the other hand, the human species has its own demands and requirements as a living species, including eating plants and animals. It is 'good' but also is it 'bad' to disrupt a natural equilibrium. On the one hand, humans may use the creation but on the other hand it is not sufficient to leave something for 'our children'. This means, of course, that both individuals and authorities have to make a new decision in each case. It seems that exactly for this purpose, humanity has, as a touchstone of what to do, its conscience.

As regards light pollution, this means that the extreme viewpoints that still are defended occasionally, both have to be discarded: on the one hand, it is not acceptable to spoil the natural night time condition of darkness exclusively on ground of progress and material well-being; on the other hand, it is not acceptable that for the benefit of astrophysical research, the whole earth will be dark at night, and consequently subject to accidents, crime and ignorance.

(e) The concept of humanity

When the three principles that have been sketched earlier are looked at in combination, a specific picture of humanity seems to arise. This picture is characterized by:

- human beings are individualists that make their own decisions;
- human beings are egotists;
- human beings are rationalists who are governed exclusively by the profit principle;
- only punishment, more precisely monetary punishment, will shift the profit equilibrium;
- compassion is never voluntary; it must be enforced by monetary punishment.

Even a cursory look at what humanity really means, shows that this picture is somewhat short-sighted. There is ample proof in daily life that compassion as a free-will act, is the most 'human' trait of humanity.

(f) The concept 'environment' redefined

One should define the 'environment' as everything that surrounds something else; more specific, as everything that surrounds humanity. For this study, this notion will be restricted to the physical world. This would then include nature and technology. In this way, this definition agrees to the definitions that are common in sociology, psychology, biology, chemistry, etc.

The two points of view regarding the relation between nature and humanity are poignantly characterized by Chaudhuri in his description of an Indian teacher who visits Britain for the first time in his life: "In the East man is either a parasite on Nature or her victim, here man and Nature have got together to create something in common" (Chaudhuri, 1989, p. 28).

(g) Policy focal points

When the environmental protection policy of governments and of inter-governmental agencies is scrutinized, the following focal points arise:

- natural resources need to be conserved;
- toxic emission must be stopped or at least limited;
- nature, also non-human nature, must be preserved;
- the harmony between humanity and the rest of nature must be established;
- infringements, both natural and man-made, of the natural equilibrium must be avoided or at least limited.

The problem, of course, is not to define these focal points, but to implement them and do it in the right order of priority. As said earlier, this optimum prohibits the exclusive rights of money making and of astrophysical research; a compromise must be found and implemented. This study hopes to contribute to this.

1.1.2 The philosophy of the night

(a) Light and dark, good and evil

When discussing light pollution, some confusion is likely to arise when one considers the place of light and dark in the frame of human history and human culture. At the one hand, most religions and most philosophical systems stress the fact that Light is the incarnation of God, of Good, of Virtue, whereas Dark is the incarnation of the Devil, of Evil, of Sin. In line with these principles, light is considered as a synonym for safety, comfort and beauty, whereas darkness is considered as a synonym for danger, fear and ugliness.

There is more to it, however. Although darkness is in some ways synonymous with evil, a more precise statement is probably that it is not so much the darkness as such, but rather the inability to see. The darkness of night is scary, but the darkness in a dark forest at night is terrifying.

Even in daytime, forests are a threat rather than a diversion, as the famous Dutch historians have explained in a poetic and circumstantial way, in their standard work on the history of the Netherlands: "Only for the people who live in the modern, industrialized culture, the forest seems to offer a refuge for humans and animals. In reality, the primeval forest is the enemy of human beings and even of animals, who never venture in it deeply. In tradition, and in fairytales, the forest is the horrible-unknown, from which no-one returns. Cowards and brigands lurk there, and, sometimes, the Gods live there. The free men, however, live in the open fields and prefer to live at the forest' edge" (Romein & Romein, 1961, Volume I, p. 18).

In discussing the work of the biologist Ronald Plasterk, who maintains that the decline of orthodox Christianity is a logical result of the Evolution Theory, it is suggested that: "The relation between science and the decrease in religious belief is evident, but it seems to me to be more a sociological relation than a logical one. The fact that almost nowhere, one may see a proper starry night, did more for the decline of the Church than whichever articulated opinion" (Ree, 2003).

"The night sky has been a canvas of our hopes and inspirations since we have been aware enough to raise our eyes from the ground. But our children are more and more growing up never seeing the stars, robbed of this inspiration of the ages. It need not happen" (Anon. 2002a).

"The starry night belongs to the few primeval phenomena that are appreciated by all people, in about the same way as phenomena like nature, sunset or the beach" (Stolk, 2001, p. 2).

"It really does not matter whether we look at darkness from outside us or from within us. The essence is the ability to find ourselves in the cosmos around us. The outside observations need to have a clear sight on the wonders above us. The innermost observations require the qualitative sensation from the starry night in order to bridge the gap between the outside and the inside. The gradual, sneaky process that obscures the starry night will obstruct both possibilities to realise and to recognize the relation between humanity and the cosmos" (Stolk, 2001, p. 5).

In sec. 8.3.5, the subjective impression of brightness is discussed in some detail, making use of the scale that is published by Hopkinson (1969; see also Schreuder, 1998, Figure 7.2.1). From that scale, it can be read the luminance for several conditions:

- clear moonless night: luminance $10^{-3,5}$ cd/m^2;
- dark moonless night: luminance $10^{-4,5}$ cd/m^2;
- ditto under the trees: luminance 10^{-5} to $10^{-5,5}$ cd/m^2 (estimated);
- perception threshold: luminance 10^{-6} cd/m^2.

Under the trees it can be, on a moonless night, one hundred times less bright than under the clear, starry night. So this is probably an important factor to take into account, when considering the relation between darkness and evil.

With this in mind it is easy to understand why humanity welcomed the availability of artificial light. By means of what is the predominant technological achievement of the second half of the 20th century, the curse of Darkness was banned once and forever. The 24-hour economy was born. The fact that the starry night was lost seemed to be a small price to pay. It is not right to blame the lighting industry for this: it was the social pressure of a culture that believes in rationality as the ultimate level of human consciousness that caused the loss.

However, with the loss of the starry night, there is much more at stake. The supremacy of rationality is essentially a concept – a relic – from the Western-European philosophy of the 18th and 19th centuries. The idea that humanity is an isolated phenomenon that sits in nature without participating in it, never convinced people who value the spiritual aspects of life. Towards the end of the 20th century with the collapse of technology, the wholeness of the cosmos became the leading idea in society. Now about the confusion that was hinted at in this section: for a human being to be conscious of the inherent unity of, and within, the cosmos, the starry night is essential. There is maybe one more interesting remark to be made about the importance of the starry night. The great German philosopher Immanuel Kant is reported to have said: "There are two thing that give me eternal wonder: the extent of the human consciousness and the infinity of the starry night." There are few other ways to experience this unity and the place of humanity in it. More in particular, the daytime when the sun blots out the rest of the cosmos is hardly suitable for this experience. So, the conservation of the starry night is essential for the development of human consciousness. In this respect, scientific astrophysics has a role to play. It is a challenge for the lighting industry to promote the one and to save the other.

In the Christian doctrine, not the light itself but the Sun is the symbol of the divine power. The following quotations are from Lenz who did describe these facets of Christian belief in a poetical fashion (Lenz, 1936). The quotations from Lenz are a free translation. Lenz, on page 114 quotes Michelangelo: "The Sun is not more than a shadow of God". And further: "So big and beautiful, so shining and powerful, the Sun is a striking symbol of magnificence of God. Still, it is not more than a created image of the Uncreated" (p. 114). "In the lordship of the Sun over Earth, we see the symbol of Gods lordship" (p. 115). "The skies tell about Gods magnificence" (from an unknown quotation). "In thousandfold splendour God's magnificence shines at the starry sky at night. For us, however, there is nothing in the Universe that reflects so brightly Gods's infinite characteristics as the Sun" (p. 115). "As the 'eye of the world', the Sun is the image of the omniscience of God, the all-seeing" (p. 115). And finally: "The Sun is an image of God and the fire is a symbol of His love" (p. 116). All quotations are from Book II 'King Sun'; Lenz (1936).

These quotations are given here to indicate that the relation between Light, Sun and religious belief is a deep rooted one – and a complicated one indeed. Furthermore, a close reading of the quotations suggest a relation with Buddhist doctrines, which makes the considerations more universal.

In summary, the opposite concepts of light and dark must be understood in two distinct ways: on the one hand, darkness (the absence of light) represents danger and fear and must be eliminated, whereas on the other hand darkness (the starry night) offers the major road towards the experience of humanity as being a part of the cosmos.

(b) *Objective day – subjective night*

It is interesting to compare this personal note to the concepts described by Helmer (1999). These concepts are briefly summarized here.

The science of the day creates a distance between subject and object by means of its objective light. At night, the inner and outer worlds merge together at night. During the day, nature can be described objectively and by logic. At night, this long detour is cut short. At night I myself am the creator of what I surmise to be around me.

(c) *The theory of darkness*

Stolk sketched a number of philosophical aspects of darkness, represented by the 'starry night' (Stolk, 2001). "The starry night belongs to the few primeval phenomena that are appreciated by all people, in about the same way as phenomena like nature, sunset or the beach" (Stolk, 2001, p. 2). Earlier in this section, we have quoted some paragraphs from Stolk. We will repeat them here. "It really does not matter whether we look at darkness from outside us or from within us. The essence is the ability to find ourselves in the cosmos around us. The outside observations need to have a clear sight on the wonders above us. The innermost observations require the qualitative sensation from the starry night in order to bridge the gap between the outside and the inside" (Stolk, 2001, p. 5).

Contrary to the philosophical outlook of Stolk, Van Essen presented a psychological outlook (Van Essen, 1939). Van Essen argues that normally, when the light disappears, we are visually excluded from the world. We are effectively blind and we loose our sense of orientation. However, darkness is still a visual sensation; it is above all a sensation of blackness. In other words, black should be regarded as a colour. This, of course, is a reflection of the age-old dilemma of philosophy: does 'nothing' exist, or does it not exist? This dilemma is briefly discussed by Blackburn (1996, p. 265) and Diemer & Frenzel (1976, p. 175-176; p. 248). The statement of Van Essen implies that darkness is an optical phenomenon: we still have a real visual experience. However, contrary to 'normal' vision that results from an external stimulation, the visual experience of darkness results from an internal stimulation. The darkness is not completely black. Usually, we are subjected to al sorts of visual impressions like e.g. luminous points or even luminous figures. In this respect it might be interesting to refer to the visual impressions that are common in sufferers from migraine, especially just before a severe attack sets in (see e.g. Sachs, 1993,

p. 44). Basically, a pure, complete 'aphotic' darkness does not exist. Van Essen himself refers to the earlier studies of Liesegang (1936) and Rich (1926).

There are many ways in which visual effects can arise in the eye without any light stimulation, ranging from electric currents to pressure applied to the eye balls.

The considerations of Van Essen might be interesting when considering what are the levels of light pollution that are visible. First the absolute threshold of the human visual system. It is commonly accepted that the lowest luminance that might give rise to any light experience is about 10^{-6} cd/m^2 (Hentschel, 1994, p. 47). In sec. 3.1, it is explained that the usual luminance value of the practical minimum of the natural background radiation is $3{,}52 \cdot 10^{-4}$ cd/m^2 (Crawford, 1997; CIE, 1997). This is much higher than the absolute luminance threshold mentioned earlier; as can be seen immediately in practice, this minimum for the natural background is almost pure 'black'. Following the reasoning of Van Essen, it is quite possible that under such conditions, the spontaneous light points or figures, resulting from non-optic stimulation of the visual system, would surpass the natural background luminance in 'subjective brightness'. Consequently, one might question whether the IAU-proposal of reducing artificial sky glow to a value lower than 10% of the natural background is realistic, at least for visual astronomy (Anon., 1978).

(d) The Moon and the Sun

Many hunters prefer the night for hunting, because most animals are drowsy. Hunters need moonlight to see enough. However, in moonlight, many preys do not see enough to be warned for the hunters. So, in a hunter-gatherer society, life is centered about the periods of the moon. Also, of course, the moon and its phases have an occult relation to the menstrual cycle of women. The moon phases are thought to have a direct link to the processes of life and reproduction. The reproduction of living organisms is equally important for the men who hunt animals as for the women who collect plants. So, it is not difficult to assume that in the hunter-gatherer societies, the Moon is the most important of all celestial bodies; it is only a small step to assume that the Moon is the most important Deity. This is precisely what can be found in several contemporary hunter-gatherer societies. As was poetically expressed in a televized programme of the National Geographic Society, the early humans used the period of near full moon to hunt, and the period of the new moon "to rest and to mate". One might expect that all this has been changed drastically, when the hunter-gatherer societies were replaced by the agricultural societies. Sowing and reaping are closely related to the seasons. It is the Sun and not the Moon who is directly linked to the seasons and their sequence. So one might suppose, that the hunter-gatherer societies were moon-oriented, and the agricultural societies are sun-oriented. The direct consequence is that the hunter-gatherer societies were darkness-oriented and the agricultural societies are light-oriented – or, night-oriented and day-oriented respectively.

In sec. 10.1.5, it is explained that in the evolutionary history of humankind, the periods where hunter-gatherer societies were predominant, span at least several million years, whereas the periods where agricultural societies were predominant, span about 10 000 years at the utmost. This implies that in the human spiritual baggage, a lot of aspects that belong much more to the mind of the hunter-gatherer that to the mind of the farmer. The televised programme that has been mentioned earlier, did express this in saying that the agricultural humans, although being forced into regarding the Sun as the most important celestial body, "still have a strong nostalgic feeling towards the Moon". It is an intriguing thought, that this deep emotion is one of the grounds for our preference for the night over the day, irrespective of the many technical and economic benefits of the day – apart even from the glorious feeling of relaxing in the sunlight, a feeling that is shared each summer by hundreds of millions of holiday makers!

It is tempting to venture a little further. Reproduction and fertility typically belong to Earth, belong to the female aspect of the human soul. So do hunting and reaping; both are related to sources of food that just 'are there'; it is a matter of reactive decision making. You pick up what you find, whereas in agriculture, you pick up what you have planted there with that particular purpose in mind. Agriculture is pro-active. Some aspects of reactive and pro-active decision making are discussed in Chapter 10 of this book.

Some alchemist treaties give an explicit description of the female aspects of the moon and the male aspects of the sun. "According to Kircher, the male divine sky of heathen times represent different aspects of the Sun – the World Spirit – like the heating powers of Apollo and Horus, and the powers to create time of Chronos or Saturn. Contrary to this, the female divine sky of heathen times represent emanations of the Moon-power. They represent the power of Ceres or Cybele to create fruits, and the power of Proserpina to make plants grow" (Roob, 1996, p. 64, referring to Kircher, 1650).

In a study, devoted to sick cities, the concepts of 'down' and 'up' attitudes have been introduced (Schreuder, 1994a). As is explained earlier in this section, there is, in hunter-gatherer societies, a division into two patterns of food collection. The division of labour requires a distinction between two attitudes, two patterns of behaviour, two 'frames of mind'. The two patterns are closely linked to the activities of men and women in the society. One might term the two the patterns of 'masculinity' and 'femininity'. A more general terminology would be 'Yin' and 'Yang'. Basically, the first is giving, active, steering and above all heaven-bound, whereas the other is basically receiving, passive, reactive and above all earth-bound. With a smile towards the modern physics of elementary particles and its 'up' and 'down' quarks, they are called 'up' and 'down' attitudes. The up and down attitudes are the building blocks of society. They are, however, closely interwoven, and, in hunter-gatherer societies, an equilibrium between the two persisted.

These considerations allow us to look for a link between the 'yin' and the 'yang' attitudes, and the way we consider the night. For many, the night, and particularly the starry night sky, is a source for contemplation. The essence of contemplation is that one picks up what comes along; contemplation is reactive. And so is astrophysics. The step between the two might seem large, but in essence, what astrophysics do, is studying the night sky as it is presented by Nature, and search for interesting items. Astrophysics is not an experimental science in the sense that the crucial experiment can be made to verify or falsify certain theories, as in explained in sec. 10.1. It is precisely the reactive character of astrophysics that make it vulnerable for light pollution: there is not much, the astronomer can do about it. Contrary to this is the 'yin'-character of technology and engineering. Engineers prefer the day over the night, because in daylight you can see what you do. The fact that the Sun is available only about half the time, is nothing much more than an inconvenience. From the very first beginning of technology, extending the time that it is bright enough to be active, has been one of the major areas of interest of engineering and technology (Zajonc, 1993). Just as soon as reliable, low cost, high lumen light sources became available, the night was doomed. It was not the aim to abolish astronomy or to severe the link with the Cosmos, but to extend human living area over all available space. Frontiers acted as an incentive. No small wonder that, because "Space is the final frontier", space exploration is the ultimate goal for engineering and technology. Engineers, contrary to astronomers, are active; they explore their surroundings. In spite of setbacks, terrible disasters, the low returns in terms of scientific results, and the need for stupendous budgets, space engineering and more in particular manned space flights, show up in the policy of many nations. In this way, engineers may be regarded as the embodiment of the 'up' attitude and astronomers as the 'down' attitude. In Table 1.1.1, an attempt is made to list the different aspects of these two attitudes.

Up attitude	Down attitude
'yin'	'yang'
masculine	feminine
heaven	earth
stress-increasing motivation	stress-reducing motivation
pro-active	reactive
long-term planning	short-term projection
hard	soft
egotistic	caring
sequential reasoning	pattern-recognition; parallel reasoning
inventive	creative
mind	soul
Sun	Moon
day	night
light	dark
exploration	contemplation
space	sky

Table 1.1.1: *Up and down attitudes. After Schreuder, 1994a.*

It is interesting to note what mathematicians think about the mathematics that are used by engineers. It is stated that attempts to try and find out how the ancient civilizations like those of Egypt and Babylon got their results, did not lead anywhere. "This seems strange and very unsatisfactory to us, who did learn our mathematics in another way, and who have followed the school of Euclidic geometry. We understand it better, however, when we consider that most of the mathematics that we teach our technologists and engineers, still consists mainly of receipts, without much attention to rigorous proof" (Struik, 1965, p. 33). Here, a clear distinction is made between the approach of mathematicians, who proceed analytically, and the engineers, who proceed in a practical way. It should be noted that this History of Mathematics is published originally in 1948, before computer-aided mathematical assessments were widespread. It is interesting to speculate how the picture would be today, since numerical approximations make a lot of tedious analytic assessments superfluous!

There is more to it, however. That has to do with the attitude of astronomers towards the Sun and the Moon. It is, of course, well-known that the Moon obstructs sensitive astronomical observations. Maybe astronomers resent the fact that they cannot make 'real good' observations for about 10 days each month, but as the source is natural, they do not recognise the Moon is the 'big polluter' – after the sun, of course.

(e) *Thoughts on light pollution; A personal note by one of the authors*

As a kid, I grew up during the Second World War in occupied Holland. In that time I was confronted with light and dark, day and night, in almost all senses of the contrasting words. First, of course, the contraposition between day and night, between light and the absence of light. In a time of absolute black-out, the nighttime obstructed all communication between people. We were thrown back in the isolation of our own home. But when there were no clouds – not the most common situation in winter-time Holland – the reward was astonishing: even from our tiny city garden, we could enjoy all the splendors of the night sky. The eternal tranquility of the stars made good a lot of the wartime and razzia-riddled daily life. Also, in a striking contrast to this, we were experiencing the contraposition of darkness-and-light in the ethical sense: we were confronted with the unfathomable darkness of the most objectionable regime we had ever experienced in our part of the world. We lived, and we were able to go on living, because of our conviction of that the light of the righteousness was at our side and that we would win in the long run – as we did.

Much later, in the period of my life when I devoted most of my time in fighting road accidents and road deaths, I was confronted with another contraposition. The day – the light – is the time of safe and free movement, the time where also you might feel safe, the time of social and business interaction. The darkness, however, is the time where road accidents and street crime soared; the time when decent people, particularly the women, the old, the young, the vulnerable are afraid to go outdoors, where social contacts are thus obstructed. Here my training as a lighting engineer and as a research physicist helped me to establish the unambiguous positive effects of high-quality outdoor lighting.

In the combat against light pollution, these three sets of contrapositioned concepts must be kept in mind carefully; also, they must be discerned very precisely. Usually, however, people are somewhat sloppy and dump all of them on a big heap. This, of course, leads to confusion and confusion is not a good basis for precise, rational decision making. First, we have to consider the fact that nighttime just means the absence of light. High-quality outdoor lighting is the obvious solution for the related problems. Dark skies, contrary to skies lit by lamps, allow us to contemplate the infinity of the Universe and the ultimate goodness of God. This is meant when UNESCO and many other organizations proclaim the dark sky as part of the World Cultural Heritage (Anon., 1992). Outdoor lighting in all its forms endangers that issue. But also, darkness is fearsome, it is a threat to the personal physical and psychological integrity. Again here, high-quality outdoor lighting is of help. It must be kept in mind that the technical requirements of the two types of 'high-quality outdoor lighting' might differ considerably.

Now what is the position and what are the possibilities of organizations like IDA who devote themselves to combat light pollution? Obviously, 'cutting out all the darned lamps' is not the answer, nor is the answer to fight everybody who installs or promotes outdoor lighting. We must realize that light pollution is only one of the many threats to a healthy, natural environment: noise, foul air, dirty water, pesticides, genetic engineering and a lot more do threaten the survival of the human species – of life on Earth in general, for that matter. They may do some good, but they must be carefully kept in check.

So what would be my suggestions for the organizations that try to reduce light pollution:
- do not hasten. Instant gratification is not to be reached; the fight will be a drawn-out one;
- persuade the people who are responsible for the decision making processes that result in poor or out-of-place outdoor lighting as regards the values of the dark – clean – night sky, not just for the fun of a few astronomers but as a major asset of human culture;
- leave the barricades; fighting from them may give some short-lived successes but it will invariably result in a long-term defeat, simply because fighting from barricades is the surest way to acquire many enemies and very few allies;
- light pollution is a world-wide problem. Recent research suggests that even remote areas of Earth suffer from it. Consequently, the problems but also the possible solutions may differ markedly from one region or continent to another; there are no standard solutions for the problems;
- join forces with the many people who are concerned about the future of Earth in the most varied ways of thinking. Barricade fighting may not be efficient, but it is downright stupid if you try to do it on your own.

1.2 Light pollution and energy conservation

1.2.1 Spill light and light pollution

(a) Spilled light

To begin with, a note about the terminology. Light that does not go where it belongs, is spilled, just as milk is spilled when it ends up beside the glass and not in it. The light is called 'spill light'. Like other jargon, the term might be somewhat confusing, but as the term is generally accepted, we will use it in this book as well.

All outdoor lighting is functional, its function being the enhancement of the visibility (utility lighting) and/or of the aesthetics (decorative lighting). The effectiveness of the lighting is the degree to which the function is fulfilled; the efficiency the degree to which the benefits surpass the costs. The benefits include the (avoided) costs of accidents, traffic jams, criminal offenses, and other economic losses. This is discussed in detail in Chapter 12 of this book. The costs include the costs of the lighting installation, maintenance, and energy use. In sec. 10.3.3, cost-benefit assessments are discussed in detail.

Light pollution represent a loss as regards electric energy. This, of course, is true. Light that is generated and disappears without having any use, is a waste. In sec. 1.2.2, it is indicated that this loss should not be over-estimated (Holmes, 1997). Good lighting design ensures that the light comes where it is needed, and does not fall elsewhere. If not, the light is 'spilled' (Schreuder, 1995). It may cause considerable economic and environmental losses. (Schreuder, 1995, 2000). The light, the money and the energy are simply wasted. And, also of course, it is worth-while to try and save the money and the energy. Furthermore, spill light from outdoor lighting installations usually is a major cause of disturbance and discomfort for those that have nothing to do with the lighting. The light invades into the private sphere of people; it intrudes into the living space of people who do not have any interest in the lighting in the first place. This is 'intrusive light' or 'light trespass'. The overall effects are, as mentioned earlier, termed 'light pollution'. The most common way that light pollution is noticed is by its resulting 'sky glow' that extends over all near and distant sources of light pollution (CIE, 1997; Schreuder, 2001).

In sec. 15.4.1, the legal matters are discussed, that are connected with the concept of 'nuisance' (McManus, 2001). As indicated earlier, light pollution is the result of the scattering of upward light in the atmosphere in such a way that it is redirected downward again and can reach the human eye – the observer. It goes without saying that there is a relationship between light pollution and air pollution. As put by Stock & Marin (1991, p. 48): "Light pollution depends on two factors: light emission and scattering particle abundance". The latter is variable over the world. It depends of course on population density but even more so on affluence. As regards the developing world, Stock & Marin (1991, p. 48) summarize their findings as follows: "Obsolete industrial installations make the application of output control difficult or impossible. Most countries do not have yet a legislature which would permit the imposition of pollution control". Also they point to poorly adjusted motor vehicles as a major source of air pollution (Stock & Marin, 1991, p. 49).

(b) Light pollution and air pollution

Earlier is it stated, that light pollution, and more in particular urban sky glow, results from light that is emitted upward and subsequently scattered back towards the surface of the Earth. Because of the atmosphere, on Earth, the scatter is always there. The air molecules scatter a considerable amount of light, as is immediately clear during the day. Even in perfectly clear weather, at sea level the luminance of the daytime sky easily can reach values of 10 000 cd/m^2 or more (Schreuder, 1964; Huijben et al., 2003). That the scatter comes from air molecules, is clear as the scattered light is blue, in accordance with the Rayleigh Law (Illingworth ed., 1991, p. 393; Feynman et al., 1977, p. 41-6).

Aerosols change the picture. Aerosols, particles floating in the atmosphere, can have many different sources. The most common are, apart from water droplets in haze and clouds, dust particles from industry, agriculture and deserts, salt crystals from the sea, soot from diesel engines, ash from volcanoes and forest fires (Mizon, 2002, p. 6). "Volcanoes are the world's natural dust makers. The amount of sunlight can fall by 2-3 percent a few months after a large eruption" (Anon., 1977, p. 60). In sec. 14.6.2, the effect of the Pinatubo eruption is mentioned (Upgren, 1997). One may add to this the artificial cirrus clouds from aircraft contrails (Anon., 2002b; Pedersen, 2001).

The close relationship between light pollution and air pollution is also pointed out by Kosai & Isobe (1991) and by Garstang (1991). The consequence of this is that light pollution countermeasures and air pollution countermeasures need to go hand in hand. It seems, however, that not all those who are involved realise this. Sometimes, the same people who fight valiantly against light pollution contribute to air pollution by using gas-guzzling cars, air conditioning and computers on stand-by in their office, and fly over the globe from one meeting to another. There seems to be a need to combine in special sessions the combat against air pollution and that against light pollution, much in the same way as the sessions that combine the consideration of light pollution, of radio frequency interference and of space debris. Some of those conferences produced reports that are 'classics' in this field. They are referred to already at an earlier place in this book. See e.g. Cohen & Sullivan, eds. (2001); Crawford, ed. (1991); Isobe & Hirayama, eds. (1998); Kovalevsky, ed. (1992); McNally, D., ed. (1994); Metaxa, ed. (1999); Schwarz, ed. (2003). It might help if in future meetings of that kind, a special session on air pollution would be included.

In sec. 14.6.2b, when discussing limit star assessments, measurements regarding the influence of localized lighting installations, it was noted that: "The densest layers of aerosols may be more limited in elevation than is commonly believed" (Upgren, 1997, p. 24). A similar suggestion follows from an unpublished study in Italy. In order to assess the light emitted almost horizontally, the luminance of the Italian city of Turin was measured from a hill at a distance of about 15 km. From that place only about 1000 luminaires out of the 84 000 installed in Turin were visible, confirming that the other are hidden in cavities. Moreover, the luminance of the sky over Turin due to the light emitted and reflected upward and diffused by the atmosphere is one order of magnitude higher that the luminance of Turin. The conclusion is that "The luminous intensity in an almost horizontal plane depends on the total luminous flux installed and not on the luminous intensity distribution of the luminaires" (Soardo, 2003). From other sources it is known that the aerosol concentrations over big cities are much higher that over open country.

(c) *Waste and scrap*

In several places in this book, it is mentioned that astronomers are bothered most by light that is projected upwards, and then scattered back to the surface of the Earth. The result is the dreaded sky glow. For a major part, sky glow results from poorly designed, or maladjusted lighting. An important contribution comes from the light that is well-directed to objects, but reflected by them. The first must, and can, be avoided; the second cannot be avoided altogether, but can be restricted. This is discussed in detail in secs. 3.3.3 and 12.4.

In these sections, it is pointed out that it is not correct, as is often dome, to consider both types of upward emitted light as 'lost'. Many people, particularly many astronomers, consider both the direct light as the reflected light as an economic 'waste'. Many publications refer to light as seen from space as "so many million dollars of energy thrown into the drain" (Cinzano, 2000; Crawford, 1991, 1997a; Isobe, 1999; Mizon, 2002).

Here, the peculiarities of the English language play a nasty trick. In essence. the term 'waste' always has two distinct meanings:

(1) Waste refers to the stuff that is thrown away without being used. This is what is referred to by Ralph Nader in his ground-breaking work "The Waste Makers". When you order a hamburger with fried potatoes, and throw most of the fried potatoes away, that is waste.
(2) Waste refers to the package. When you order a hamburger with fried potatoes, eat all of it, and throw the container away, that is also called waste in English. Most other languages have a different word for it. In English, one may use 'scrap', although that is normally used for metals only. The point is that 'waste' is what is thrown away without being used; that is really 'a waste'. Scrap, or rest materials, or whatever term, is also thrown away, but only after it served its purpose.

The point is, that it is incorrect to say that all upward light, emitted from Earth into space, is automatically an economic loss. The reflected – or 'used' – light is, however, a real contribution to light pollution, and it should be restricted as far as possible.

1.2.2 Energy consumption for outdoor lighting

It is not easy to estimate the amount of money nor the amount of energy that is involved in light pollution. In Chapter 13 of this book we will discuss in detail the environmental impact of light pollution on the global energy use and especially on the amount of CO_2 that is issued into the atmosphere, and mention a few of the related cost aspects. Here, we will summarize the main findings. The first step is to estimate the amount of energy that is used in outdoor lighting. Most studies agree that, first, the contribution of electric energy to the total energy household of most industrialized countries is only about 10%. The other 90% is from road transport, heating etc. And secondly, the energy usage for public lighting is very small indeed: often below 1% of the electric energy and about 0,1% of the total energy. Still, at a rate of 0,125 euro per KWh, the 600 GWh that is used per year – as an example – in the Netherlands, amount to about 7,5 million euro, a considerable sum of money (Schreuder, 1998, table 14.2.3). More important, 600 GWh correspond to an extra CO_2-emission of about 300 000 tonnes of CO_2 (Slater, 2000).

In Figure 1.2.1, an example of the energy chain from generator to lighting installation is given.

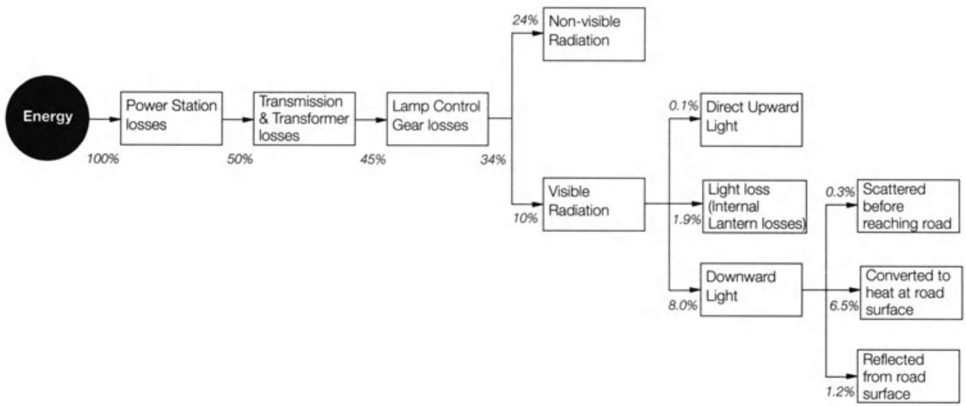

Figure 1.2.1: *The energy chain from generator to lighting installation. After Holmes, 1997, fig. 1.*

"The overall process of obtaining light from a basic energy source, via electricity, is very inefficient. The upward light from luminaires must be reduced for environmental reasons, but in the overall energy scheme it is very much smaller than the other losses in the chain. The percentage figures are illustrative only and their precision is not important to the overall conclusions" (Holmes, 1997, p. 28).

1.2.3 Energy losses as a result of light pollution

All outdoor lighting may cause light pollution. Sky glow is the result of light that is projected upwards, and then scattered back to the surface of the Earth. Part of the stray light is projected directly upwards. Usually this results from poorly designed, or maladjusted lighting; it may, however, also occur when the light is aimed upwards on purpose. Another major contribution to the stray light is the light that is well-directed to objects, but reflected by them. Road surfaces, grass, and buildings reflect a fair amount of the incident light, and the reflected light usually goes upwards. It should be stressed that most of the light has been 'used' in the appropriate way. It is the function of the lighting installation to make objects (surfaces etc.) visible. This can only be done by directing light at them which is – in part – reflected into the eye of the observer. After being 'used', the light may go up and contribute to the sky glow. It is, however, nonsense to consider all light that goes up as economic loss, such as is often stated in the estimates of the cost of light pollution (sec. 1.2.1c).

As indicated earlier in this section, it is estimated that the annual energy consumption for road lighting in the Netherlands was 635 GWh in 1990. For 15,5 million inhabitants, the total power consumption for road lighting was about 41 KWh per person per year. Assuming that road lighting represents about 70% of the total outdoor lighting, the total yearly consumption is about 59 KWh per person. Taking into account that most lighting installations are not too well maintained, one may assume that about 65% of the light will leave the luminaires. This corresponds to 38 KWh per year per person. Taking into account that most lighting installations are not too well designed, one may assume that about 50% of the light will reach its goal. This means that half of the light is 'wasted', corresponding to 19 KWh per year per person. At a price of 0,125 Euro per KWh, this means a loss of about 2,38 Euro per year per person. Now when we look to the USA, the price is different as a result of the much lower costs for energy. For a price of about 0,08 Euro per KWh, this would mean about 1,52 Euro per year per person. With 250 million inhabitants, the total yearly loss will be about 380 million Euro.

When this sort of rough estimate is compared to several well-known studies on this subject, a considerable discrepancy is found. Crawford calculated on the basis of a number of 'rule of thumb' assumptions the loss of one billion dollars annually in the US alone (Crawford, 1991, 1997a). This is about three times the amount estimated here. Isobe has given similar data but then more detailed for specific towns and locations (Isobe, 1999).

As indicated already, these assessments include the reflected light. According to the Italian data, only a small part of the sky glow results from direct light; the major part from the reflected light that cannot, as indicated earlier, be avoided without compromising the function of the lighting itself (Fellin et al., 2000; Gillet & Rombauts, 2001, 2003; Laporte & Gillet, 2003). The estimates by Crawford and Isobe overestimate the energy losses quite considerably. It is likely that this accounts for the factor of three that was signalled earlier.

1.2.4 Environmental impact of light pollution

At present, most electric energy is generated by means of thermal power stations, most of which work on fossilized fuel. The generation of electricity results therefore in the emission on CO_2. For typical UK conditions, the generation of 1 KWh results in the production of just over half a kilogramme of CO_2. The value of 600 GWh per year corresponds to an emission of 300 000 tonnes of CO_2. Lighting accounts for around 20% of total UK electricity consumption and about 6,5% of all UK CO_2 emission (Slater, 2000). Mass-motorization is a major cause of the increase of CO_2 emission. Around 1990, the number of passenger cars world-wide was about 400 million (Seager, ed., 1991, p. 77).

CO_2 as such is a harmless gas that favours plant growth and even may be useful to increase crops. However, it is a greenhouse gas; the increase in CO_2 in the atmosphere leads to an increase of the temperature world-wide. The estimates are not very precise at the moment because the temperature has been measured on a world-wide scale only since the middle of the 20th century and because the temperature changes considerably by natural causes. In sec. 13.1.1, we will discuss in detail the effect of the light pollution on the CO_2 abundance, and the overall effect of the CO_2 abundance on the temperature of the Earth and on the environmental aspects in general. The conclusion is that, although the contribution of light losses – that cause the light pollution – are small compared to many of the other causes of environmental pollution, the effect of the reduction of light pollution might be considered worth-while because, as is said in the Netherlands: 'Alle beetjes helpen' (All little bits may help).

1.2.5 Remedial measures

Basically there are two ways to avoid or at least to reduce the light pollution, more in particular the disturbance for astronomical observations: avoid the light (switching, gated viewing) or reduce the disturbance (light control, spectral selection). The most important remedial measures will be indicated here briefly. A number of the measures will be discussed in greater detail in other sections of this book.

(a) Switching out the lights

This obviously is the final solution as regards the astronomical observations. However, it cannot be done in full as other equally important aspects of our social life require night-time activities and consequently artificial light at night. As is explained in detail in sec. 15.5, many local by-laws and ordinances impose time restrictions in the use of lighting installations. Modern electronic ballasts allow for a less drastic solution, as almost all gas-discharge lamps can be equipped with a dimmer (Baenziger, 2002).

(b) Gated viewing

Gas discharge lamps emit light essentially only when electric current is passed through the plasma. This means that (on a 50 c/s grid) lamps are extinguished 100 times per second. This gives the possibility to apply the principle of 'gated viewing': the shutter of the photo apparatus at the telescope, or of its electronic equivalent, is opened 100 times a second, and only during the periods that the lamp does not emit light. In this way, the observer will not 'note' the presence of the light (Schreuder, 1991, 1992).

The principle of gated viewing is not new. However, in public lighting it has not been put into practice at any considerable scale. An installation designed for gated viewing, is equipped with dimmers that allow light emission only in a small part – for example 50% – of the period of the alternating current. These dimmers are standard equipment, and can be used for almost all types of lamps. That means that, in half of each period, the installation does not emit any light at all. The measuring equipment of the observatory is synchronized in such a way that only in the 'off' period, measurements are made, or pictures taken. In the 'on' period, the shutter is closed – or its electronic counterpart, of course. If the arrangement is carefully executed, the people enjoy adequate light, whereas the observatory can function as if it were in a region of absolute and complete darkness.

There are a number of technical aspects to take into account, of course. First, the whole outdoor lighting installation – probably a whole village – must be fed by a one-phase alternating current system, and not by the usual three-phase arrangement. Usually, this will require a separate electric generating plant. The overall system efficiency may be somewhat lower – a few percent at the most – than the current three-phase systems. However, a separate generating plant allows to use a higher frequency that the current 50 or 60 Hz, which eliminates any visual stroboscopic effects. What is usually called 'high-frequency operation', i.e. a frequency of several KHz, is probably not feasible to be used in gated viewing installations due to the plasma temperature in the lamp. Also, it is not clear whether the luminous efficacy for high-pressure sodium lamps increases in high frequency operation, as is often found in fluorescent tubes. Details are given in De Groot & Van Vliet (1986, p. 210-211). Only lamps that have no 'afterglow' can be used in outdoor lighting. Incandescent lamps and some types of fluorescent gas discharge lamps cannot be used. That is, however, not a severe restriction.

The main problem for the application of the gated viewing system is that it is not tested on any large scale. Most administrators are rather conservative. It will cost some money, particularly in the first stages of design and construction; it is not feasible in large cities with existing elaborate outdoor lighting installations; it is not feasible in places where a large part of the outdoor lighting is privately owned, and finally, it does not reduce the overall sky glow. It seems, however, to be a very promising system for small villages, that until now have no electric lighting, and are near to major astronomical observatories. In these cases, the financial burden is light, and it can easily be carried by those agencies that promote clear, dark skies.

A method that has something in common with gated viewing is based on the effect of 'nulling', or destructive interference of light (Hartmann, 2002). For this, a phase shift of half a wavelength is needed. This works fine for one colour, or rather one wavelength; see e.g. Feynman, et al. (1977). For astronomical observations, an achromatic phase shift is needed. The method described here used a dispersive medium, e.g. two different sorts of glass with a certain analogy to an achromatic lens. According to A.J. Mieremet, who is extensively quoted in the article, theoretical considerations suggest that a 'dimming' of about a factor of one million is possible. It is expected that within a few years, such a system will be operational on the European Very Large Telescope array (VLT) on Mount Paranal in Chile, in the study on exo-planets, or planets that do not belong to the solar system. It is not known at present, whether such a system of achromatic destructive interference could be applied in the efforts to reduce the negative impact of light pollution.

(c) Light control

Light control means, in simple terms, preventing light being emitted above the horizon; more precisely, it means that the light is directed to the objects to be illuminated. In practical terms, this means primarily the selection of the appropriate light distribution and the best optical design of luminaires for outdoor lighting. The positioning of the luminaires needs to be taken into account because optimising the light distribution and the positioning are supplementary measures. In sec. 7.1.4, the classification of luminaires as regards their light distribution, is discussed in detail. As regards the road lighting, the measures to reduce light trespass are similar to those that enhance the economic efficiency of the lighting installation (Schreuder, 1998).

(d) Reduction of reflection

Theoretically speaking, this remedy is just as important as the two that have been mentioned earlier. In practice, however, the possibilities to manipulate the reflective characteristics in the real world are very limited indeed. Furthermore, reducing the reflection of the road surface may be counterproductive, because in order to arrive at a certain luminance level for a 'dark' road surface, the luminous flux aimed at the road must be higher. A higher luminous flux means, however, a greater amount of stray-light, and thus an increase in light pollution. In sec. 12.4.4, we will discuss more in detail the influence of reflected light.

(e) Using monochromatic light

As has been indicated earlier, the most effective way available at present to reduce interference is the use of monochromatic or quasi-monochromatic light sources, more in particular the use of low-pressure sodium lamps. These lamps emit a very narrow spectral band, almost a line, in the yellow part of the spectrum. As will be explained in sec. 8.2.3 and in sec. 14.1.2, most traditional photometry is done in terms of photopic vision or daytime vision, whereas the observations are usually made at lower luminances in the mesopic vision range. The consequence is that it is sometimes necessary to adapt the weighing factors when comparing different light sources.

(f) Filtering the light

Finally, reducing the width of the spectral range of the emitted light is an effective countermeasure against the interference by light of astronomical observations, particularly in those cases where the use of low-pressure sodium lamps is impossible or undesirable.

1.2.6 Implementing remedial measures

(a) Education aspects

As is explained in sec. 1.2.5, basically, there are two ways to avoid or at least to reduce the disturbance for astronomical observations: to avoid the light, like e.g. switching, gated viewing, or to reduce the disturbance, like e.g. light control, spectral selection.

It is fairly simple to list a number of remedial measures to eliminate, or at least diminish light pollution. It is not so simple, however, to indicate how these measures can be implemented. Details are given in CIE (1997); Schreuder (1987, 1987a, 1988, 1994a, 1997, 1998, 2000, 2001, 2003). The different means that are relevant for the implementation of remedial measures, are discussed in detail in Chapter 15 of this book.

The first obstacle seems to be the lack of knowledge of the relevant aspects from the side of the authorities. One should try to convince the authorities that the cause of the astronomers and other interest groups, is a legitimate one. Furthermore, one should try and persuade the authorities that the means to fulfill the requirements are available and technically feasible, that many are within reasonable financial limits, and that some solutions may also have economic advantages. Clearly, this is a matter of schooling and education, matters that are discussed in detail in sec. 15.3.1. In this respect, it is interesting to note that the astronomical world as a pressure group is a powerful force. Most astronomers do not seem to realise the power they wield in public opinion, and therefore in politics. Astronomy as a world force is discussed in sec. 15.1a.

(b) Attitude changes

A further obstacle is the fact that lighting engineers and astronomers often seem to be two opponent groups, who have interests that cannot be reconciled, and, even worse, that they are not willing to reconcile them. The reality is different. True, astronomers and lighting engineers usually know very little of each other, and in the pressure of day to day activities, they have little time to meet. Furthermore, they hardly understand each other because of differences in 'jargon' and working methods. Astronomers often think in mathematical terms, whereas lighting engineers are practical technicians who think in terms of operational costs. However, both groups are professionals who are capable, each in their own field, and who are proud to do their jobs well. Both regard themselves as servants of humanity, be it in different realms. Both are severely restricted by politicians and financial bosses in doing their work adequately. Finally, neither of the groups seem to realise the large benefits that society receives from their activities, be it, as said, in different realms.

Which implies that there is no conflict between astronomers and lighting engineers. There is some misunderstanding, and there is quite a lack of knowledge of the field of the other. Fortunately, things are changing rapidly for the better. After a hesitant start, cooperation resulted in several joint reports and, more recently, in working joint groups, where both professional world organizations are represented. Some of these group activities are mentioned in sec. 1.3.

One of the leading principles in the efforts to reduce light intrusion and light pollution, is that not in all places, nor at all times, the same degree of protection is needed. This principle did lead to the concepts of zoning and curfew, that are discussed in detail in sec. 7.1. When considering the implementation of remedial measures, there is a factor that is usually overlooked.

(c) Functional requirements

Just as it is not feasible and not necessary to have, in all places, or at all times, the same degree of protection, it is not feasible and not necessary that astronomical observatories can make, in all places and at all times, all types of observation. In other words, it is not only possible, but necessary, for the astronomical world to set up a system of functional requirements as regards the operation of observatories. These functional requirements would include the type of observations, the management plans to do in the observatory, by which staff, at which time, and using which equipment. Also, the type of observers needs to be taken into account. A help might be the classification of observatories, that is suggested by Murdin (1997). This classification is discussed in sec 7.1.1. In Table 1.2.1, a summary of these suggestions is given.

CIE 1997	CIE 2000	ALCoR	Designation
E1	E 1a	5	world class
E1	E 1b	4	international class
E1	E 1c	3	academic 1 m
E2	E 2	2b	graduate 1 m
E3	E 3a	2a	amateur 0,5 m
E3	E 3b	1b	amateur 0,3 m
E4	E 4a	1a	casual sky viewing
E4	E 4b	0	casual object viewing

Table 1.2.1: *Observatory classifications and designations. After Murdin, 1997; Schreuder (1994, 2000).*

Notes to Table 1.2.1:
- CIE 1997: according to CIE, 1997;
- CIE 2000: accepted by CIE TC 4.21 in 2000 (CIE, 2000a);
- ALCoR: according to Murdin, 1997;
- Designation: according to Murdin, 1997.

The table combines the astronomical designation with the zones in which such observatories could function. What could be added, and what astronomers ought to deliver, is the type of observations that each observatory class ought to be capable of. This is what we have called the 'functional requirements'. To non-astronomers, it seems to be a natural matter that for observations of distant, very vague galaxies, different equipment is needed, than for the precise determination of the position of bright stars, etc. It seems also natural, that different equipment suffers in different degrees from light pollution. Some astronomers seem to feel, however, that any astronomical observatory must be allowed to perform any type of observation. If this requirement really would be effected, it would mean that in most cases, top-notch equipment would be used for observations that could be made just as well with more simple and less expensive equipment. It would also mean, that many observations could be made in locations where the light pollution is noticeable. Obviously, it would require a world-wide division of labour between astronomers as well as between observatories. The ideas about education, that are discussed in detail in sec. 15.3, would be applicable.

The next step would be that, based on the functional requirements of the observatories, the astronomers must provide the functional requirements for outdoor lighting, including the restrictions in the lighting. Based on these functional requirements, the lighting engineers can provide adequate lighting designs and adequate lighting equipment. The functional requirements for the lighting need to cover the requirements regarding the angular and time distributions of light, restrictions in spectral emission, etc.

It should be stressed here that the establishment of functional requirements is essential for all areas of astronomical observation; more specifically, it is not sufficient if only the professional astronomers who observe deep-sky objects with sophisticated equipment on remote mountain tops in the subtopics of the Southern Hemisphere indicate what they require. The large number of amateur astronomers, who provide the most data on comets, asteroids, and meteors, and who do a large amount of photometry, must be in the position to formulate their functional requirements as well.

(d) Cost considerations

When considering light pollution, and the way its impact can be curtailed, cost aspects cannot be overlooked. In sec 14.2.3d, when discussing the integration time in radiometry, it is explained that, in the case where observations are constrained by sky glow, a 'figure of merit' can be introduced. It can be shown that the integration time needed, is proportional to the background luminance, the square of the seeing, and inversely proportional to the efficiency of the detector and the telescope area (Tritton, 1997, as quoted by Schwarz, 2003). So doubling the background luminance doubles the required integration time. Put differently, one needs a telescope with double the area to get the same signal-to-noise, or S/N, in the same time. That means increasing the mirror diameter r by the square root. Since the price of a telescope is approximately proportional to $r^{2,8}$, doubling the sky increases the cost of a telescope by a factor of 2,6 or so (Schwarz, 2003). Murdin (1997) used a slightly different rule-of-thumb: the costs of a telescope increase with the third power of the lens or mirror diameter – that is, with the volume of the dome!

These values are in agreement with the data from Crawford (1992) that are quoted in sec. 3.3.2. Artificial sky glow reduces the effectivity of telescopes. In Table 3.2.2, the loss of effective aperture is given in relation to the level of sky glow (Crawford, 1992, table 2.1). According to that table, if the sky luminance as a result of artificial light is 10% of the natural background luminance, the relative effective aperture of the telescope would decrease by 12%. A sky glow of 10% corresponds to the value that is proposed by IAU as the maximum permissible sky glow. In several sections of this book, the question is raised whether this requirement might be considered as too high to be realistic. Sky glow values of 0,2 to 0,5 times the natural background are quite common in less favourable observatories. According to Table 3.2.2, this would result in a decrease of the relative effective aperture of the telescope of 22% and 42% respectively. Using the exponent of 2,8 (Schwarz, 2003), the relative costs would be 1,52; 1,75 and 2,69 respectively of the 'ideal' location, with a sky glow equal to zero.

Observatories are expensive, particularly if they are constructed in remote places. In 1991, it was estimated that the total bill for the observatories in North Chile at Cerro Tololo would amount to about 1200 million US$ (Smith, 1991, p. 41). Incidently, it is likely that the overall bill will be much higher than that, because the plans for the observatory still expand, and because most equipment is not constructed, or paid for, in Chile. In 1999, the yearly costs were about 60 million US$ for construction and 40 million US$. Thus, the observatory contributes about 100 million US$ to the Chilean national economy.

These costs are not the only costs of an observatory. A major observatory would require a staff of over 100 persons (Schreuder, 1991). Cerro Tololo, being not one, but a number of observatories at the same location, would need maybe 250 staff. Assuming the observatory is a fair employer, this would mean some US$ 30 000 per person per year, including insurances, taxes, etc. or some 7,5 million yearly. Related to the capital costs, it means that a world-class observatory is predominantly a capital investment.

The implication is, that measures to restrict artificial sky glow, might cost a lot of money, and still be cost-effective. We will use the Cerro Tololo as an example, and use published data as input. At the moment, it is one of the best locations in the world as regards light pollution. At Cerro Tololo and Cerro Pachon, it is at the moment not possible to measure any artificial light pollution at elevations over 45 degrees, meaning that the artificial sky brightness in the zenith is less that 0,08 magnitude per square arcsecond over natural background (Smith, 2001, p. 41). So, it may classify as 'ideal'. If we use the data given earlier in this section, a measure to prevent the sky glow to deteriorate from 'ideal' to 'good' (10%), may cost $0{,}52 \cdot 100$ million = 52 million annually, and still be cost effective. A measure that would prevent the sky glow to deteriorate from 'ideal' to 'considerable' (20%), may cost $0{,}75 \cdot 100$ million = 75 million annually, and still be cost effective. A measure that would prevent the sky glow to deteriorate from 'ideal' to 'severe' (50%), may cost $1{,}69 \cdot 100$ million = 169 million annually, and still be cost effective.

It is maybe difficult to imagine what these figures really mean. As an example, we will quote here what is mentioned in sec 13.2.2. In 1990, the total energy used for all road lighting in the Netherlands – 41 000 square kilometre, 15,5 million inhabitants – was about 700 000 MWh annually (Table 13.2.1). Since then, there are more light points but more efficient lamps. So we may take the same number. Electricity costs about 0,1 Euro per KWh, so the total energy costs for road lighting are about 70 million Euro annually. Usually, the total annual costs of road lighting is about 3 times the energy costs. One might pay for all road lighting in the Netherlands with about 200 million Euro. So, the Cerro Tololo people could use almost all the money needed to light the whole of the Netherlands to prevent really serious damage. This is, of course, only an example to clarify the amount of money we speak of in cost-benefit assessments of anti-light pollution measures.

It is hard to accept that it seems that this type of very basic cost-benefit assessments are not made. If they were, there would be no qualm to pay a little money – a small fraction of the total budget – to improve the situation near the top-class observatories.

Of course, the astronomical world is more than the small number of top-class observatories. One may make the following crude estimate for the major observatories in use by professional astronomers (Schreuder, 1992; 1993). World-wide, there are probably 10 top class observatories, each costing 1000 million Euro. There are maybe 100 large national observatories, each costing 10 million Euro, and maybe 1000 regional observatories, each costing 1 million Euro. The total would be 12 000 million Euro. Amortization over 15 years, at a modest interest rate, is 6,6% annually, so world-wide 792 million Euro in capital costs. One may assume that a top class observatory will employ 100 people, large national observatory 30, and a regional observatory 10. One may add 3000 professional astronomers. In total 17 000 persons. Personal costs, including taxes, insurance and overhead will be maybe 70 000 Euro, so the personal costs world-wide will be 1190 million Euro annually. In total, that is 1982 million Euro annually. If we assume that observations are made 2000 hours per year, the costs of professional astronomy world-wide are about 1 million Euro per hour.

These estimates seem to be reasonable when comparing to the estimate made about world-wide astronomy, which seems to include much more that only the major observatories in use by professional astronomers (Woltjer, 1998). "Annual spending on astronomy, including planetary science, is large. Rough figures are as follows: Western Europe 1300; USA 2200; Japan 500 (in millions of US$). For other countries, a realistic evaluation is more difficult, but it is clear that worldwide spending on astronomy is in the range of 4000 to 5000 million US$ per year. The investment in facilities is also large: we may estimate the ground-based equipments in 2000 to represent an investment of some 2000 million US$, and functioning satellites and space probes about 7000 million US$" (Woltjer, 1998).

(e) *Obtrusive light audits*

Audits are a common tool in finding out in how far the aims and goals of a policy decision have been implemented. The principle is simple: one knows the goal and one knows the results. A straight-forward comparison will show the effect. And that is precisely what is done in light audits.

The term 'audit' is a bookkeeping term; the dictionary defines it as "an official examination of accounts of a business or institution", where an account means "a record of money matters, services or goods".

The policy decisions as regards outdoor lighting are made primarily by the authorities, in most cases by the municipalities. Depending on the level of sophistication of the city government and its decision-making processes, the policy is founded on objective criteria in different degrees. In many cases, the goals of the lighting installations are based on general policy principles such as providing road and public safety to citizens, or to enhance the economy of the region. The functional approach as regards road lighting is described in detail in Schreuder (1970, 1991a, 1998).

After the goals have been established, the lighting design is made. The design is based on recommendations, regulations, or standards. For road lighting, the CIE and CEN documents give internationally accepted guidelines (CEN, 1998; CIE, 1992, 1995). National standards usually are based on these documents. Such national standards usually need to be followed in order to win governmental financial support for the lighting. From this, the visibility requirements of the lighting installation can be derived, which lead in their turn to the photometric and geometric characteristics of the installation so that it may fulfill the requirements. This is the supply-and-demand model that is described in sec. 10.2.1b. In sec. 11.2, the process of the design of outdoor lighting is discussed in detail. The lighting installation is realised according to the design. Finally, the result is measured.

Usually, one assumes that the goals are reached, when the measured values agree with the design, or, one step more convincing, the lighting agrees to the norms that were used. It is a task of any democratically elected government to take care of the interests of the citizens as well as taking care of the more general interests of the community. Most governments extend the matter to the world: most governments feel a responsibility to protect the Earth by working according to a well-defined environmental policy plan.

Part of the policy relates to – or at least should relate to – the protection of the dark sky. So measures related to avoiding, or at least reducing, obtrusive light are an essential part of that policy. This implies that the requirements and the decisions as regards the outdoor lighting take the requirements of the dark sky into account. These processes are discussed in detail in Chapter 15 of this book.

The audit system is a tool to find out in how far the policy goals are realised – in this case as regards the dark sky. The audit involves several steps:
(1) To establish what the policy goals are of the government as regards the outdoor lighting;
(2) To establish what the standards, ordinances etc. are that have to be applied or followed;
(3) To establish what the photometric characteristics of the lighting installation are if the policy aims and the standards are adhered to;
(4) To establish what has been installed in the area (viz.: the municipality in question). This involves making an inventory of the outdoor lighting (Narisada & Kawakami, 1998).

When this is done, a comparison can be made. Based on this comparison, recommendations can be made to the government as regards the future policy (improvements etc.). An example of how an obtrusive light audit may look is given in Anon (1996), referring to Directive on Environmental Management, issued by the European Union. As described in Anon, 1995, p. 10, an environmental audit has to go through the following steps:
(1) Establishing an environmental management system;
(2) Establishing an environmental policy;
(3) Analysis of the present situation;
(4) Establishing an environmental programme;

(5) Periodical control of environmental checkpoints;
(6) Continuous adaptation of the environmental objectives;
(7) Establishing an environmental declaration;
(8) Check of the environmental management system;
(9) Check of the audit report;
(10)Registration.
In this survey, it is not specified which environmental protection aspects are to be included. It is clear, however, that light pollution countermeasures fit without any problem in the scheme.

1.3 International organizations

1.3.1 ICSU

This section is based in part on McNally (2002). ICSU is the code for Council for Science. It was formerly called the International Council of Scientific Unions. It is the parent body for the international scientific unions. It sets the rules under which they can operate. For example, it requires their accounts annually; it deals with governments on behalf of the Unions; it sets practices on discrimination against individuals and groups to ensure that scientists are not disadvantaged on social, ethnic, religious or any other grounds.

It has established many inter Union committees, for example COSPAR (Committee on Space Research), SCOPE (Scientific Committee on the Problems of the Environment), SCOSTEP (Scientific Committee on Solar Terrestrial Environment Problems) etc. These Committees are self-sufficient and while they get some funding from ICSU, they must raise other revenues – usually by sale of publications.

Some scientific unions are ICSU Associates, although CIE is not. However, ICSU does not encompass associations of a science commerce nature.

ICSU holds a General Assembly biennially. ICSU in the past was the vehicle of the Unions; in recent years it has moved away from this primary purpose towards leadership in interdisciplinary projects like the Geosphere/Biosphere project. These projects in which the Unions and Committees are prime movers, if adopted by ICSU, then ICSU will help with fund raising.

The international scientific Unions were founded in 1918/1919 by the League of Nations. The parent body was the International Research Council. The IRC had got so embroiled in politics by the end of the 1920s that ICSU was established to take over its supervisory role in the early 1930s. Since then it has maintained the essential non-political stance necessary.

1.3.2 IAU

This section is also based in part on McNally (2002). The International Astronomical Union (IAU) was founded in 1919 in the first tranche of scientific unions. It has been built on more than 50 years of wide astronomical cooperation. Astronomical research is heavily dependent on international cooperation and consequently the IAU is much more of a 'hands on' Union than most of the other unions within ICSU. This shows in the IAU having a large individual membership – the IAU is much closer to the concept of an astronomical Society.

The IAU aims to identify areas of research requiring international cooperation and then to bring together practioners from about 60 different countries at present. It holds meetings at which current astronomical research is presented and discussed – e.g. Symposia, Colloquia, Regional Meetings, and General Assemblies. It identifies areas requiring specific research and where appropriate, will provide specialist services e.g. the IAU Telegram Service, join with other Unions to provide inter-Union services e.g. IUCAF (to preserve radio frequency space for the passive services) and IERS (International Earth Rotation Service). The IAU sets up working groups to examine specific problems in research areas – sometimes these are of limited duration, sometimes they develop into Commissions to bring together major interests e.g. Interstellar Matter, Bibliography, Education, and Preservation of Observatory Sites. There are 38 Commissions currently organised into more than 10 Divisions.

The IAU is financed, as are all the ICSU Unions, by national contributions, augmented income from sales of publications, ICSU subvention, grants, and interest on its bank accounts. The income of the IAU is rather less than one million Euro. It achieves a big multiplier through its members and their institutions.

The IAU keeps contact with its members through its Information Bulletin published biannually. The cover of the IB has a back cover which gives details on the IAU. Its membership is now in excess of 8600 from about 60 countries.

1.3.3 CIE

(a) *The origins of the CIE*

This explanation is based in part on Hermann (2001). The Commission Internationale de l'Eclairage CIE (the International Lighting Commission) is an organization devoted to international cooperation and exchange of information among its member countries on all matters relating to the science and art of light and lighting. The CIE is an autonomous organization. It was not appointed by any other organization, political or otherwise, but it has grown out of the interests of individuals working on illumination.

Its predecessor, the 'International Commission on Photometry' was founded in 1900 as the first international body concerned with light measurement, in particular of incandescent gas lamps, at that time the most common light source. In the course of the years the new technology of illuminating engineering did develop rapidly, leading to new and more efficient light sources and lighting equipment. The measurement of light did become only a part of a much wider activity: the study of how to use to the best advantage the light which these new sources could provide. A wider scope of the Commission was suggested; in 1913, the 'Commission Internationale de l'Eclairage' was founded.

Right from the beginning, the CIE was accepted as representing the best authority on the subject. As such, it is recognized at present by the International Standards Organization ISO and the International Electrotechnical Commission IEC as an international standardizing body. The CIE standards are submitted to ISO and IEC for direct endorsement. Recently, an agreement was signed with the Comité Européen de Normalisation CEN on technical cooperation with the aim to enhance the collaboration and to avoid duplication of work.

(b) The objectives of the CIE

In a summarized form, the objectives of the CIE are:

(1) To provide an international forum for the discussion of all matters relating to the science, the technology and the art in the fields of light and lighting;
(2) The develop basic standards and procedures of metrology in the fields of light and lighting;
(3) To provide guidance in the development of international and national standards;
(4) To prepare and publish standards, reports and other publications in the fields of light and lighting;
(5) To maintain liaison and technical interaction with other international organizations on matters related to the fields of light and lighting.

It should be noted that it was agreed to consider the electromagnetic spectrum in the Infrared and the Ultraviolet regions, as well as Image Technology as belonging to the field of interest of the CIE.

(c) The organization

CIE has only countries – or more precisely, National Committees – as members. In 2003, CIE had just over 40 members. In recent years, the number of less industrialized and of Third World countries has increased considerably. In addition, individuals or organizations from countries where a National Committee has not yet been established, may join as Associate Members. They have no right to vote but they are welcome to participate in the technical work of the CIE.

The affairs of the CIE are vested by the General Assembly, consisting of the Presidents of the National Committees of all Member Countries. The General Assembly meets every two years – once every four years during the formal Sessions of the CIE and once in the mid-session meetings. The daily matters of governing the CIE are taken care of by the Board of Administration; the work is supported by the Central Bureau which is headed by the General Secretary.

The scientific and technical activities of the CIE are taken care of by the Technical Committees. Each Technical Committee has a specific objective and, in principle, a limited life-span – this to avoid a proliferation of Technical Committees. Members of the TC's are proposed by its president and acknowledged by the relevant National Committee.

(d) The working programme

The working programme can be divided broadly in the two areas of fundamental research (covering such topics as vision, colour, and measurement) and lighting application subjects. In all, the CIE work is subdivided in a number of Divisions. The description of the areas of interest of the different divisions is based on their Terms of Reference:

(1) Division 1: Vision and colour: To study visual responses to light and to establish standards of response functions in areas such as photometry, colorimetry and visual performance;

(2) Division 2: Measurement of light and radiation: To study standard procedures for the evaluation of UV, visual and IR radiation; to study optical properties of materials, luminaires and physical detectors;

(3) Division 3: Interior environment and lighting design: To study and evaluate visual factors which influence the satisfaction of the occupants of a building; to study the interaction of the visual factors with thermal and acoustical aspects; to provide guidance on relevant design criteria for both natural and man-made lighting;

(4) Division 4: Lighting and signalling for transport: To study lighting and visual signalling and information requirements of transport and traffic, such as road and vehicle lighting, delineation, signing and signalling for all types of public roads and all kinds of users and vehicles, and visual aids for modes other than road transport. One of the TC's in Division 4 is CIE TC 4-21 'Interference by light of astronomical observations'. Several CIE publications are of special interest (CIE, 1980, 1993, 1997);

(5) Division 5: Exterior lighting and other applications: To study procedures and prepare guides for the design of lighting for exterior working areas, security lighting, flood lighting, pedestrian and other urban areas without motorized traffic, areas for sport and recreation, and for mine lighting. One of the TC's in Division 5 is: CIE TC 5-12 'Obtrusive light'. One CIE publication is of special interest (CIE, 2003a);

(6) Division 6: Photobiology and photochemistry: To study and evaluate the effects of optical radiation on biological and photochemical systems (exclusive of vision).

(7) Division 8; Image technology: To study procedures and prepare guides and standards for the optical, visual and metrological aspects of the communication, processing and reproduction of images, using all types of analogue and digital imaging devices. It might be added that Division 7 was disbanded several years ago. For further detail on CIE, see Hermann (2001).

1.3.4 The International Dark-Sky Association

This section is based in part on Crawford (2003). It is noted that valuable information about good lighting can be gotten from a number of sources, like the CIE and many national illumination organizations. These are great resources to learn about good lighting and how to use it. However, educating the public or even non-lighting industry individuals and organizations is usually not their primary goal. The International Dark-Sky Association (IDA) is a non-profit membership based organization whose goal is to educate everyone about the value of good nighttime lighting and of the night environment, including dark skies. To do so, there must be educational resources available. For IDA, these include a web site (www.darksky.org), a newsletter, many information sheets (most available on the web site), slide sets and other visuals, CD's, videos, posters, and other items, for members and for non-members. IDA also has many local and regional Sections, and a number of active Working Groups. Lists of these are available on the web site. IDA members are actively involved in other organizations, in the lighting industry as well as in the environmental arena. As of early 2003, IDA has nearly 10 000 members from over 70 countries, including all of the states in the United States. About 500 of these are organizational members. Members are of all types: lighting engineers and designers, amateur and professional astronomers, environmentalists, and individuals bothered by poor local lighting in their area. Membership is still growing rapidly.

IDA believes that good nighttime lighting has great value. lt minimizes glare and other obtrusive effects of poor lighting, saves energy, and improves our nighttime environment, for humans and for the ecological system. With good lighting, we all win, and we help preserve of view of the universe. For further details on IDA, see Crawford (1991).

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2 Aim and purpose of outdoor lighting

Outdoor lighting is defined as the fixed artificial lighting to illuminate the areas, where there are no roofs, i.e., outdoor areas. The aim of the outdoor lighting is, by illuminating the area, to maintain or to improve visual performance of the persons conducting human activities. The visual performance is defined as the speed and accuracy with which visual task is performed. Visual task is the task of seeing the objects that are relevant to the task.

The purpose of the outdoor lighting is to increase the efficiency of human activities during the time when it is dark and to make production, transportation, construction, city beautification, etc. in the outdoor areas efficient, safe, secure and comfortable. The increase in the efficiency of human activities during the time after dark sometimes contributes, indirectly, to the increase in the efficiency of human activities in daytime.

2.1 The contribution of outdoor lighting to the efficiency of human activities at night

2.1.1 Functional activities

Before discussing the efficiency, the concept of efficiency must be considered. As is well-known, the term 'efficiency' is used for a variety of matters. The concept of efficiency used for technical matters is easiest to understand. For technical matters, efficiency means the relationship between the amount of energy that goes into a machine, system, engine or lamp, and the amount that it produces (Anon., 2001).

The efficiency concerning most human activities, however, is not as easy to describe as in the cases of technical matters, since neither the input – the amount of energy – nor the output – the amount that is produced – can be easily measured or calculated in a quantitative way. In this section, therefore, the efficiency of human activities will be discussed qualitatively.

It is to be expected that the efficiency of human activities under artificially lighted outdoor environment after dark will be influenced, amongst others, by the following four factors:

(1) The photometric conditions of the visual environment provided by the outdoor lighting;
(2) The physical conditions of the lighted environment;
(3) The physiological conditions of the people who are conducting the activities;
(4) The psychological conditions of these people.

These four possible factors are always interrelated in a complex way. The photometric conditions provided by the outdoor lighting are closely related to the physiological performance of vision to detect, perceive and distinguish the existence, size, shape, colour, texture, moving, distance, changes in the brightness or colours, etc. of the objects to be seen.

Also, the photometric conditions influence the psychological conditions of the persons in the environment. As described above, as the photometric conditions improved by the lighting, the visual performance is improved (Blackwell, 1946). Consequently, one may expect that the efficiency of the human activities will be increased. As the visual performance improves, the persons in the lighted environment can carry out their visual task more easily and comfortably. As a result, their morale, motivation and/or willingness will be improved. Consequently, their psychological efficiency carrying out human activities will be also improved.

2.1.2 Non-functional activities

The psychological efficiency, however, is not always improved by the increase in the visual performance. For example, when a few persons are sitting intimately together around a small table in a relatively dark garden in the evening, enjoying conversation or drinking quietly, the persons do not need to see the fine details of anything, such as the facial expressions and the clothes of other persons, the dishes and the cups on the table, the flowers, trees, fountains in and around the garden, etc. Their only need is a pleasant and beautiful background.

This does imply that only increasing the visual performance by means of the outdoor lighting does contribute to the improvement in the 'efficiency of the human activities'. Nevertheless, if there is no outdoor lighting installed in the garden, and no moon in the sky, the environment is very dark and nothing is visible. The 'efficiency' of talking and drinking will be extremely low. This is an example of the outdoor lighting being indispensable even for such a psychological and non-functional activity.

It is evident that, for non-functional activities, the widely accepted concept of efficiency cannot be applied. Still, an appropriate level of the outdoor lighting is necessary. The appropriate outdoor lighting, no doubt, contributes to the psychological efficiency of enjoyable human activities in the dark garden. In the following, however, such a special efficiency will not be discussed in further detail.

2.1.3 The indirect contribution of outdoor lighting to the efficiency of human activities in daytime

Without outdoor lighting, almost no outdoor activities can be conducted as efficiently as they are at present. As a consequence, all the production activities in the outdoor areas have to be stopped in the evening. This will make continuous works to be carried out in the outdoor areas, such as construction works and continuous production in the chemical and petroleum processing industry impossible. Similarly, if there is no outdoor lighting, loading or unloading of cargos for trains, ships, and airplanes, and maintenance works for various facilities will be impossible to carry out at night. If these activities have to be conducted only in the daytime, huge amounts of time, energy and labour will be wasted. This shows that the existence of the outdoor lighting itself is already contributing extensively to the efficiency of daytime human activities.

2.2 The contribution of outdoor lighting to commercial activities at night

Outdoor lighting has a special relevance to commercial activities at night. In most shops, activities are carried out indoors under interior lighting. Outdoor lighting is not relevant for the selling activities. The shopkeepers, however, need many shoppers to come to their shops or to the shopping areas in order to carry out their commercial activities. To attract many shoppers to the shops or shopping areas at night, all the routes along which the shoppers come, by car or on foot, to the shops have to be lit by means of outdoor lighting, so that they are able to come along, safely, easily, in security, comfortably, and even enjoyably.

High-quality outdoor lighting on the streets in front of their residences, and on the streets to and in the shopping areas, encourage people to go and shopping in the evening.

To attract attention of shoppers to the shops in the shopping areas, luminous signs, illuminated advertisements or floodlighting, which all classify as outdoor lighting, are used. Also, by providing the outdoor lighting for parking lots adjacent to the shops and shopping areas, the shoppers are able to come to the shops by car. All these functions contribute to the commercial activities at night.

By providing good outdoor lighting, the commercial goods coming from the suppliers to the shops can be unloaded, and the rubbish can be loaded into trucks at night. At the same time, shopping streets can be cleaned before the commercial activities start again the next day. These examples also show the important role of the outdoor lighting for commercial activities at night.

2.3 General characteristics of outdoor lighting

The term 'outdoor lighting' seems to speak for itself. The essential aspect of outdoor lighting is the absence of a roof. In practice, there are other distinctions, mainly related to the fact that within the art and science of illuminating engineering, indoor lighting is treated quite differently from outdoor lighting. This is immediately obvious when one looks into the lighting engineering handbooks: usually, they start by making a distinction between indoor and outdoor lighting. From there on, almost everything is different. Lighting standards, products, manufacturers, calculating and measuring systems, all is different. As an example, it is interesting to consider two 'classical' handbooks, one on outdoor lighting and the other on indoor lighting, written by professor De Boer, one of the most distinguished lighting engineers ever (Van Bommel & De Boer, 1980; De Boer & Fischer, 1981). The scope, the lay-out and the contents of the two books are in stark contrast. In essence, however, there should be no such distinction, because it is the same human observer with the same visual system who is going to use the light.

One of the few who tried to amalgate the two was the equally famous Parry Moon (Moon, 1961; Moon & Spencer, 1981). The idea of a unified 'photic field' was never taken up by the illuminating engineering world. The idea is based on the work of Gershun (1939). Even the work of the almost equally famous Richard Blackwell, although termed a 'unified framework', essentially is only applicable to interior lighting (CIE, 1981).

When discussing light pollution, the fact that outdoor lighting installations are roof-less installations, is of course the crucial aspect. Light, either direct or reflected, goes upwards and as there is no roof to block it, goes up unhindered into the atmosphere, where it may be reflected or scattered, and, of course, absorbed. The reflected and the scattered light cause the light pollution.

There are other aspects of outdoor lighting that may be mentioned. Firstly, contrary to indoor lighting that is often primarily decorative, outdoor lighting is almost always functional. This implies that the recommendations as well as the design methods are focussed on visual performance in stead of visual comfort and aesthetics. Secondly, as a direct consequence of this, the basic considerations are expressed in terms of luminances of the area that determine the visual task, in stead of illuminances on planes, or of luminous intensities of light sources and luminaires. It should be noted that, contrary to outdoor lighting, most indoor lighting designs are supervised by national and not by international regulations and standards. Thirdly, in indoor lighting, glare is usually restricted by considerations of discomfort, whereas in most functional outdoor lighting, glare is restricted by considerations of disability. And fourthly, probably the most important, the lighting levels that are recommended or prescribed in outdoor lighting are usually but a small fraction of those that are commonly used in interior lighting. In sec. 9.1, this will be discussed in more detail.

As explained in the 'Guidelines', published by the CIE: "Sky glow is the result of light that is projected upwards, and then scattered back to the surface of the Earth. Part of the stray light is projected directly upwards. Usually this results from poorly designed, or maladjusted lighting; it may, however, also occur when the light is aimed upwards on purpose. Another major contribution to the stray light is the light that is well-directed to objects, but reflected by them. Road surfaces, grass, and buildings reflect a fair amount of the incident light, and the reflected light usually goes upwards" (CIE, 1997)

The CIE Guidelines continue as follows: "The main sources of stray light that may interfere with astronomical observations are (in random order):

- lighting of industrial sites, airports and building sites;
- road and street lighting;
- advertising signs
- floodlighting of buildings, discos and monuments
- lighting of billboards
- lighting of greenhouses
- lighting of sports facilities
- area lighting of sales areas, parking lots, farm yards, railroad yards etc." (CIE, 1997, Chapter 5).

2.4 City beautification

Outdoor lighting makes cities or towns at night beautiful. First, it is because lighted landscapes, buildings, monuments etc. stand out against the dark surroundings, which are not lighted. Second, the direction, configuration, the luminous distribution, and the colours of the light used for the outdoor lighting are different from natural daylight. By applying appropriate lighting designs, the lighted buildings, monuments, etc. can be made much more beautiful and attractive in the night. If arrangements of lighted buildings etc. in the city or town are carefully planned, the city or town as a whole is made beautiful. In a way, these activities are more the work of lighting designers than of lighting engineers (Pasariello, 2003). This usually is called 'city beautification', in which outdoor lighting has a major role. City beautification schemes encourage inhabitants and visitors of the city to go into the city centres at night, and enjoy various social, commercial and sightseeing activities of the city or town at night.

The reasons that many municipal authorities pay attention to city beautification is primarily to promote the city as an environment which is worth-while to live in. In the second place, its aim is to promote the city as a place worth-while to visit for reasons of tourism and commerce (Schreuder, 2001, 2001a). In this respect, many cities boast successfully specific buildings, streets, squares etc. Some examples are the Ramblas in Barcelona, Time Square in New York, the Todaiji Temple in Nara, the Bund in Shanghai, the Red Square in Moscow.

The technical aspects of city beatification are critical. There is ample literature on improving the nighttime aspects of buildings. See e.g. Cohu (1967) and Forcolini (1993). However, little attention is paid to the nighttime architecture of larger urban areas.

2.4.1 Streets and squares

(a) Streets

In the first place the lighting for streets in the cities and towns is installed for the convenience, safety, and security of pedestrians. The first requirement of a footpath at night is that pedestrians are able to walk without fear of stumbling over a stone, or wander from the footpath. Such things are very unlikely to happen on paved streets lit by modern street lighting. The next requirement is to make a pedestrian, who is walking along a street in an unfamiliar town at night, able to judge the orientation and the current position on the street.

For this purpose, floodlighting of well-known big buildings. like e.g. churches, temples, palaces, railway stations, bus stops, commercial buildings, municipal buildings, parks, ponds, and luminous advertising signs are important and effective. Further details of lighting of the building will be described in the further parts of this section.

It is a well-accepted fact that the street lighting reduces street crime at night. If there is a fear of street crime in the town, people try to avoid going out in the town for shopping, entertainment or sightseeing at night. As a result, the pedestrian traffic at night will be lower, and people who attempt street crimes might feel encouraged to conduct crimes on the dark and empty streets. Commercial activities and sightseeing activities in the town will be diminished even further.

Effects in reduction of street crimes at night are two-fold. The first is to discourage the persons attempting crimes on the street for the fear that the crime will easily be eyewitnessed. The second is, by judging how people on the street ahead are behaving from a sufficient large distance, to enable pedestrians to escape from approaching dubious people.

Good lighting increases the opportunities for eyewitnesses of the crime, criminals, their clothing, the type and colour of the car, escaped directions of the criminals, etc., and helps the police with general patrolling, access to the location of the crime, investigations after the crime and pursuing criminals.

Consequently, safe and secure streets promote various activities of the town at night, for example, commercial, social, sight-seeing, travel activities, etc. In sec. 12.1.2, the ways in which public lighting may help to prevent or to reduce street crime, are discussed in detail.

(b) Squares

Squares are important locations in a city. At a square, car traffic from various directions meets in a complex way. The inhabitants and visitors gather together there and they enjoy their stay in the square.

Squares are frequently surrounded by many tall buildings. On the ground floor of the buildings, many shops and restaurants are located. To show the visitors the orientation of the streets, entering and leaving the square, some of the important buildings are floodlit. The luminous advertisements play an important role in giving the orientation to the visitors. To display the status of the square or the town, sometimes beautiful fountains, statues, and flower beds are located in its centre. They, of course, usually deserve ample lighting.

A high level and high quality outdoor lighting is necessary to make the drivers able to see the directional signs or the names and numbers of the buildings, sidewalks, pedestrian crossings, possible obstacles, cars parking in the square, other slow traffic and bicycles, etc. At the same time it is also necessary to allow the visitors to see directional signs or signs on the buildings, approaching automobiles, other visitors, statues, fountains, flower beds and general landscape of the square, etc.

As in the cases of street lighting, high level and high quality outdoor lighting improves the security level of the square.

2.4.2 Historical buildings and sites

Historical buildings, such as castles, churches, palaces, museums, temples, shrines and old bridges, etc., have a unique shape, finish and arrangement. In the daytime, they are seen as elements of the colourful landscape of the town – the cityscape. At night, if the external walls of the buildings are lit with well-designed artificial outdoor lighting, their appearance may change considerably from that in daytime. Their bright walls will stand out against the dark sky and the dark, unlit surroundings. The trees and bushes in front of the buildings are seen as beautiful silhouettes against the bright walls of the buildings. It must be stressed that moderation is needed: if the contrast between the lit and the unit areas is too great, glare may result, and the overall visual aspect is harmed.

Floodlighting will highlight parts of the building that are in the shadow during the daytime; for example, the upper edges of the windows are seen as bright parts at night. Also, the bright parts of the building in the daytime, such as the front pillars of classical buildings, if lighted in this way, are seen as black silhouettes at night. Such differences in appearance in the daytime and the night give quite different impressions as if they were a different building. To see such a difference in the appearance of the buildings is a joy for the visitors of the town.

2.4.3 Trees, flowers, parks and gardens

Very old trees have a unique and beautiful shape. In daytime, however, they are seen among various other trees and artificial buildings. At night, if the outdoor lighting properly highlights the trees, then they will stand out in the dark surrounding and show different shape and beauty from those in the daytime.

In the flowering season, the beauty of the trees in the daytime and the night are quite different. Many people like to see flowering trees in the spring. The outdoor lighting presents a great joy for most visitors as well as for the town inhabitants.

2.4.4 Monuments

Monuments are important for history lovers. In the daytime, small monuments surrounded by trees and bushes tend to be overlooked. If they are lit during the night, they will stand out in the dark surroundings; they will not be overlooked easily.

If a large monument is not lit, even if visitors noticed its existence, they cannot read what is written or carved on them. By means of lighting, the visitors can recognise the details of the historical descriptions or the details of statues. By means of lighting, the time during which the monuments contribute to the cityscape, can be extended.

2.4.5 Rivers, ponds, fountains, bridges

Brilliant reflections of luminous surfaces or the luminaires with various colours on the rippling water surface make the landscape at night beautiful, fantastic, and attractive. The luminaires to be located on the banks or bridges of rivers, lakes, or ponds, must carefully be selected and located. Projection lighting for fountains at night presents the size and dynamics of the water jets of the fountains.

2.5 Lighting for motorised road traffic

2.5.1 Road lighting as functional lighting

Modern society is a very complicated system; it involves a large variety of human activities. Artificial lighting permits performing those activities also at night, when natural daylight is absent. Road transport takes place in the open, so outdoor road lighting is needed, just as for other outdoor activities. From this point of view, artificial outdoor lighting is one of the major assets of our culture.

All lighting is functional, its function being the enhancement of the visibility (utility lighting) or of the aesthetics (decorative lighting). As is explained in sec. 1.2.1, good lighting design ensures that the light comes where it is needed, and does not fall elsewhere. If not, the light is 'spilled', which may cause considerable economic and environmental losses. The light, the money and the energy are simply wasted. Furthermore, spill light from outdoor lighting installations may cause disturbance and discomfort for many persons, also for those that have nothing to do with the activities for which the lighting is installed. This is obtrusive light or 'light trespass'. Light trespass has victims; one group of victims are the astronomers – both the professionals and the amateurs. They are restricted in their ability to make accurate observations. In the Chapters 4, 5, 13 and 15, the various aspects of light trespass are discussed in considerable detail.

All outdoor lighting may cause light pollution, but when discussing the subject, most emphasis is placed on road lighting, because there is a lot of information about road lighting and its effects on safety and security, but also on light pollution.

2.5.2 Accident prevention

The situation regarding road safety varies considerably for different countries, their affluence being an important factor. In sec. 12.1.1, details are given on a comparison of the road safety situation in different countries. The conclusion of that comparison is that within the 'top 10' countries, the 'danger ratio' is almost the same.

Detailed research efforts by leading scientific institutes, spanning several decades, have established beyond any doubt that road lighting has a positive effect on the reduction of road traffic accidents (CIE, 1968, 1992). More recently, all available material has been re-evaluated by applying the meta-analysis approach, where the value of each individual study is evaluated and expressed in a score (Elvik, 1995). The results of the different studies can be summarized as follows:

(1) On major urban thoroughfares, good road lighting results in a reduction of about 30% of the night time casualties. A similar effect is found on rural trunk roads and motorways;
(2) Increasing the light level decreases the accident risk. Within the range of adequate road lighting, doubling the road surface luminance leads to a reduction of the night time risk (night/day accident ratio) of about 13%.

2.5.3 The relation between public lighting and crime prevention and reduction

Crime and fear of crime are major problems in many industrialized countries. The two major reasons seem to be, firstly, the very high level of the actual crime rate. The probability to be robbed, mugged, or raped in a specific year is much higher than the probability to be involved in a road or domestic accident. And secondly, the crime in modern society, particularly in big cities, seems to have no preference for any person – it seems to be governed by blind fate.

Poor outdoor lighting is not useful for normal pedestrians but it might be for those who plan crimes in the streets at night. The eyes of criminals lurking in the dark in the poorly lit street for a considerable time are able to adapt fully to the very low luminance of the dark spot and able to perceive necessary details of their targeted pedestrians coming in their direction in the dark. The opposite is true of the eye of unsuspicious pedestrians in poorly lit streets. They remain adapted to the higher luminance in the not-so-dark areas where they were walking just a few moments ago, such as a railway station, an underground rail, a bus or a tram stop, a restaurant, a theatre, a supermarket, a shopping street, or their house from which they just emerged. The adaptation from an average luminance to a very low luminance will take quite a while. According to the classic studies of Hecht (1921), the adaptation from an illuminance of 925 lux – corresponding to some 100 cd/m^2 – to 10^{-2} cd/m^2 will take about 2-3 minutes; to 10^{-3} cd/m^2 it will take at least 5 minutes (See Schreuder 1998, Figure 7.2.10).

So, pedestrians who have not yet adapted to low levels of luminance, cannot identify the criminals approaching in the dark. Similarly, the eyes of the policemen whose eyes are adapted to the relatively high luminance cannot detect the criminal lurking in the dark from the patrolling cars, and it is difficult to chase them when they try to run away. This implies that the poorly lit streets are the most dangerous spots in the town (Schreuder, 2000). Details of the crime-reduction capability of road lighting are discussed in sec. 12.1.2.

Fear of crime is the largest of all obstructions for social contacts, particularly during the dark. The fear is not evenly distributed over the different groups of the society. Women and the elderly are the most subject to this fear. The question in how far this fear is justified, is not relevant as long as it is a real fear. Very few elderly people dare to leave their house at night. A study in the Netherlands by the Ministry of the Interior suggested that one in three citizens was troubled in their sleep by the fear of crime. In short, many people believe that the fear of crime is one of the major problems of our society at present.

In many, but not in all, cases, a reduction in crime rates is reported after the lighting is upgraded. This applies for all sorts of street violence, robbery, breaking in, etc., and more specially for sexual assault. So, street lighting is often considered as primarily a 'woman-friendly' measure – quite rightly so. In some cases, very dramatic reductions have been quoted. However, in many cases these reductions were accompanied by an increase in crime rate in another nearby location, which suggest not a prevention of crime, but rather a shift. Still, the benefits can be quite pronounced (Painter, 1999; Painter & Farrington, 1999). Details on these studies are given in sec. 12.1.2, where it is shown that there are still many things unclear as regards this statement.

2.5.4 Amenity

The beneficial effects of the functions quoted above are often considered as very important. More in particular, the subjective aspects of social safety of residents and pedestrians ('fear of crime') and the amenity for residents are considered very important.

In fact, in many countries, these aspects are the most important for the decision to light roads and streets, both urban and rural. Surveys pointed out that the opinion of residents about lighting and crime have three, closely interrelated, aspects:
- amenity (is the situation agreeable?);
- subjective estimates of crime reduction (do people believe that lighting helps against crime?);
- fear of crime (are people less afraid of criminal acts when the lighting is good?).

For feeling secure and for avoiding criminal assault it is necessary to be able to see the surroundings. So visibility and recognition are important aspects, during the day as well as after dark. It works two-ways: if the potential victim can see the potential aggressor, the aggressors know that they can be seen and easily recognized. There is plenty of proof that this may work as an effective deterrent, and not only as a means that pedestrians may feel more secure. And finally, feeling secure is a deterrent in its own right. Most criminals are cowards; they prefer to attack weaker persons, and particularly those who are afraid. And feeling sure is reinforced by surroundings that suggest order – that someone around is caring. Details are given in secs. 12.1.4 and 12.1.5.

2.5.5 Construction or maintenance sites of roads

For road construction or maintenance, the road is sometimes blocked to traffic, or traffic is delayed for some time. The traffic must sometimes negotiate steep curves on temporary roads, and various equipment or vehicles for the works are unexpectedly placed or parked on the locations close to the driving lanes of the site. The lighting of traffic signs for guidance of the traffic to correct directions and the appropriate outdoor lighting, which improves visual conditions, can reduce accidents at night.

2.5.6 Intersections and junctions

(a) Intersections

At level intersections of roads, if no signal control is installed, the streams of motorized traffic and the pedestrian traffic cross each other. The accident rates at the intersections are higher than at other road sections.

If drivers approaching a large intersection do not recognise the road lay-out of the intersection ahead, they may arrive at the intersection too fast. Consequently, the driver may not be able to stop the car safely in time. Outdoor lighting for an intersection, which indicates the existence and the road lay-out of the intersection already from a large distance, is very important and effective for traffic safety at night.

When approaching the actual intersection, where the traffic intersects with other traffic streams, the driver must be able to judge the distance, the speed, and the lateral position of vehicles. When in the dark or in foggy conditions, or due to curves, it is not possible to see the whole carriageway clearly, it is often difficult to judge correctly the different positions of vehicles. Errors, made in the judgement of the lateral position of approaching vehicles, will lead to dangerous consequences. The outdoor lighting to make the carriageway brighter reduces such an error of judgement. For these reasons, the outdoor lighting on the intersections reduces traffic accidents at night.

(b) Junctions and interchanges

Major traffic junctions, the places where two or more roads meet, or the interchanges, the places where a main road joins a motorway, or where two motorways meet, are designed in such a way that vehicles leaving or joining the road, do not have to intersect other streams of traffic. They only merge or split. To achieve this, the roads are connected by a number of curved stretches. Additionally, viaducts and underpasses are needed to avoid the crossing of streams, leading to grades also in an otherwise flat country. The drivers coming to a diverging point of a junction or an interchange have to select, within a short time, one of the diverging roads so as to proceed toward the intended destination.

To select the correct road, the driver needs to know where the roads diverge and which is the road in the right direction. As is explained in sec. 10.3, drivers need to know this more than about 10 seconds before reaching the point at which the decision has to be made. On curved stretches in the junctions or the interchanges, such advance information is difficult to collect at night by means of only the vehicle headlighting, because the beam from the headlamps diverges from the direction of travel on a curved stretch of road.

If drivers cannot collect visual information regarding the diverging point of the roads at a sufficient distance ahead, and if the decision making is delayed, they have to brake abruptly or make abrupt steering manoeuvres close to the diverging point. This leads to a dangerous situation. By improving visual conditions, the outdoor lighting helps drivers to collect the necessary visual information and to decide which diverging road to take at a sufficient distance ahead. This reduces the number of traffic accidents.

2.5.7 Bus terminals

Normally, the configuration of roads, movements of buses and passengers in the bus terminal are complex. In the first place, the movements of buses have to be recognised easily and reliably by passengers, their families, or friends who come to meet the passengers getting off the bus. The bus drivers need to be able to see other buses moving around, as well as passengers, who sit or walk in the waiting areas, or even those illegally walking in the traffic zone. After dark, if the lighting installed is poor, it is usually not possible to acquire the required visual information. The risk of accidents as well as errors in the selection of which bus to take, or failing to meet passengers, etc., will increase. Appropriate outdoor lighting makes the bus terminal safer and more convenient for passengers.

2.6 Automobile lighting

Car lighting – often called automobile lighting – is not a fixed lighting. For this reason, it is usually not included in textbooks or handbooks under the category of outdoor lighting. In spite of the fact that car headlights are indispensable when no other lighting is present, the safety effects of headlights have never been thoroughly investigated. It was considered self-evident that they constitute an effective accident counter-measure. Another thing is, that the huge amount of car traffic on the roads means that the effects of car headlamps on light pollution cannot be disregarded.

Most of what follows in this section is explained in much greater detail in sec. 12.2. Car headlamps are aimed in such a way that the main luminous flux is emitted in a direction that is almost parallel to the road surface. Only in this way can the required 'reach' of headlamp beams of at least 50 to 100 m be realised. Traditional headlamp systems have two beams; the high beam or driving beam, that is used when there is no opposing traffic, and the low beam or passing beam that is used when other traffic is met. In most countries, the traffic is so dense that high beams can hardly be used at all. The low beam is characterised by a light distribution that shows a sharp cut off. Little light is emitted above the horizon, where the eye of opposing drivers may be, whereas as much light as possible is emitted just under the horizon to maximise the reach. Though the direction of the luminous flux projected from the headlight is critically controlled, some light is still emitted to the upper directions. This can be seen clearly when the stream of cars on the road at night is seen from high positions, such as from a high building or a hill or from an aircraft. A great many brilliant headlamps moving with cars, which are emitting a considerable amount of luminous flux to the direction toward the observers, are seen along the road.

Over the years, the beam pattern has been adapted to the advantage of drivers of high-speed roads by increasing the intensities just under, and also sometimes above, the horizon. This means that the glare for opposing traffic as well as the light above the horizon which may cause light pollution, increased as well. Before World War II, European beam patterns were symmetric, showing a very sharp cut-off (Schreuder, 1972). Practically no light was emitted above the horizon, restricting glare but also the reach and therefore the permitted driving speed. In the 1940s, in North America the 'sealed beam' pattern was introduced. This was characterized by two almost identical beams, the high beam pointing straight ahead and the low beam pointing slightly down to the right (for right-hand traffic). The reach of the low beam was much higher than for the European symmetric low beam, allowing higher speeds. However, glare and stray light above the horizon were considerable.

In the 1950s, the European asymmetric low beam was introduced combining the two. It is characterised by restricting the light straight ahead by a sharp cut-off and allowing a considerable amount of light to the right hand side of the road, both under and above the horizon. As with each compromise, something was lost. The reach was less than for the North American sealed beam pattern, whereas the glare and the stray light emitted above the horizon was much higher than with the European symmetric beam (De Boer & Schmidt-Clausen, 1971; Schmidt-Clausen & Bindels, 1974; Schreuder, 1976). The introduction of the iodine lamps, and later of the more sophisticated quarz-halogen lamps, and finally of the High Intensity Discharge lamps (HID-lamps), meant in each stage a higher luminous flux for the same size of the light-emitting surface – or, in other words, a higher light source luminance. In each step, the reach was increased, but also the glare and the amount of stray light. More seriously, the beam patterns became more critical when at the same time the influence of the stylists in the car industry increased. The net result was a lamp that was much more sensitive to mis-aim and to the influence of dirt, water, salt and dust on the lens surface. The new lamps do permit a slightly higher speed, but they cause much more glare and much more stray light above the horizon (Schoon & Schreuder, 1993). They may be better under some high-speed conditions, but worse for moderate speeds and urban, and mixed, traffic.

As was mentioned earlier, the contribution of car headlights to light pollution has never been studied in detail. Casual observation from hills, or from airplanes, show clearly that the contribution may at times be considerable, more in particular in the directions just above and close to the horizon. In secs. 6.2.3 and 12.4, is explained in detail why these directions are more in particular the 'light-pollution sensitive' directions. It does not show clearly on satellite pictures, because these concentrate on near vertical observation.

There are reasons to believe, however, that under many circumstances, headlamps may have a considerable influence on light pollution. Even when the headlights are clean, intact and well-adjusted, there is a considerable amount of light over the horizon, which, as indicated earlier, contributes to the light pollution. When the headlights are dirty or mis-aimed, the light pollution will increase as may be seen from the increase of the glare. In recent years, no systematic measurements of glare or of mis-aim from headlights have been made. One might conjecture that this has to do with the fact that the main interest of lighting designers and car sales people is to offer cars that do particularly well on high-speed motorways. Other, more frequent but less glamorous, traffic conditions are disregarded. This special interest leads to an ever-increasing glare level, which can be noticed easily by just driving or walking at night in any street. Measuring the glare increase does not favour car sales, however. Details of the considerations about to what extent car headlights contribute to light pollution as well as an estimate of the magnitude of the contribution, are given in sec. 12.2.9.

2.7 Sports lighting

There are huge numbers of sports lovers and a great many kinds of sports all over the world. The sports lovers enjoy sports by playing themselves, or by watching sports matches in stadiums or on television screens, etc.

2.7.1 Lighting for recreational sports

On weekdays, except holidays, many people who are working at offices, factories, shops and hospitals, etc., cannot enjoy sports in the daytime. To enable these people to enjoy sports every day in the evening after work, sports lighting is needed.

If no lighting is provided, many people have to enjoy sports themselves on weekends or holidays during short periods of daytime. This means that, if no lighting is provided, a great number of recreational sports facilities must be built in many places.

This will result in an extensive waste of money, materials, energy, and labour for construction and maintenance for new sports facilities to be built, and also a waste of investments and other resources, due to the decreased efficiency of operation and management of the increased number of sports facilities, which are used by many people concurrently for only a short period of time. Consequently, for the investors it will be difficult to make a profit from the increased sport facilities. In spite of this effort, still many people cannot enjoy sports on weekdays, for reasons of time. Finally, if lighting is used on a considerable scale, many existing sports grounds will become difficult to maintain due to decreased operational efficiency as a result of the increasing number of sports facilities with lighting. It is likely that also the unlit facilities eventually will be equipped with lighting.

Another point to consider is that sports facilities with poor lighting may cause discomfort and disability glare for road users (Folles, 1979; Schreuder, 1979).

In view of the fact that sports are one of the most important fields of human activities in spare time, those wastes and low efficiency have to be avoided as much as possible.

The waste brings about other adverse consequences to the atmospheric environment. In order to produce or to transport the additional materials for construction of many new sports facilities for recreational purposes, the consumption of energy will be increased. The increase in energy use may be greater than the energy consumption for the lighting in existing recreational sports grounds during the night. As is explained in sec. 13.1, any additional consumption of energy, even if small, accelerates the global atmospheric temperature rise. It also increases the amount of particles and vapours that float in the atmosphere. An increase in particles and vapours in the atmosphere will increase the scattering of lights, and hence the sky luminance by other improper lighting installations.

If good lighting installations without excessive spill light are installed in important sports grounds, many people can enjoy sports after work on most weekdays until late at night. Of course, the lighting must be switched off as soon as the outdoor activities have stopped. This is expressed in the concept of curfew that is explained in sec. 6.1b. The energy consumption is less than needed if new sports facilities without lighting are constructed.

2.7.2 Lighting for large-size sports stadiums

Watching large-scale sports events taking place in big stadiums is also fun for many sports lovers. They watch either from the rows of seats in the stadium where the favorite sports events are taking place, or watch the broadcast sports events on TV. If good lighting installations are provided in the stadiums, many sports lovers are able to enjoy their favorite sport in the time after dark in the stadium, or in front of the TV. If there is no lighting provided, the sports lovers will have to go to the stadium at daytime. Their cars will consume a huge amount of energy, in comparison with the energy consumed by the lighting of the stadium and the TV's at home at night.

In some countries, for example in Japan, where the summer climate is very hot, broadcasting the interesting sports events in summer daytime increases extensively the energy consumption for the TV receivers and the air conditioners in the home. This is because many people must stay in the home to watch the broadcast sports event on TV, instead of outdoor activities such as going swimming or mountain climbing etc. during the daytime in the hot sun. Such extraordinary increases in energy consumption raise the peak consumption of electric energy and sometimes require new power plants to be built. This deteriorates the efficiency of the total electricity network of the country.

2.8 Industry and commerce

2.8.1 Industry

(a) Importance of industries

Industry is one of the most important sectors of human activities in the modern technology-oriented society. There are many kinds of industries, from open mining of iron ores to purified silicon disks in dust free factory rooms, from simple spoons to sophisticated space ships, from soft fabrics to hard armour plates, from small miniature toy cars to huge oil tankers, etc. The products of these industries are almost equally important for modern life all over the world, and in cases when any of the production plants is unable to supply the necessary quantity or volume of products, there will be serious economic consequences for the social lives or relevant industries.

Depending on the kind of the products, and on the production process, some of them are produced in outdoor plants. All outdoor plants need outdoor lighting for their production activities at night.

The outdoor lighting installations provided for outdoor plants have at least the following five aims:
(1) To make possible the production activities at night efficiently and safely;
(2) To make possible the large-scale maintenance work at night, efficiently and safely;
(3) To maintain the required security level of the production plant also at night;

(4) To carry out emergency actions and rescue efforts in case of explosions, fires, outflow of hazardous products, chemical materials, fuels, gases or water, collapse of constructions, earthquakes, terrorist attacks, and other accidents in the production plant efficiently and rapidly, also if they happen at night;
(5) To allow safe transportation of products out of the plant and of materials or parts into the plants, also at night.

(b) Outdoor lighting for production works at night

Many industries, for example chemical industries and metal industries, cannot stop their production process, except for special maintenance periods, inspections, or renewal works. Normal production goes on 24 hours a day throughout the year. This is an aspect of what is often called the 24-hour economy or 24/7 economy. Although most of the processes in these industries are fully automated at present, still a considerable amount of production or inspecting activities are carried out by human workers. To carry out these tasks efficiently and safely at night, high-quality outdoor lighting is indispensable. If no outdoor lighting is provided in these plants, their production activities have to halt in the evening. Since those production plants cannot stop or start immediately, if the work is possible only in daytime, the production process have to halt every evening. And a lot of energy and materials will be lost. As a consequence, the production yields of these industries will be seriously reduced and many investors cannot accept to continue their production activities.

(c) Outdoor lighting for maintenance works at night

In order to carry out production efficiently and safely, the maintenance work is of essential importance for any production plant. During large-scale maintenance works, usually the production has to be interrupted. In most cases, the large-scale maintenance is, for this reason, carried out at night when there are no production activities. To conduct the maintenance efficiently and safely, outdoor lighting is necessary. Usually, this regards permanent lighting, that, if needed, may be supplemented with temporary installations.

(d) Outdoor lighting for security

Nowadays, any plant or factory can be a possible target of terrorism. To reduce the chance of a terrorist attack, outdoor lighting is not only needed for production plants; the premises of the factory also have to be lit to a sufficient level. The roads adjacent to the premises also have to be lit so as to eliminate parking of vehicles used by the terrorists and to make it easier to identify the type, colours, and license number of their vehicles. Such provision of lighting will also reduce the general crimes in the premises at night on adjacent roads of the factory. Such lighting is often called security lighting.

(e) Outdoor lighting for emergency actions at night

An emergency event may happen unexpectedly in production plants at night. Under emergency conditions, many actions have to be carried out simultaneously and rapidly. The director of the rescue parties must see the whole picture of the event as much as possible. He needs good lighting over the whole area of the plant. The rescue parties must find where the origin of the event is, where and how many wounded people there are, how to help those wounded to get out, where the place is destroyed or damaged, and how to access rescue parties to the point of event, etc. To accomplish the rescue mission effectively, it is necessary that those in the rescue parties see details reliably and clearly from a distance.

For this purpose, good outdoor lighting is essential, since most of the people in the rescue parties, who come from the outside fire brigade or police department, are not familiar with the details of the arrangements of the plants and various constructions in the premises.

(f) Outdoor lighting for transportation

Products of the day have to be transported from the factory as soon as possible under reasonable conditions. Also, some materials and parts need to be transported in at night. For these activities, outdoor lighting for transportation is necessary.

2.8.2 Lighting for commerce

(a) Lighting for shops

One of the fundamental elements of commerce is the individual shop. In most industrialized countries, shops sell their products indoors. The lighting for commerce, therefore, is installed in the interior of the shop buildings. Some lights from the windows of the shops, however, illuminate outdoor spaces at night. In some shops, for example petrol stations, the luminaires for lighting are mounted under the ceiling construction in the station. The luminaires illuminate, however, not only the area below the ceiling construction but also the general outdoor areas of the station, where cars are parked or maintained. This is a kind of outdoor lighting.

(b) Outdoor lighting for shops

Outdoor lighting for shops is installed in adjacent parking lots or advertising signs or boards for the convenience of the shoppers. Sometimes the facade of the building is floodlit by groups of projectors, or illuminated by means of small incandescent lamps, sometimes with different colours. They are arranged on the facade or along the edges of the building or between buildings or trees and are used to decorate the appearance of the shop.

(c) Outdoor lighting for shopping malls

A shop alone, however, cannot carry out commercial activities sufficiently, since the shop needs to attract as many shoppers as possible from places as far away as possible. To attract many shoppers, a large number of shops of different kinds form shopping malls or shopping streets in an area. Shopping malls, shopping streets included, are not just a group of many shops.

In the shopping mall, many kinds of shops are arranged along both sides of a relatively wide street or streets with parking facilities adjacent. A number of streets to give people access to the mall from nearby railway stations or bus stations are also provided. Sometimes small parks, flower beds, benches, trees, bushes, monuments, fountains, etc., are included in the design. Many people, not only shoppers, but also tourists, casual walkers, nearby residents are attracted to the shopping mall to enjoy the cheerful atmosphere. If the outdoor areas of the shopping mall at night are well-lit, the general atmosphere of the mall will become much more fascinating and enjoyable than in daytime. Sometimes, the shopping streets are covered by ceiling constructions and constitute arcades. The lighting for arcades is not interior lighting but also not real outdoor lighting. Nevertheless, a number of light points will illuminate a part of the outdoor spaces.

(d) Effects of the outdoor lighting

Even when the shops are closed at night, the shop windows, which are seen brighter than their surroundings at night, attract attention of visitors of the mall, and the effects of the window displays are increased. People enjoy eating, drinking, talking and, meeting in the restaurants and the open-air sidewalk terraces.

The lighting design of the lighting of the shopping malls must be planned with great care. The light from the luminaires must illuminate what is to be lit, and not wasted by directing light toward areas that are unnecessary to illuminate. The brightness of the luminaires arranged in the shopping mall or parking lots must not be glaring. On the other hand, to avoid street crimes or car crimes in the shopping mall, strong shadows must be avoided. The same applies to narrow paths or alleys between buildings. Blank spaces, big trees, bushes in and around the mall must not be left unlighted from any directions so that no dangerous people and no potential criminal can hide behind them, as is explained in secs. 2.5.3 and 12.1.2.

(e) Traffic safety

In and surrounding shopping malls, there will be considerable pedestrian traffic towards or from the shopping mall. There will be heavy urban motor traffic. Many visitors of the shopping mall are not familiar with the orientation or the streets. To avoid possible traffic accidents, a sufficiently high level of street lighting for motor and pedestrian traffic has to be provided on the relevant streets. This, of course, is similar to the road and street lighting that is discussed in sec. 2.5.

2.9 Agriculture, fishery and forest burning

2.9.1 Greenhouses

Greenhouses are widely used to change the growing pattern of plants, more in particular of flowers and fruits. The principle is well-known: a greenhouse is a heat trap. The energy from the sun gets in and cannot get out again. In the terminology of physics, it begins with the sun. The surface temperature of the sun is 5785 K (Herrmann, 1993, p. 105). According to the Wien Law, a high temperature corresponds with a short wavelength (see e.g. Breuer, 1994, p. 181; Illingworth, 1991, p. 39; Schreuder, 1998, sec. 4.2.2). The short-wave sunlight can pass through the transparent cover of the greenhouse. The radiation hits the soil – and the plants – in the greenhouse, heating them up to a temperature somewhere around 20° to 50° Celsius or about 300 to 330 K – much lower than the sun temperature. The soil radiates back the energy at a very long wavelength that cannot pass through the cover. The result is a rise in temperature – the effect that was sought for. The same effects play a role in the global warming that is discussed in sec. 13.1.1a in more detail. By raising the ambient temperature, the growing, flowering and fruiting patterns of plants can be changed. The aim is either to have the products available at a time when they would not be so in the open, or to increase the productivity. The result may be 'horizon pollution' but nothing more.

In several countries at a medium or high latitude however, like e.g. the Netherlands or Belgium, the winter sunshine is weak and it is available only a few hours a day, even on cloudless days. Here, the greenhouses are often equipped with artificial lighting. This is called assimilation lighting. In this way, not only the summer temperatures but also the summer day-and-night rhythms are simulated. The problem is that, in order to do so, quite elevated levels of lighting are needed. Most flowers need between 4000 and 6000 lux, whereas many fruits require levels even up to 10 000 lux. It goes without saying that very elaborate lighting installations are needed to achieve this. For 10 000 lux, high-pressure sodium lamps with 100 lm/W, and a luminous efficiency of the installation of 0,5, one needs 0,2 kW/m^2.

In the Netherlands, there is about 1500 hectare or about $15 \cdot 10^6$ m^2 of artificially lit greenhouses (Neefjes, 2001; Schmidt, 2002). Modern greenhouses screen almost all light emitted in horizontal directions and up to 95% of the vertically emitted light. Still, 75 lumen per m^2 is emitted when the average reflection of the soil and the plants in the greenhouse is taken as 15%. One can compare this to a city. For 2000 inhabitants per km^2 and 2000 lumen per capita, this is $4 \cdot 10^6$ lumen per km^2 or 4 lumen per m^2. In this example, a greenhouse would emit almost 20 times as much light as a city per unit of area! The total area of artificially lit greenhouses in the Netherlands of $15 \cdot 10^6$ m^2 would correspond to more than half a million people – the total population of a city the size of Amsterdam. If there was no screening, the effect would correspond to the astonishing number of 11,25 million people – or 70% of the total population of the whole country. It is not an exaggeration to say that the assimilation lighting in greenhouses is by far the greatest problem in the Netherlands as regards light pollution.

In the Flanders region of Belgium, the situation is less severe because there are 193,8 ha greenhouses of which 8,2 ha have assimilation lighting – just over 0,5% of the area in the Netherlands (Vandewalle et al., 2001, p. 89). Still, they consume 36 210 kW compared to the 155 181 kW of the total of outdoor lighting, or over 23% (Vandewalle, 2001, tables 1 and 2).

2.9.2 Fishery

In many countries it is customary to fish at sea during the night. The catch is lured to the surface – and towards the nets – by bringing light sources along. "The most spectacular source of light is in the Sea of Japan, where a fishing fleet displays over 100 MW of lights on its boats" (Sullivan, 1991, p. 12).

2.9.3 Forest burning

In the tropics, the major sources of light are the fires that are the result of grassland burning, slash-and-burn agriculture, and clearing of forest (Sullivan, 1991, p. 11, quoting Seiler & Crutzen, 1980). Since the early 1990s, when this was written, the relentless and often criminal burning of tropical forests has developed into one of the major concerns as regards environmental protection and as regards global warming – even as regards the world-wide climatic changes more in general. In secs. 13.1.1 and 13.1.2, more details are given.

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3 What is light pollution?

Sky glow presents itself as a background luminance over the sky, against which the astronomical objects are to be observed. The interference of astronomical observations is caused by the resulting reduction in luminance contrast. A value that is often used for the practical minimum of the natural background radiation is 21,6 magnitude per square arcsecond, corresponding to $3{,}52 \cdot 10^{-4}$ cd/m^2. Several effects from outside the earth atmosphere as well as from within the atmosphere contribute to the natural background radiation. A major contribution to the natural sky brightness comes from the influence of the Sun. As the solar radiation changes during the well-known 11-year period, the influence on the natural sky brightness varies as well.
In most places of the world, the contribution of artificial light exceeds that of the natural background radiation. Residents suffer most when the light invades their private life, when it falls directly into the living space (light immission). Astronomers are restricted in their possibilities to make accurate observations by the diffuse urban sky glow. Also, plants but mainly insects, birds and mammals suffer from light pollution.
Sky glow is the result of light that is projected upwards, and then scattered back to the surface of the Earth. Another major contribution to the stray light is the light that is well-directed to objects, but reflected by them. In almost all cases it is the light that is reflected from a surface that is 'useful'.
The environmental approach towards reduction of light intrusion includes two principles, viz. zoning and curfew. Both are based on the principle that the consequences of light pollution are not equally severe in all places in the world, nor at all times of the day and night.

3.1 The natural background radiation

Sky glow presents itself as a background luminance over the sky, against which the astronomical objects are to be observed. The interference of astronomical observations is caused by the resulting reduction in luminance contrast. The effect on observations will be discussed briefly in sec. 3.3. The glow is caused by non-directional scatter of light by particles in space and in the atmosphere. Part of the light, and part of the particles are natural, and part is man-made. The 'natural background radiation' is defined as the radiation or luminance, resulting from the scatter of natural light by natural particles. For earth-bound observatories, the natural background luminance is the absolute lower limit for observations.

A value that is often used for the practical minimum of the natural background radiation is the value of 21,6 magnitude per square arcsecond, corresponding to $3{,}52 \cdot 10^{-4}$ cd/m^2 (Crawford, 1997). This value is of the same order of magnitude as the widely used value of $2 \cdot 10^{-4}$ cd/m^2 that is quoted by Anon. (1984). Cinzano et al. (1999) use a value of $2{,}5 \cdot 10^{-4}$ cd/m^2. Leinert (1997) quotes a value of 23 magnitude per square arcsecond for the blue part of the spectrum, and 22 magnitude per square arcsecond for visible light. Further explanations may be found in Levasseur-Regourd (1994) and Leinert (1997).

In view of the variations of the background sky brightness that will be briefly discussed hereafter, these values are used as a first approximation only. The data agree very well with measurements at Kitt Peak National Observatory, where 21,9 mag per square arcsecond was measured (Davis, 2001, p. 124, quoting Pilachowski et al., 1998). It might be noted that "faint galaxies will be observed with telescopes in Chile down to surface brightness levels at or even below 29 mag per square arcsecond, i.e. about 700 times fainter than the natural solar-minimum background at V" (Smith, 2001, p. 40-41). Further information of how this is reached, is not given. It should be noted, however, that the ratio 700 corresponds to a contrast, defined in the usual way as in sec. 9.3.1, of 0,143% – far less than the usual threshold for the contrast sensitivity that is about 1% (Schreuder, 1998).

According to Levasseur-Regourd (1992, 1994), the major contributions to the natural background luminance are:
(1) The light from sub-liminal stars;
(2) Interstellar dust (forming part of the galaxy);
(3) Dust in the solar system (forming part of the solar system);
(4) Air molecules;
(5) Dust in the atmosphere;
(6) Water vapour in the atmosphere.
Contrary to the contributions (1), (2) and (3), which come from outside the earth atmosphere, the contributions (4), (5) and (6) are from within the atmosphere. Obviously, their influence diminishes when the layer of air above the observatory is thinner and the air is cleaner. It should be mentioned that (5) may include a considerable fraction of man-made aerosols as well, as is discussed in Chapter 13 of this book. This is the main reason that most major observatories are built on top of high mountains in desert areas – as far away as possible from any human activities.

During the UNESCO-conference, the following estimates were made regarding the contribution of several of these factors to the background radiation (Levasseur-Regourd, 1992; see Table 3.1.1). It should be noted that these values do not appear in the written contribution (Levasseur-Regourd, 1994). The values are expressed in the luminance equivalent to the number of stars of the tenth magnitude per square degree (S10). A conversion of (S10)-values into luminance values is given in the following formula:

$$L = 0,7 \cdot 10^{-6} \text{ (S10).}$$

with L in cd/m^2. (Cinzano, 1997, Formula 3.32, p. 113; see also Schmidt, 2002). Details are given in sec. 14.6.

Source	**Relative contribution** (S10)	10^{-6} cd/m^2
night glow	80	56
zodiacal light	between 80 and 200	56 - 140
stars over 6 magnitude	average about 20	14
subliminal stars	between 50 and 200	35 - 140
galactic dust	20	14
extragalactic dust	2	1,4

Table 3.1.1: *Contributing factors to the background radiation in relative measure. Based on data from Levasseur-Regourd, 1992.*

It might be noted that the categories used in this table, are slightly different from those used in the list given earlier in this section. Night glow is related to air molecules and zodiacal light to galactic dust.

From the table it is clear that the zodiacal light and the subliminal stars give the greatest contribution of the non-terrestrial sources. The table serves primarily to suggest that there is not a single, simple value for 'the' natural background sky brightness. See also sec. 14.3.2.

A major contribution to the natural sky brightness comes from the influence of the Sun. As the solar radiation changes during the well-known 11-year period, the influence on the natural sky brightness varies as well. "The natural sky background at new moon near the zenith at high ecliptic and galactic latitudes varies by a factor of about 1,7 – i.e. by about 0,6 mag ($21,3 < V < 21,9$) per square arcsecond over the course of the 11-year solar activity cycle" (Smith, 2001, p. 40, quoting Krisciunas, 1997).

The International Astronomical Union IAU has expressed as their goal that man-made sky glow should not be more that 10% of the natural background radiation (Anon,. 1978). As a policy goal this is an excellent proposition. When considering the variations in the natural background sky brightness that have been discussed here, the IAU-proposal does not offer, however, a firm base for the design of outdoor lighting installations. Furthermore, it is explained in several places in this book, that the 10%-value must be regarded as very strict, probably too strict. In sec. 8.3.4, it is mentioned that this value is not always relevant for visual astronomy because of the characteristics of mesopic vision (CIE, 1989).

It was suggested at the Vienna conference in 1999 to introduce a 'reference sky brightness' for the purpose of lighting design. The value should correspond to that of the solar minimum; it is proposed to use the value of 21,6 magnitude per square arcsecond, which corresponds to $3{,}52 \cdot 10^{-4}$ cd/m^2, as is proposed by Crawford (1997).

3.2 Direct light; light intrusion

As already indicated several times, a good lighting design ensures that the light comes where it is needed, and does not fall elsewhere. If not, the light is 'spilled', which may cause considerable economic and environmental losses. The light, the money, and the energy are simply wasted. Furthermore, spill light from outdoor lighting installations usually is a major cause of disturbance and discomfort for many people, also for those that have nothing to do with the activities for which the lighting is installed. The light invades into the private sphere of people; it intrudes into the living space of people who do not have any interest in the lighting in the first place. As indicated earlier, this is intrusive light or light trespass (CIE, 2003). The overall effects are termed 'light pollution'. Some legal aspects of light trespass are discussed in Chapter 15 of this book.

Intrusive light has 'victims'. A victim matrix is given in Table 3.2.1, which includes both the victims as well as the major types of lighting installations that may cause the intrusive light. The table is quoted from Schreuder (1999, 2001); it was used in drafting the recent Recommendations for the Netherlands (NSVV, 1999).

Victims	Lighting for: sports	industry	floodlight	roads	advertizing	greenhouse-lighting
residents	X	X	X	X	X	X
astronomers	X	X	X	X		X
life in nature	X	X	X	X	X	X
road users	X		X		X	X
shipping	X	X			X	

Table 3.2.1: *The victim matrix. The relevant areas are marked by X.*

In Table 3.2.1., the term 'industry' is supposed to include 'general area lighting' as well. The two groups of victims that receive most attention are the residents and the astronomers.

Residents suffer most when the light invades their private life, when it falls directly into the living space. This is often called light immission. The effects are discussed in detail in Assmann et al., 1987; Hartmann, 1984; Hartmann et al., 1984. These studies form an essential part of the recommendations of the CIE (CIE, 2003). In many cases it relates to light falling into bedrooms, but also to light intruding into living rooms or private gardens. See also sec. 15.4.3.

Astronomers are restricted in their possibilities to make accurate observations. Astronomers include both the professionals and the amateurs, but also the much larger group of persons who enjoy the darkness. Their main concern is the diffuse 'urban sky glow' that is discussed in detail in sec. 3.3.

A third important group of 'victims' is termed 'life in nature' in Table 3.2.1. It includes plants but mainly insects, birds and mammals. The term 'road users' speaks for itself. For brevity the heading might be considered to include rail transportation as well. The influences for these victims are discussed in sec. 4.4 and 7.2.1 respectively.

Light intrusion results from outdoor lighting. One might discern three major classes of outdoor lighting, viz.:

(1) The purely utilitarian lighting like e.g. road traffic lighting, lighting of industrial complexes or sports facilities, etc. This is discussed in detail in secs. 2.2 and 2.5. Its purpose is to ensure adequate visibility for the tasks to be performed in those situations. The main aspects are the promotion of safety and security. The characteristics are described under the heading functional lighting (Schreuder, 1970, 1998; Van Bommel & De Boer 1980);

(2) Amenity lighting like e.g. the lighting of pedestrian malls, residential streets, floodlighting of public buildings, etc. where visibility aspects are important but the promotion of the feeling of well-being ('amenity') is equally important. Crime prevention and the reduction of criminal acts are prevalent, more in particular the promotion of feeling secure (the subjective crime aspects). Apart from the functional requirements as indicated earlier, a major goal of amenity lighting is to enliven the surroundings (Schreuder, 1989, 2000, 2001a, b). Details are given in secs. 2.4 and 2.5.3.

(3) Decorative lighting like e.g. illumination of Christmas trees, laser beam displays, floodlighting of fountains and trees. Their function is exclusively to enliven the scene. In this respect, the lighting is functional as well, but the function of decoration is rather different from the safety and security aspects mentioned earlier. Details on this type of lighting may be found in the proceedings of recent lighting conferences like e.g. CIE (1999), Anon. (2000). See also CIE (1993) and Cohu (1967).

Because outdoor lighting is essentially functional, 'switching off the lot' is never a good solution to fight intrusive light, as it might conflict with the primary functions of lighting. Quality lighting is the obvious answer. The requirements for quality lighting are considered by the International Lighting Commission CIE (Anon., 1978; CIE, 1978, 1993a, 1997; 2003).

3.3 Sky glow

3.3.1 The effect of sky glow

There is another type of light pollution that must be considered. Even if the luminaires of the outdoor lighting installations are well-placed, well-adjusted and well-screened, they direct some of their light into the sky above. Furthermore, the light that is reflected from the surfaces that have to be lit, will end up in the sky as well. The result is what is commonly known as 'sky glow': a diffuse haze that stretches over the sky, or at least a large part of it, making the observation of astronomical objects hard or even impossible. It is not only the professional astronomers with their large telescopes that suffer from it; also the thousands or even hundreds of thousands of amateur astronomers who marvel the wonders of the sky, are the victims. One might argue that there are more important things in life to bother about than the fact that some stars are a little less clear; as is explained in sec. 1.1.2, considerations of philosophers, religious leaders, and teachers suggest otherwise. If humanity loses contact with the cosmos, it may lose contact with some of its most profound spiritual fundaments. This has been expressed in many different places in the Holy Books of many religions but also in the scientific literature (Crawford, 1991, 1994; Murdin, 1994; Percy 1998, 1999; Schreuder, 1987).

To understand the effect of the diffuse sky glow, one must realise that all observations, both visual, photographic, and electronic, of light emitting objects are essentially observations of contrast. This is discussed in more detail in sec. 5.1.1. The stray light causes a light veil that extends over the field of observation. This veil has a luminance as well, that has to be added to all luminances in the field of observation. As is explained in more detail in sec. 9.1.3, when discussing the loss of contrast, as a consequence of this veil, all contrasts are reduced.

When the object to be observed is a star, one might suppose that its observed luminance equals the intrinsic luminance of its surface, and therefore is much, much higher than the veiling luminance. However, while a distant star is a close geometric approximation to a 'point source', its image in the instrument with which the observations are made is not a point at all. The image can never be smaller than a certain limiting size, even with excellent optics, such as the well-known refraction limited optics (Schreuder, 1998, sec. 4.5.3 and Van Heel, 1950). In sec. 9.1.7, the consequences of the contrast reduction for astronomical observations are discussed in mathematical terms.

3.3.2 Methods of astronomic observations

The influence of the system of measurements on the accuracy and speed of astronomical observations is obvious. Not so the influence of the light pollution. Measuring has become much easier in the last decades. 25 years ago, even the very best photographic materials used for astronomy wasted at least 99 percent of the light collected by the telescope (Latham, 1985, p. 25). Photomultipliers typically record up to 10 to 20 percent of the incoming light (Latham, 1985, p. 25-26). Silicon diode arrays have efficiencies as high as 70 or 80 percent. CCDs, or charge-coupled devices, are the most common form of diode array (Latham, 1985, p. 26-27). It might be noted that since the time of the publication of the book of Latham, the efficiency and the flexibility of these devices has increased in a remarkable way. See for details sec. 14.5.1. All this means that exposure times for observations can be much shorter, resulting in a smaller influence of scintillation, of poor 'seeing' and of space debris. Sky glow, however, still has the same influence, as the sky glow luminance is amplified in just the same degree as the signal. Because, however, the statistical fluctuations of the sky luminance and of star-like objects is different, the 'signal-to-noise-ratio' does not essentially need to be the same. The mathematical support for this statement is given in sec. 14.2.3. A treatment of the influence of sky glow, based on the signal-to-noise ratio concept, is given by Tritton (1997).

There is another way to consider the influence of stray light on astronomical observations. "A small portion of the sky surrounding the target is always included in the measurement, and it must be removed from the data. This is done by measuring an adjacent region of blank sky. By subtracting the blank sky data from the data in the first measurement, astronomers are left with a relatively 'clean' measurement of the target object" (Crawford, 1992, p. 40). As a consequence, according to Crawford (1992), artificial sky glow reduces the effectivity of telescopes. In Table 3.2.2, the loss of effective aperture is given in relation to the level of – artificial, urban – sky glow. As an example, the loss of effective aperture for a 4 m telescope is added in that table. See also sec. 1.2.6.

Relative sky glow (%)	**Relative effective aperture** (%)	**Example** (m)
100	100	4,0
110	88	3,81
120	78	3,65
150	58	3,27
200	39	2,83
300	23	2,31
500	11	1,79

Table 3.2.2: *Relative effective aperture in relation to relative level of sky glow. After Crawford, 1992, table 2.1.*

It is sometimes stated, that all observatories must be able to perform all kinds of astronomical observations, because it is not possible at the moment of construction, to anticipate what will be the working area of the observatory. It seems, however, that this requirement is not justifiable. There are many types of astronomical observations, all equally important scientifically, that pose quite different requirements on the equipment and on the surroundings. The ALCoR methodology, proposed by Murdin (1997), seeks to combine the two. The methodology includes six classes, called ALCoR 0 to ALCoR 5. Each class designates astronomical observatories, and relates the requirements to the equipment, to the location and to the operators. The regional classes are described in sec. 3.4.1. Here, the different kinds of astronomical observations are briefly described. The description is based on Murdin (1997, table 1).

- ALCoR 0: No astronomical activity.
- ALCoR 1: Casual viewing of the constellations; eye inspection of planets, double stars, and galaxies.
- ALCoR 2: Infrared spectroscopy; infrared imaging; infrared photometry; high-resolution optical spectroscopy of brighter stars.
- ALCoR 3: Intermediate-resolution spectroscopy, photometry.
- ALCoR 4: Narrow-band imaging; low-resolution spectroscopy; continuum imaging in general.
- ALCoR 5. Low-resolution spectroscopy of the faintest sources; wide-field imaging.

3.3.3 Reflected light

Sky glow is the result of light that is projected upwards, and then scattered back to the surface of the Earth. Part of the stray light is projected directly upwards. Usually this results from poorly designed, or maladjusted lighting; it may, however, also occur when the light is aimed upwards on purpose. Another major contribution to the stray light is the light that is well-directed to objects, but reflected by them. Road surfaces, grass, and buildings reflect a fair amount of the incident light, and the reflected light usually goes upwards.

It should be stressed here that, in this respect, the light only serves its purpose if it hits the eye of the observer. In some cases, like signalling, it is the light source itself but in almost all cases it is the light that is reflected from a surface that is 'useful'. So, the suggestion that may be heard at places, to make all surfaces black so there is no reflected light, really is nonsense. Even if it were possible to do so, the result would be to make the lighting installation useless. This is particularly true for road surfaces. It should be stressed that the contribution of the reflected light to the overall sky glow is still under discussion. At present, quite different estimates are used, but a stringent theoretical framework, as well as sound experimental results, are still lacking. An outset is given by Gillet & Rombauts (2001, 2003) and Laporte & Gillet (2003). See also Cinzano & Diaz Castro (2000), Broglino et al. (2000). In sec. 12.4.4, details are given about the difficult question of how much of the reflected light has been 'used' and in which mathematical way the reflection can be described. In sec. 1.2.1c, the related problem of 'waste' and 'scrap' is discussed in some detail.

All sources of man-made sky glow have one thing in common: they all represent an economic loss. Crawford calculated on the basis of a number of 'rule of thumb' assumptions the loss of one thousand million dollars annually in the US alone (Crawford, 1991, 1997). Isobe has given similar data, but more detailed for specific towns and locations (Isobe, 1999). See also Cinzano (2000) and Cinzano et al, (1999).

These calculations include the reflected light. According to the Italian data, only a small part of the sky glow results from direct light and the major part from the reflected light that cannot, as indicated earlier, be avoided without compromising the function of the lighting itself (Fellin et al., 2000). The result is that the calculations over-estimate the energy losses quite considerably (sec. 1.2.1c). Nevertheless, the losses are unacceptably high! As indicated already, in sec. 12.4.4, the influence of the reflected light to the sky glow is discussed in detail.

3.4.4 Horizon pollution

Light emitted by outdoor lighting upward into the atmosphere is the cause of light pollution. It is, however, important to note that there are at least three major aspects of light pollution. The first aspect is the effect of light that is emitted more or less straight up. This light is scattered in the atmosphere and in part sent back to the surface of the Earth. It causes the well-known 'sky glow'. The sky is brighter than would correspond to the natural background radiation that is explained in sec. 3.1. As is explained in sec. 5.1.1, this brightening of the sky reduces the possibilities to observe celestial bodies that form a weak contrast to their background.

The second aspect has to do with the fact that not all light that goes straight up, reflects straight down. It is also scattered in near horizontal directions, and can reach distant places (sec. 12.4.4). From a distance, the scattered light looks like a 'light blob' directly over the source, like e.g. a big city. The blob is often easily visible from a great distance. As the blob is the result of the light emitted almost vertically upwards and scattered in the atmosphere, it can not be higher than the thickness of the atmosphere. If we take that as being about 8 km, above which the atmospheric pressure and the amount of aerosols are too low to cause much scatter, the elevation of the top of the blob will be at 50 km distance about 9 degrees and about 4,5 degrees at 100 km. Because few astronomical observations are made at smaller elevations than some 15 degrees, this blob represents 'horizon pollution' but it is no threat to astronomical observations (Schreuder, 2000).

In sec. 1.2.1b, more details are given about the relation between light pollution and air pollution. Aerosols, particles floating in the atmosphere, can have many different sources (Mizon, 2002, p. 6). Light pollution countermeasures and air pollution countermeasures need to go hand in hand. In sec. 14.6.2b, it is mentioned that the densest layers of aerosols do not reach very high (Upgren, 1997, p. 24). A similar suggestion follows from an unpublished study in Italy (Soardo, 2003). From other sources it is known that the aerosol concentrations over big cities are much higher than over open country.

The third aspect is particularly important for large-scale astronomical observatories. Light emitted by a source at near-horizontal elevations may travel far through the atmosphere and be scattered downward right above observation places, even at a considerable distance from the source. The range above, but close to, the horizon is particularly relevant for the interference of astronomical observation at distant astronomical observatories (Cinzano & Diaz Castro, 2000). This effect is depicted in Figure 12.4.2. The Atlas that is mentioned in sec. 5.3, suggests that this distance may be up to 100 km; see e.g. the light halo around the drilling platforms in the North Sea as depicted in Cinzano et al. (2000, figure 13). It is found that the upward light emitted by a big city could indeed extend over distance of about 100 km (Schmidt, 2002, p. 157; Smith, 2003). This finding is essential to the warning that emanates from the publication of the Atlas. The farther reaches of this light halo are rather weak, corresponding to an increase of the night sky brightness of only a few percent over the natural background radiation. Nevertheless, it was found that, due to this wide scattering of the light, a considerable part of the world population is severely hindered in observing the starry night (sec. 5.3.1; Beekman, 2001). This means in a more practical sense that the reduction of this wide, rather faint, haze must be the first priority of the lighting engineers when planning outdoor installations. We will come back to these priorities in sec. 11.2. One may conclude that stray light emitted by outdoor luminaires in a direction close to the horizon is more harmful than the light emitted straight upwards. Thus, it is important for lighting designers to have a good, and generally accepted, classification system for outdoor lighting luminaires. A classification that fulfills these requirements is introduced in sec. 7.1.4.

There are further points to be mentioned here. Earlier in this section it is pointed out that, at distant astronomical observatories, the observations are disturbed most by light that is emitted by the source at angles close to the horizon (Cinzano & Diaz Castro, 2000). At such angles, the light that is reflected at the ground in the direction of the observatory, is limited by buildings, trees etc., at the site of the source. So, the shielding should be taken into account (Soardo, 2003). It might be argued that, as regards distant observatories, the direct light is the most damaging, and that, therefore, luminaires with the minimum upward flux should be recommended.

In sec. 9.1.7d, the conspicuity of distant luminaires is discussed. Many people, astronomers and naturalists alike, complain about the fact that distant luminaires are conspicuous in such a way that they cause pollution. This effect is most noticeable when the distance between the site of observation and the light source – an urbanization or an industrial site – is somewhere between 3 and 10 km. At such distances, the direct light from the outdoor lighting luminaires is clearly visible and may cause considerable disturbance, whereas the light that is reflected of the ground is reduced strongly by trees and buildings. When the distance is much longer, say 100 km, the light sources themselves are not visible any more;

all that remains is the sky glow. As can be concluded from the Tables 9.1.14 and 9.1.15, even luminaires with the strictest possible cut-off will still be quite conspicuous at a distance as large as 10 km! One might put this in another way. The visual system is so sensitive that even very dim lights can easily be discerned. This is clearly so; otherwise, stars would not be visible! The fact that the luminaires are quite visible, however, does not imply that they may have a detrimental effect on astronomical observations. Still, they may look ugly and therefore we will need another term in stead of the term 'light pollution'. Here we will use the expression 'horizon pollution'. In sec. 9.1.7d it is concluded that distant, normal, well-adjusted outdoor luminaires near the horizon have, in most cases, no negative influence on astronomical observations. If one wants them removed, this must be done on purely aesthetic grounds; it is not correct to use arguments about obstructions towards astronomical observations to do so.

3.4 The environmental approach towards reduction of light intrusion

3.4.1 Zoning

The consequences of light pollution are not equally severe in all places in the world; this implies that the light intrusion restriction measures do not need to be equally stringent for all places. For this, 'the world' is divided into zones. Zoning is a well-established practice to establish a base for environmental regulations. Zones are defined as areas where specific activities take place or are planned, and where specific requirements are recommended for the restriction of obtrusive light. The CIE has proposed a zoning system that is specifically focussed on this purpose (CIE, 1997, 2003). Zoning does not stop environmental pollution, but it may serve as a frame of reference for anti-pollution legislation and regulation.

The CIE zoning system for general purposes is closely related to the system of zoning that is in use in many countries. The zones are characterized by their Zone rating (E1 ... E4). A description is given in Table 3.4.1. and 3.4.2.

Zone rating	Description
E1	Areas with intrinsically dark landscapes: National Parks, Areas of outstanding natural beauty (where roads are usually unlit);
E2	Areas of 'low district brightness': generally outer urban and rural residential areas (where roads are lit to residential road standard);
E3	Areas of 'middle district brightness': generally urban residential areas (where roads are lit to traffic route standard);
E4	Areas of 'high district brightness': generally urban areas having mixed residential and commercial land use with high nighttime activity.

Table 3.4.1: *Description of the environmental zones according to the CIE Zoning System. After CIE (1997). See also CIE (1993a, 2003) and Pollard (1997).*

Zone	Surroundings	Lighting environment	Examples
E1	natural	intrinsically dark	national parks or protected sites
E2	rural	low district brightness	agricultural or residential rural areas
E3	suburban	medium district brightness	industrial or residential suburbs
E4	urban	high district brightness	town centres and commercial areas

Table 3.4.2: *Description of the environmental zones, adapted from CIE, 2003, table 2.1.*

The specific lighting design aspects of installations near astronomical observatories as well as the operation of the observatories call for a more detailed zoning system, where one or more of the CIE zones are split up in sub-zones. The sub-zones that are given here, are based on the ALCoR system, proposed by Murdin (1997). See also Schreuder (1994, 1997). The description of the environmental sub-zones is given in Tables 3.4.3 and 3.4.4, together with examples of astronomical activities that can take place in these zones.

Environmental zones	Examples sub-zones
E1	Areas with intrinsically dark landscapes
E1a	– nature preserves
E1b	– national parks
E1c	– areas of outstanding natural beauty, protected landscapes
E2	Areas of low district brightness: rural agricultural areas, village residential areas
E3	Areas of middle district brightness
E3a	– sub-urban residential areas
E3b	– urban residential areas
E4	Areas of high district brightness
E4a	– urban areas having mixed residential, industrial and commercial land use with considerable nighttime activity.
E4b	– city and metropolitan areas having mixed recreational and commercial land use with high nighttime activity

Table 3.4.3: *Description of the environmental sub-zones.*

Environmental sub-zones	Examples of astronomical activity
E1a	observatories at world-class sites
E1b	observatories of (inter)national standing
E1c	observatories of academic level, 1 m class
E2	observatories of postgraduate level, 1 m class
E3a	observatories of undergraduate level, amateurs, 50 cm class
E3b	amateurs, 30 cm class
E4a	naked eye viewing
E4b	naked eye viewing of bright objects

Table 3.4.4: *Examples of astronomical activities in the environmental sub-zones.*

In view of what is mentioned in sec. 3.3.2 about the different subjects of astronomical observations, the ALCoR classes as introduced by Murdin in 1997 will be summarized. ALCoR stands for: "Astronomical Lighting Control Region". Alcor is of course the name of the small star next to Mizar in Ursus Major (Herrmann, 1993, p. 222-223).

- ALCoR 0: No kind of astronomy is practical.
- ALCoR 1: Casual sky viewing.
- ALCoR 2: Undergraduate or equivalent public exercises from an observatory on a university or museum campus.
- ALCoR 3: Amateur observations made on a work-related basis from a selected convenient location.
- ALCoR 4: Professional observations from a selected remote location.
- ALCoR 5: Professional observations from a highly selected site of a quality rarely found in the world.

ALCoR 0 corresponds to zone E4 as given in Table 3.4.2. ALCoR 1 and 2 correspond to zone E3 as given in Table 3.4.2. ALCoR 3 corresponds to zone E2 as given in Table 3.4.2. ALCoR 4 corresponds to zone E1 as given in Table 3.4.2. ALCoR 5 is above the range of the CIE zones.

All proposals are brought together in Tables 3.4.3 and 3.4.4.

3.4.2 Curfew

Similar to the location aspects, the consequences of light pollution are not equally severe at all times of the day and night; this implies that the light intrusion restriction measures do not need to be equally stringent at all times. To accommodate this idea, the concept of 'curfew' is introduced. The period of darkness is subdivided in the 'evening' and the 'night'. Often, the transition is chosen at about midnight; usually, however, the exact time is set down in national legislation.

In general terms it is recommended to operate after 'curfew' only the light that is directly related to safety and security and to switch off the rest. This would imply that the road traffic lighting will operate also at night as well as the street lighting as far as pedestrian safety and crime prevention is concerned. Decorative lighting should, however, be switched off. It should be noted that many recommendations for road and street lighting include provisions to reduce the lighting level for the night time operation as a result of changes in traffic volume and composition. As an example, see Anon (1997a); CEN (1998); CIE (1977, 1995); NSVV (1990, 1999).

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4 Adverse effects of light pollution

Light pollution is a form of annoyance. It may be described as follows: "Annoyance is a feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group in which stress plays in important role". In this context, the effects of light pollution on different aspects of society are discussed. Natural parks are important because they are often the seat of major astronomical observatories. Also the landscape in general is important, particularly for the many thousands od amateur astronomers all over the world. In this respect, the Netherlands may serve as a good example. The Netherlands is one of the most densely populated countries in the world.
It has been customary in some circles to regard astronomers as the only 'victims' of light pollution. However, plants and animals may suffer as well from excessive lighting, as do human beings.
To a certain degree, light pollution may have public health consequences. In order to judge these consequences, a brief discussion is given on the beneficial aspects of light, more in particular on light therapy.
The chapter concludes with a brief discussion on a Petition concerning the artificial light and some remarks on addiction and other compulsive behaviour.

4.1 Annoyance

Light pollution is a form of annoyance. It is good to consider here briefly that concept. According to the World Health Organization, annoyance is described as follows: "Annoyance is a feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group" (Pijnenburg et al., 1991, p. 15; see also Lindvall & Radford, 1973). It is generally assumed that stress plays an important role in annoyance. "Stress occurs when something happens that is considered important at that moment for the well-being of the subject in terms of important goals or values. The relation between annoyance, stress and physical complaints is discussed in detail in Van Kamp, 1990" (Pijnenburg et al., 1991, p. 15; see also Lazarus Folkman, 1984). In the conclusion of that report it is stated that: "The intensity of the light emitted by greenhouses is not high enough to cause by humans any influence on the circadian rhythm. The only way that assimilation lighting can influence human health is via stress. It depends on the stress level whether the health will be influenced. Before stress may occur, the lighting must be considered as annoying" (Pijnenburg et al., 1991, p. 17).

4.2 Effects on nature

4.2.1 Natural parks and nature reserves

4.2.1.1 National parks

(a) National parks as an institution

Many, indeed most, countries have national parks where nature is protected in one way or another. The definition of a national park and the way of protection, as well as the results of it, depend on the climate, the population density, the cultural relationship towards nature and, not in the least, on the national legislation. It is not useful, therefore, to try and make a comprehensive list of all natural parks worldwide. Rather, a number of important initiatives will be discussed briefly.

National parks are not something of the recent past only. "In the USA – the cradle of the protection of nature – George Catlin pleaded already in 1833 to protect the forests along the Missouri River. In 1864, the Yosemite National Park in the Sierras of California was founded, followed in 1870 by the famous Yellowstone park (Mörzer Bruijns & Benthem, eds., 1979, p. 253). In the Netherlands de 'Vereniging tot Behoud van Natuurmonumenten' (the Society for the Preservation of Nature Monuments) was founded in 1905, whereas already in 1899 the first nature preservation areas (Kootwijkerzand and Waddeneilanden – the Frisian Islands) were founded (Mörzer Bruijns & Benthem, eds., 1979, p. 253). It is interesting to note that the 'Vereniging Natuurmonumenten', as it is called today, is at present the second largest private organization in the Netherlands with close to 1 million members. Kootwijkerzand is the core of the oldest and largest National Park in the Netherlands whereas the Waddeneilanden are the core of the wetlands area of the Waddenzee. As we will indicate later on, it is one of the largest sweet water eco-regions of the world (WWF, 1999, p. 29).

(b) The United Nations

The 'United Nations List of Natural Parks and Protected areas' is prepared by the International Union for Conservation of Nature and Natural Resources (IUCN). (Anon,. 1994, p. 150). This list contains five categories:
(1) Scientific reserves – strict protection;
(2) National parks;
(3) National monuments;
(4) Nature protection areas;
(5) Protected landscapes.

In sec. 3.4.1, the proposals have been discussed that are made by CIE and others regarding zoning. It is possible to correlate the IUCN categories with the proposed sub-zones as follows:

IUCN category	Environmental sub-zone
1	E1a
2	E1b
3	E1b
4	E1c
5	E1c

Table 4.2.1: *IUCN categories and environmental sub-zones.*

(c) The Global 200

The Global 200 represents an initiative of the World Wildlife Fund for Nature WWF. "In 1997, the World Wildlife Fund defined a list of all areas of natural importance that, as a minimum, must be protected in order to keep nature on Earth alive" (WWF, 1999, p. 24). In 1999, this list contained 237 different areas or eco-regions (WWF, 1999, p. 253-254). Hence, the list is often referred to as 'Global 200' (WWF, 1999, p. 24). It does not stop at being a long list; "The governments of over 30 nations worldwide have agreed to take care that in total almost 4 000 000 square kilometers will be protected. In spite of the good intentions, 47% of the eco-regions on land are seriously affected, and more than 50% of all sweet water and coastal eco-regions are threatened in one way or another" (WWF, 1999, p. 29).

(d) Natural parks in Europe

In the German survey document on the Environment over 1992/1993, a list is given of the natural parks in Europe (Anon,. 1994, p. 150). A selection of that list is given in Table 4.2.2, in descending order of percentage.

(e) Land degradation and deforestation

In spite of all the efforts of governments and private institutions and individuals, the deterioration of the natural environment goes on, often at an ever increasing pace. As an example, some world-wide data are quoted in Table 4.2.3 about land degradation and in Table 4.2.4 about forest loss (Bradford & Dorfman, 2002).

Country	Number	Percentage of national area
Norway	18	6,1
Great Britain	11	5,7
Germany	10	2,0
Finland	19	1,9
France	6	1,6
Italy	8	1,5
Austria	3	1,4
Sweden	16	1,4
Netherlands	10	0,9
Poland	17	0,5
Switzerland	1	0,4
Spain	9	0,2

Table 4.2.2: *Number and area of national parks in Europe, 1991. (Selection, after Anon,. 1994, p. 150).*

Cause	Area (million km^2)
overgrazing	6,7
deforestation	5,7
agricultural mismanagement	5,4
firewood consumption	1,4
industry and urbanization	0,2

Table 4.2.3: *Causes and extent of land degradation, 1996 (after Bradford & Dorfman, 2002, p. 18).*

Region	Percentage change
Europe	+0,84%
Asia	-0,67%
N. and C. America	-1,04%
Oceania	-1,85%
South America	-4,19%
Africa	-8,01%
Total world	-2,43%

Table 4.2.4: *Forest loss per region (after Bradford & Dorfman, 2002, p. 19).*

(f) Example: Abruzzo

The organization of many national parks is rather complicated and differs from country to country. As an example, we will discuss briefly the parks in the Italian district of the Abruzzi – in the middle of the country in the mountainous region of the Apennines. The data come from the Internet (Anon., 2002c). The region is about 150 km wide and covers 10 794 square kilometers. The region contains three national parks, of which the best known is that of Abruzzo; one regional park, 11 state reserves, two special biotopes, six WWF Oases, 15 regional natural reserves, and 7 territorial equipped parks. The National Park of Abruzzo, founded in 1923, is the oldest park in Italy. Its present area is 440 square kilometers. It includes 22 towns. The park is divided in four zones:
(1) Full reserve;
(2) General reserve;
(3) Protection zone;
(4) Development zone.

To a certain extent, these zones overlap with the categories that were discussed earlier, e.g. the 'United Nations List of Natural Parks and Protected areas', or the CIE-zones. But there are considerable differences. More in particular, the zone 'full reserve' is split in two; one being accessible only at limited occasions for park wardens, and the other only accessible on request for scientists. So is the 'general reserve' zone. Part of it is accessible only on request for members of acknowledged organizations, and the other for the general public, but only at an entrance fee and at designated times under stringent restrictions, e.g. as regards transportation. The protection zone is open to the public under certain restrictions. In the development zone, some settlements are permitted.

(g) Zoning in national parks

The main reason to discuss national parks in some detail is the fact that they call for a further extension of the zoning principe that has been discussed in sec. 3.4.1. This is particularly relevant for the reduction of light pollution, because many of the major astronomical observatories are located within the boundaries of national parks. Therefore, restricting light pollution is of common interest for astronomy and for nature preservation alike.

As is explained in sec. 3.4.1, zoning is a well-established practice to establish a base for environmental regulations. The basic idea is that, in case the polluting activity cannot be avoided altogether, the environmental consequences of the pollution are not equally detrimental for all locations. Zoning does not stop environmental pollution, but it may serve as a frame of reference for anti-pollution legislation and regulation. In the CIE system, the zone with the most stringent restrictions is zone E1, defined as "Areas with intrinsically dark landscapes: National Parks, Areas of outstanding natural beauty, where roads usually are unlit" (CIE, 1997, Table 1). In practice, however, this zone E1 proves to include a variety of areas and regions, requiring quite different types of outdoor lighting – if there should be any sort of lighting at all. As described in sec. 3.4.1, subzones are needed (Schreuder, 1994, 1997).

In most countries, the broad category of National Parks and areas of outstanding natural beauty consist of sub-zones of a completely different nature. In many cases, the most restrictive sub-zone is formed by the actual nature reserves where admission is only allowed for a small number of qualified surveillance people and scientists, as explained in an earlier part of this section, regarding the National Park of Abruzzo. Permanent structures like roads and buildings, are strictly forbidden and outdoor lighting is definitely out of the question under all circumstances. The second sub-zone consists of natural parks that have strict restrictions in entrance and where permanent structures are kept to a minimum, and so is outdoor lighting. The third sub-zone consists of protective landscapes and may include some small-scale farming or small hamlets. Here, permanent structures are permitted but only on a restricted basis. Further commercial activities are usually prohibited. The legal and practical realization is, however, quite different in different countries. As a result of these considerations, zone E1, consisting of areas with intrinsically dark landscapes, is split up in three subzones:
(1) E1a: nature preserves;
(2) E1b: national parks;
(3) E1c: areas of outstanding natural beauty, protected landscapes.

As we have seen from the example of the National Park of Abruzzo, under circumstances a further subdivision of zones might be called for. Further subdivisions will not, however, be discussed as they will in all likelihood depend very much on local circumstances so that no general rules may be given. There must be a limit, of course, to defining sub-zones, in order to keep the system manageable.

The relevance for astronomical observation is that in many cases an exception to the strict rules is made for astronomical observatories, which sometimes may even be found in the nature reserves themselves. In this respect, not only the high-class professional astronomy but also the educational astronomy and the activities of amateur astronomers must be taken into account. These different aspects may be expressed in the 'astronomical land use'. Furthermore, it should be noted that requirements are made for almost all other environmental pollutants, like noise, vibration, EM radiation, water, soil, and air pollution etc. differ in a similar way for the different sub-zones.

In sec. 15.6.2, details are given of a number of sites that are of particular interest for astronomy. Some are national parks where observatories are located, some are sites of major international observatories where the surrounding area got a status comparable to that of a Nature Reserve, and some are 'areas of darkness', meant more for the general public as well as for amateur astronomers. In chapter 15 of this book, some attention will be given to the particular problems – and their solutions – for astronomical sites in developing countries.

4.2.2 The landscape

4.2.2.1 The UNESCO World Patrimonium

The UNESCO World Patrimonium allows 'cultural' landscapes to be included in its list. In fact, many cultural landscapes are already on the list of the World Patrimonium (Lowenthal, 1997, p. 19). Cultural landscapes are mainly the work of nature, even if human settlement may have changed them (Lowenthal, 1997, p. 20). UNESCO differentiates three kinds of cultural landscapes (after Lowenthal, 1997, p. 18):

(1) Landscapes that are clearly limited and consciously created, like city parks, e.g. Central Park in New York;
(2) Organically developed landscapes, like agricultural areas with specific characteristics, e.g. the Yorkshire Dales in the UK;
(3) Associative landscapes. like sacred places, e.g. Uluru, usually known as Ayers Rock, in Australia.

Lowenthal concludes: "Just like the peoples of the world depend on the joint management of the environment for their physical survival, so their spiritual well-being depends on the responsible management of the landscapes" (Lowenthal, 1997, p. 20).

A summary of the World Patrimonium is given in Anon (1997). It is interesting to note in that overview, that one of the criteria that landscapes may be included in the World Patrimonium is that they "(iii) contain remarkable natural phenomena or areas with an exceptional natural beauty and aesthetic importance" (Anon., 1997, p. 7). Although darkness is not mentioned explicitly in these documents, it seems easy to interpret them in that way. It is unfortunate that this has not yet been done by UNESCO, in spite of many efforts (Anon., 1992; McNally, ed., 1994; Schreuder, 1991; Smith, 2001).

4.2.2.2 The Netherlands

(a) A crowded country

The Netherlands is one of the most densely populated countries in the world, that, additionally, has the busiest harbour and one of the largest complexes of chemical industries in the world. It has the third largest airport in Europe. It is the largest producer of natural gas in Europe. Also, it produces a number of world-renowned agricultural products, like tulips, cheese and vegetables. Furthermore, it has a number of world-famous cultural monuments that became major tourist attractions, such as the cities of Amsterdam, Delft and Gouda, the Kinderdijk windmills, the Keukenhof flower shows, the miniature city of Madurodam, the Delta civil engineering works. It has some of the best and definitely some of the most crowded beaches in Europe. But it has also the largest area of protected wetlands in the world, and the largest natural inland sand dunes in Europe (WWF, 1999, p. 24). All this in a country where 16 million people – including 2 million people from other non-European cultures – live in an area of only just over 41 000 km^2. At the other side of the scale, the light pollution in the Netherlands is the third largest in the world (Cinzano et al., 2001; Schmidt, 2002).

Small wonder that the Government of the Netherlands, often at the price of staggering costs, is doing its utmost to preserve as much as possible the natural resources. In the following paragraphs we will discuss a number of the activities in the Netherlands in some detail. It should be noted that over the years, the first priority has been to restrict air pollution – including bad smells – followed by water pollution. After that, Governmental policy was focussed on the restriction of pollution by noise, by electromagnetic disturbances, and vibrations. Only more recently, in part under pressure of the International Dark Sky Association Holland (IDN) and the Illuminating Engineering Society of The Netherlands (NSVV), the restriction of light pollution became a matter of the highest priority. See e.g. Anon (1997a, 2002a), IJsselstijn (2000), Schreuder (1994, 1999, 1999a, 2000).

We will discuss in some detail the situation in the Netherlands and the plans to improve the situation, because this may serve as a good example for other countries or regions of what can be done.

(b) Workshop 'Working together for darkness'

We will start our survey of what is going on in the Netherlands at present with the discussion of a recently held workshop 'Working together for darkness' (Workshop samen werken aan duisternis). In the following part of this section, some quotes are given from the proceedings of that workshop (Anon., 2002a).

- When discussing the consequences of obtrusive light for humans and for nature, the following may be quoted from the conclusions and statements:
  - A wider policy is needed to reduce obtrusive light: centralised, nation-wide approach; collaboration between authorities, including the theme of obtrusive light reduction in the policy of the Central Government in Ministerial Notes regarding the environment, the land management and the nature and landscape policy;
  - Establishing regulations for areas where they do not yet exist like e.g. floodlighting, advertisement lighting;
  - Darkness is a 'primeval quality' of the living environment of people and animals;
  - Designation of 'dark areas' to guarantee the preservation of the primeval quality". (Van Den Berg, 2001, p. 12-13)

- As is stipulated by Gorter (2001), the darkness in the landscape was discussed in the Netherlands for the first time around 1990 when the Ministry of Transport considered the illumination of motorways over a length of 600 km, in part passing through national parks and wildlife reserves. After many discussions, even in Parliament, the new policy of the Ministry of Transport emerged: 'no lighting, unless....'. This policy is explained in Anon. (1997a), IJsselstijn (2000) and Schreuder (2000). Nevertheless, outdoor lighting in the Netherlands increases with about 6% per year. This did lead to a marked increase in public awareness, in which aspects of ecology, experience of nature, religion, technology, public health, significance of the environment played a role. One felt that is important to be able to see the Milky Way. In the footsteps of the Ministry of

Transport, also the Ministries of the Environment and that of Agriculture are paying much attention now to 'quietness and silence' in nature, combined with darkness at night. It should be noted that the legislation of the Netherlands makes an explicit distinction between 'quietness' and 'silence', the first referring to the absence of bustling people and the second to the absence of sound. A quote: "The awareness of the activity of local authorities (municipalities) is, however, disapointingly low. For these, a three-pronged policy might be helpful:
- Custom-made solutions;
- Emphasis on saving energy and costs;
- Reduction of upward light emission.

It is often felt that by using these policy principles and by applying existing technology, the Netherlands could be 'twice as dark'" (Gorter, 2001, p. 15).

Another quote: "This could be achieved by three policy directions:
- Effective policy realization and regulation;
- Better coordination between authorises, nature and astronomical organizations;
- Increased public awareness" (Gorter, 2001, p. 16).

- In the conference, the need was stressed to introduce standard measuring geometries and to establish certified measuring systems (Schreuder, 2001).

- Finally, the proceedings of the conferences contain an appendix in which a number of relevant Governmental policy papers are discussed. This appendix contains a number of essential elements out of the present policy of the Central Government of the Netherlands in the form of a number of crucial quotations from present policy documents. We will give a few quotes from those papers that are directly related to the reduction of light pollution. It should be noted that these documents, just as all official Governmental documents in the Netherlands, are written in the Dutch language. The translations presented here have no statutory authority.

(1) Assimilation lighting of greenhouses (Anon., 2000b)
In regulation 1.5.1. it is stipulated that 95% of the horizontal emission via the side facades must be reduced by appropriate provisions at the facade or within 10 m of it. Furthermore, the lamps themselves must be invisible from the surroundings. At present, there is no standard measuring method available (Anon., 2002a, p. 47, referring to Anon., 2000b). This side protection is particularly a benefit for other greenhouses and for residents nearby. As the upward emission is not restricted, the benefits for nature in general, and for astronomical observations are marginal, or non-existent.

In regulation 1.5.4 it is stipulated that assimilation lighting must be extinguised between 20.00 h and 24.00 h (Anon., 2002a, p. 47-48, referring to Anon., 2000b). This time restriction is particularly a benefit for residents nearby. Because the assimilation lighting may be switched on for the rest of the night, again here the benefits for nature in general and for astronomical observations are marginal or non-existent.

In regulation 1.5.6 it is stipulated that other types of outdoor and advertising lighting must be installed in such a way that light shining into nearby houses does not cause undue hindrance (Anon., 2002a, p. 48, referring to Anon., 2000b). This restriction is a benefit only for residents nearby. Again here the benefits for nature in general and for astronomical observations are marginal or non-existent.

(2) Nature for people, people for nature (LNV, 1999)
"Nature in particular is for many people the place to come to rest. Not only during the day, but in particular also during the night, when the sparkle of stars in the clear night sky adds an extra dimension to the quietness and silence around you. Also Nature itself needs quietness, silence and darkness: plants and especially animals thrive best in a quiet, still and – at night – dark surrounding. Quietness, silence and darkness are, however, not automatically there. When a limit of 40 dB(A) is taken for quiet natural areas, it has been found that in more than 30% of the basic ecological areas from the 'Ecological Main Structure' (the Ecologische Hoofdstructuur, EHS, which is discussed later on in this section), already at present this limit is exceeded. When no action is taken, this would be 40% in the year 2030. It is striking that noise pollution measures are focused on homes and factories, whereas nature areas are hardly considered at all at present in Governmental policy. The policy regarding noise protection needs to be supplemented. The same holds for light pollution" (LNV, 1999, p. 14, quoted in Anon., 2002a, p. 49).

"The Government of the Netherlands is convinced that 'quietness and darkness' represent socially important functions of nature; functions that are needed for. The Government of the Netherlands will determine in the National Plan for the Environment no. 4 ('Nationaal milieuplan 4; NMP4') which measures will be used to reduce the disturbance of nature" (LNV, 1999, p. 63, quoted in Anon., 2002a, p. 50). For NMP4 see NMP (2000).

(3) Fifth Note on Land Planology (VROM, 2001)
"Wide landscapes and polders, and the more confined landscapes on the sandy parts of the soil, in the dunes and on the hillsides become more scarce. People look, aside of the turbulent city life, for quietness, space and darkness in nature. These qualities become ever more scarce" (VROM, 2001, Chapter 3, p. 13, quoted in Anon., 2002a, p. 51). "The IJsselmeer (formerly the Zuyder Zee) has a rare open and natural character. The central qualities of the IJsselmeer-area are: open horizon, quietness, space and darkness" (VROM, 2001, Chapter 6, p. 35, quoted in Anon., 2002a, p. 51).

(4) Planning Central Decision Fifth Note on Land Planology (VROM, 2001a)
"The Government of the Netherlands has given requirements for regional structure land plans, with the aim to give the landscape a full-fledged position in such structure plans. One of the requirements is that a description will be given of the landscape quality of the various landscape types. The following aspects have to be included:

- Identity and diversity of the various landscape types;
- Quietness, space, silence and darkness as well as the accessibility;
- Recognition of the history and the renewability of the landscape;

- A vital and recognizable water system;
- Diversity of, and differentiation in, the landscape;
- Its green character and the efficient use of it" (VROM, 2001a, nr. 4, chapter 3, p. 22, quoted in Anon., 2002a, p. 52).

(5) Towards a rural area for 16 million inhabitants (LNV, 2001)
"The main objective of the development-aimed landscape strategy is to make the rural area attractive for the 16 million inhabitants of the Netherlands. This means: preservation and development of identity, variation and experience of the landscape and structures that allow to use the landscape in a functional way. Such beautiful landscapes are characterized by eight different core-qualities. Number 2 is: Quietness, space, silence and darkness" (LNV, 2001, quoted in Anon., 2002a, p. 52).

(6) National Environmental Policy Plan (VROM, 2001b)
"The quality of the space to live in is, in the Netherlands, under pressure from an accumulation of environmental problems that are caused by the increase in mobility, the changes in living style, the infrastructure, and the civil engineering works; the pressure by the growth of the population and the growth of the economy" (VROM, 2001b, quoted in Anon., 2002a, p. 53).

(c) 'Natural Netherlands – of course'

In 2001, a consortium of almost all private organizations that work in areas like nature preservation, animal and plant protection, tourism and recreation, as well as a number of local and lower governmental authorities, was established to ensure that the Central Government of the Netherlands will take its responsibilities for the preservation of nature and of the rural landscape even more seriously than they do already. The following quotes are from a working document, issued by the consortium, for the different Ministries to consider (Anon., 2001a).

"In 1990, the Government of the Netherlands took a major first step towards a 'strong nature' by establishing the 'Ecological Main Structure' (Ecologische Hoofdstructuur EHS), as the natural backbone of the country" (quoted from Anon., 2001a; see also Anon., 1990, as quoted in Anon., 1997a). The Ecological Main Structure consists of a large number of ecologically important areas that are connected by 'corridors' into one big grid, stretching over the whole country. In these areas, agriculture, industry, road and rail infrastructure, tourism and residential living are allowed, but these are restricted by a set of regulations that was set up to ensure the preservation of the natural characteristics. Details of the Ecological Main Structure are described in Anon., 1997, referring to Anon., 1990, 1990a, 1993, 1993a. It should be added that several of these documents overlap to a certain extent with the documents cited in Anon., 2002a. The idea of the network is important because, in a crowded and small country, isolated areas usually are too small for the survival of many species of animals and plants. The network structure allows, by means of the corridors mentioned earlier, individual animals and plants to migrate from one area to another, thereby enlarging the 'genetic pool' that is needed for survival. For this, a separate policy aim has been formulated, called 'defragmentation'. The defragmentation policy and its mechanisms are discussed in detail in De Molenaar et al., 1997, 2000, and De Molenaar & Jonkers, 1997.

A small but important item that is part of the considerations of the Ecological Main Structure is the management of grass shoulders along National Roads and motorways. Soft shoulders along National Roads form an important link in the National Landscape Structure Plan of the Netherlands, within the Ecological Main Structure (Anon., 1999, p. 13).

The main contributions of the action group (consortium) 'Nederland Natuurlijk' are two-fold:

- To acquire areas to support the defragmentation;
- To select a large number – twenty-one in fact – of projects for active nature preservation, that serve, on the one hand, as core areas in the Ecological Main Structure and serve, on the other hand, as examples from which authorities, particularly local authorities, can find out the best way to reach the environmental goals.

The action group 'Nederland Natuurlijk' suggested to the Government to reserve at least 1500 million Euro per year over the next 10 years (Anon., 2001a). This is a sizeable sum, even for an affluent country such as the Netherlands. The justification for spending this amount of money is that such activities are essential for the survival of the country as a whole. The Government has yet to come to a decision, but one should not expect too much in view of the ways the Government has been trying to reduce expenditure over the last two or three years.

In these different aspects, the landscape elements play a decisive role, whereas the whole country is involved in an integral way. In the note that is discussed here, emphasis is on policy and regulations and not on practical countermeasures (Anon., 2001a). Nevertheless, it is important to note that darkness is mentioned explicitly: "Planning solutions are needed to reduce the ecological pressure on natural areas, such as to enlarge the 'buffer zones' to at least 1000 meters. At the same time, measures are needed, both in nature areas as in rural areas, to ensure adequate quietness, space and darkness for humans and nature" (quotes from Anon., 2001a).

4.2.2.3 Germany

In Germany, a number of classes of landscape and nature protection areas are defined (Anon., 1994)

(1) Nature protected areas (Anon., 1994, p. 129);
(2) National parks: "... no or only small influence by humans" (Anon., 1994, p. 132);
(3) Biosphere protected areas: "... environmental protection" (Anon., 1994, p. 133).;
(4) Protected landscapes: ".. to preserve the character of the area" (Anon., 1994, p. 136);
(5) Nature parks: "... reserved for recreation and tourism" (Anon., 1994, p. 138);
(6) Protected forests: "... no influence on the biological development; no forest cultivation nor direct damage" (Anon., 1994, p. 142). This might also mean 'no light pollution', but it is not stated explicitly.

It is interesting to note that darkness as a natural asset is not mentioned explicitly. In Table 4.2.5, the area of these classes of landscape and nature protection is given. The sequence of the classes in Table 4.2.5 is given according to Anon. (1994). It is not known whether this sequence has any significance.

Class	Number	Area (ha)	% of national area
(1)	4888	617 034	1,7%
(2)	11	180 302	0,5%
(3)	12	628 690	1,8%
(4)	6206	9 039 801	25,3%
(5)	73	5 569 498	15,6%*)
(6)	564	16 443	0,17%**)

Table 4.2.5: *Area of different classes of landscape and nature protection (Anon., 1994).*

Notes: *) the way of registration results in a number of double-countings
**) of all forests.

4.3 Influence on plants

4.3.1 The influence of light on plants

It is, of course, well-known that most plants need light to live. This is true, without any exception, for 'green' plants that need light for photosynthesis, an essential life process for such plants. "Light influences physiological activities (assimilation) and morphology (growing), and induces a.o. flowering, reproduction, growing and resting of plants" (Anon., 1990b, p. 2). "The preliminary conclusion is that strong artificial light sources are not likely to have a large influence on flora and vegetation. Any influence is certainly restricted to individual plants or parts of plants close, in the order of a few metres, to the light source" (Anon., 1990b, p. 3).

The influence of light reaches further. The seasonal rhythm is manipulated in greenhouses. "Most plants have seasonal rhythms. Particularly, the reproduction is governed by changes in the length of days and nights, viz. matters like flowering, rutting, and brooding. Because of the costs involved, the manipulation of the day length to increase productivity is applied only in mass production and only as long as there are no alternatives" (Hartman, 1987). "Some plants wait until the length of the day or the night changes before they come into bloom. When one wants to cultivate such plant the whole year through, the duration of the 'night' must be artificially influenced by darkening or by lighting. The formation of flower buds is governed by fytochrome – a sort of pigment – that is available in the plant's leaves. Under the influence of light, this pigment changes from its 'night form' into its 'day form'. The night form is instrumental in the forming of a flowering hormone. When the nights are too short, there is not enough fytochrome to form an adequate amount of flowering hormone. The alternation of day and night is used to manipulate the growth and the moment of flowering" (Pijnenburg et al, 1991, p. 13-14).

4.3.2 The influence of light pollution on plants

Not much is known on the influence of light pollution on plants. One study considers 'higher plants' (Roman et al., 2000). Bertels presented a survey of what was known in the Netherlands in 1992 (Bertels, 1992). In 1999, a comprehensive study was made on the impact of outdoor lighting on living organisms, focussing on public health effects (Anon., 2000). Plants and animals are discussed as well. With permission, a part of that study is quoted here (Anon., 2000, p. 18).

Plants not only need light for their energy supply and the photosynthesis but also for the induction of flowering. Based on the information function of light, a distinction between short-day and long-day plants can be made. The short-day plants flower only if the length of the day is shorter than a given maximum and therefore mainly occur in the tropics and subtropics. On the other hand, long-day plants flower if the length of the day is longer than a given minimum. These species of plants generally occur in areas of high latitude. The reaction of plants to changing light conditions differs markedly for each species; each species has a characteristic ecological optimum curve, which describes the relationship between light intensity and growth. For example, there are light-favouring species, such as pioneers, and shade-resistant species, such as undergrowth plants in a forest.

The consequences of outdoor lighting for plants appears to be limited to individual plants, or their parts, close to the light sources, and include delayed loss of foliage, accelerated branch growth and, in the case of plants near street lighting lamps, production of a second bloom in the autumn. This therefore concerns species that respond to the length of the day and for which no other restrictive environmental factors apply (Grit & Bomers, 1992). It seems that the light levels usually are too low to affect the plants in the wild. Also, no influence of the spectral composition of the light has been found (Bertels, 1992; De Molenaar et al., 1997).

It is obvious that light has a major effect on growth and on other life functions of plants. Otherwise, assimilation lighting would have no effect. To improve the carbon dioxide assimilation, average illumination values of 2000 to 4000 lux are needed for the situations that are common in the Netherlands. This implies that one luminaire with a 400W high-pressure sodium lamp is needed for each 20 to 10 m^2. These levels are needed as a supplement to daylight, up to a – simulated – day length of 16 to 18 hours (Lakwijk, 1989, p. 615). If, however, the plant cultivation has to take place under artificial light only, much higher levels are needed – up to 20 000 to 80 000 lux (Lakwijk, 1989, p. 616). But regular outdoor lighting is too weak to have an influence on the general well-being of plants.

It might seem strange that so little is known about the influence of light pollution on plants, in spite of the fact that so much is known about the influence of light on plants in general. This fact is underlined in the following quotation, where the author describes his own study: "The report is based on two comprehensive literature surveys: Smith (1982) and Frank (1988)". (Anon., 1990b, p. 1). The results of these studies are in line with other sources and are, in turn, widely quoted. In other words, authors base themselves on the same sources, that are only small in number.

4.3.3 Greeneries

As has been indicated already in sec. 2.4, cities and towns may be adorned with greeneries, usually as part of a city beautification scheme. As a part of such schemes, it has been a custom for many centuries to plant trees alongside roads. As an additional benefit, travellers can use the shadow of the trees to avoid direct sunshine. When the roads are lit, however, there might be a problem. Trees and lighting columns can get in each other's way. More in particular, the street lighting luminaires may end up in the top of trees. The result may be three-fold:

(1) Some of the light is absorbed in the trees, reducing the lighting efficiency of the installation. When the trees lose their foliage in winter, the light distribution on the road will be dependent on the season as well;
(2) Light pollution will, however, be reduced by the same process. It will be clear that reducing the light pollution by absorbing light is not an efficient way to do so, because the light pollution reduction will be dependent on the season as well;
(3) The foliage of the trees will be influenced by the street lighting lamps, particularly if they have a considerable component of blue light, like e.g. high-pressure sodium lamps. Incidently, that is the reason why these lamps are used in assimilation lighting.

In Table 4.3.1, some rules-of-thumb are given to adjust the positions of trees and columns in order to avoid problems. For the justification of the rules-of-thumb, see the original publication (Anon., 1994a).

Mounting height (m)	Spacing (m)	Distance to first tree (m)	Number of trees between columns
4	25	2	n.a.
6	30	10,75	2
8	40	16,00	2
10	45	19,25	1
12	60	26,5	1

Table 4.3.1: *Relation between trees and lighting columns. Based on data from Anon, 1994a, p. 17.*

4.4 Influence on animals

4.4.1 Animals in general

Until recently, it was customary to consider only human beings as 'victims' of light pollution. The majority of studies was made by astronomers and most pressure was made to protect the sites of astronomical observatories. To a lesser extent, also the public health aspects were investigated. As is mentioned in sec. 4.3.2, a major study has been made in The Netherlands, sponsored by the Ministry of Public Health (Anon., 2000). This study includes a comprehensive survey of the literature as well, particularly regarding the influence of light pollution on animal life. Studies have shown that many animals, like e.g. insects and birds, suffer from light at night. An 'anecdotical' survey is given in Anon. (2002a). See also Bertels (1992). Also other animal like sea turtles may suffer considerably from light pollution (Irvine & Belalidis, 1999). A number of general aspects are dealt with in the older studies of Schanowski & Späth (1994) and Verheijen (1985). Insects have been dealt with in some detail by Steck (1997). In sec. 4.2.2, we will come back to that study.

The most general effects of excessive outdoor lighting on animals are according to Anon. (2000, p. 18-19):

(1) Effects on orientation, ranging from improved orientation to disorientation. Examples are given by Baker (1990) and Abt & Schulz (1995);
(2) Attraction, fixation and repulsion. This area has received considerable attention (De Molenaar et al., 1997; Frank, 1988; Kiefer et al., 1995; Rydell et al., 1992; Opdam, 1991; Opdam et al., 1993; Bertels, 1992);
(3) Disruption of biological rhythms, both the day-night rhythm (the biological clock) and the seasonal rhythm (the biological calendar). Details are given by Molenaar et al. (1997) and Abt & Schulz (1995). The effect on human beings is discussed in sec. 4.5;
(4) Change in habitat quality. In this respect, noise and lighting may interact. See Reijnen (1995) and De Molenaar et al. (1997).

These different factors are graphically represented in a figure given in the report quoted here (Anon., 2000, figure 1, based in De Molenaar et al., 1997).

Another report states that "It is likely that animals may be disoriented by light as a result of disturbances of the natural beacons. The result is not clear at the moment, but it deserves attention" (Anon., 1990c, p. 8-9). "Strong artificial light sources may influence mating but it is likely to be a very local effect only with a very small radius of action" (Anon., 1990, p. 10). "It is likely that the disturbance of the biological clock caused by strong artificial light sources will have a larger influence on insects than on their larvae" (Anon., 1990, p. 11).

4.4.2 Insects

In Germany, a detailed study has been made on the influence of light on insects, with special attention to light pollution (Steck, 1997). The study begins with details on relative spectral sensitivity of the visual system of insects, based on data from Cleve (1967) and Menzel (1979) (Steck, 1997, sec. 2.2). The following results are quoted:
(1) The sensitivity curves in different insect species are quite different;
(2) Most insects are sensitive for UV light;
(3) The maximum of the sensitivity curve in insects is more towards the blue as compared to the human visual system;
(4) Consequently, most insects are more sensitive for blue light and less sensitive for yellow and red light as compared to human beings.

Based on insect catching experiments, the relative approach flight density can be determined (Steck, 1997, sec. 2.4). In line with the results of the studies on the relative spectral sensitivity of the visual system of insects, it is found that for all insects that are common in Germany, high-pressure mercury lamps have the highest attraction value, as compared to fluorescent tubes and high-pressure sodium lamps. In 73 insect-collection sessions the following numbers were caught:
- High pressure mercury lamps: 8360;
- Compact fluorescent tubes: 2800;
- High-pressure sodium lamps: 1760.

(After Bauer, 1993, quoted by Steck, 1997, p. 12).

In another study, similar results have been found (Gorter & Kuipers, 1996). In an insect collection experiment, 3,2 grams of insects were caught in yellow light and 18,6 grams in white light under similar conditions. It should be noted that these data are not included in the printed text.

Based on the insect catching experiments that were mentioned earlier, the influence of different luminaires on the attraction of insects has been investigated (Steck, 1997, sec. 2.6). It was found that the light distribution of the luminaires has considerable influence on insect behaviour. In general, luminaires that emit light in all directions attract many more insects than luminaires that emit light in the lower hemisphere only (Steck, 1997, p. 15). More in detail, it was found that street lighting luminaires with a semi-cut-off light distribution attract 1,5 times as many insects as cut-off luminaires, whereas non-cut off globe lights attract 8 times as many insects as semi-cut-off street lighting luminaires and 12 times as many insects as cut-off street lighting luminaires (Steck, 1997, p. 16). The classification of luminaires is discussed in detail in sec. 7.1.4.

In conclusion, it is recommended that:
(1) In outdoor lighting, only lamps that emit long-wavelength light should be used, i.e. preferably low-pressure sodium lamps. High-pressure mercury lamps and fluorescent tubes should, if possible, be avoided;

(2) Luminaires that emit light upwards or sideways should be avoided. This recommendation also refers to decorative lighting luminaires;
(3) Floodlighting and area lighting luminaires should preferably have a horizontal, flat cover.

When insects are attracted by light, the attraction might cover a wider area. The many insects may attract predators and, in their turn, secondary predators. "Street lighting is on the one hand favorable for predators. Lighting may, however, cause unnatural death" (Anon., 1990b, p. 6).

One must note the fact that the recommendations based on the benefits for insects are almost identical to the ones that benefit astronomers. See also Anon. (1990c).

4.4.3 Birds

In the wake of the studies made in the Netherlands related to the lighting of rural motorways in natural settings (see Anon., 1997a), a large number of literature studies and a number of experimental studies have been made. A compilation of the literature may be found in the studies of Van den Berg (Anon., 2000) that was quoted earlier, and De Molenaar et al. (1997). As an example, one of the many experimental studies is described in De Molenaar & Jonkers (1997); the results have been published (De Molenaar et al., 2000). This study on godwits might be considered as a methodological example of how such studies ought to be made.

In Brazil, a survey was made on the main effects of light intrusion, focussing on the Brazilian urban situation (Pimenta, 2002). In this publication, a Canadian study is quoted. On the basis of the data provided by the Canadian Fatal Light Awareness Program (FLAP), it is estimated that annually 100 million birds are killed in collision with man-made structures (Pimenta, 2002, p. 96).

The German survey report that was mentioned earlier, contains a section on bird life (Anon., 1994). In this section, it is stated that: "The reasons that birds are endangered, range from direct loss of life as a result of collisions with cars, with fences, window panes, electricity cables and support wires, to the destruction of habitat as a result of building activities or agriculture. Added to this are the electrocutions, disturbances by tourism and reductions as a result of hunting, destruction of nests etc." (Anon., 1994, p. 113-114) It is striking that in this very comprehensive critical data collection, the influence of stray light and light pollution are not even mentioned.

One must be careful not to attribute all changes in growing and flowering patterns of plants and all changes in behaviour of animals to the influence of light pollution. A survey was made in which was stated that many changes are the result of global warming (De Vos, 2003). In some studies, the influences of the two causes are not clearly separated. The reason is that global warming and the use of outdoor lighting do increase in almost the same pace – probably because they are both results of the same underlying common cause, such as the growing world economy. This, of course, is just conjecture.

Several examples are given:
(1) The area of occurrence of many insects has shifted more than 300 km to the North over the last decades;
(2) The habitat of one particular species of mocking bird ('orpheusspotvogel') was limited in the 1970s to Northern Italy, now the habitat has shifted to Holland – a shift of well over 1000 m;
(3) Some common species of tits lay 10 days earlier since 15 years;
(4) Several migrating species of thrush that arrived in 1980 of 4 April in the Netherlands, whereas in 2002, they did so on 27 March.

Reference is made to the well-known report of the Intergovernmental Panel on Climate Change (IPCC). In Chapter 13 of this book, global warming, as well as several other environmental issues, are discussed in detail. World-wide, the temperature increased in the 20th century by 0,6 degrees Celsius. It is expected that in the 21th century the rise will be between 1,4 and 5,8 degrees Celsius. From these data, the following expectations are derived for the Netherlands for the 21th century:
(1) Increase in temperature by 1 to 6 degrees Celsius;
(2) Rise in sea level by 0,2 to 1,1 m;
(3) Increase in precipitation in summer by 1 to 4%, in winter by 6 to 25% (De Vos, 2003, p. 11).

4.5 Health effects of light

4.5.1 Image forming and non-image forming effects of light

When we consider in this book the negative aspects of excessive lighting, it is good to consider the beneficial aspects of light as well. This is necessary in order to arrive at the best compromise between too much and too little light. In other sections of this book, we have dealt with these facts as regards outdoor lighting. When considering health aspects of light, attention must be paid to different beneficial aspects of light. True, these aspects refer mostly to interior lighting, but in order to understand any possible negative influence of light pollution, it is necessary to consider them briefly. One additional, but obvious, reason to do so is that, in many cases, interior lighting 'escapes' through windows and may contribute considerably to outdoor light pollution. This point is discussed briefly in sec. 2.8.2a.

Light may fall on any part of the body of plants, animals, and humans. As regards plants, the influence of light is mentioned in sec. 4.3.1, when reference was made to photosynthesis. There are, of course, many more ways in which light may influence plants. A few have been mentioned in sec. 4.4.1. Contrary to plants, most animals have eyes. So, naturally, most interest is aimed at the effects of light on the eye, although there are many examples of light having influence on other body parts of animals and humans. Some are mentioned in further parts of this section. See also NSVV (2003).

When restricting ourselves to light that strikes the human eye, until about one or two decades ago, most people thought of light as a visual phenomenon only. More recently, it is understood that light has a much wider influence on living organisms. Functionally, one may discern image forming effects and non-image forming effects of light. It should be stressed that both effects are related to light that enters the eye, and that hits the retina. The image forming or IF effects of light are, of course, those that are related to vision and visual perception. These effects are discussed in detail in the Chapters 8, 9, and 10 of this book. In this section, we will concentrate on the non-image forming effects, or NIF effects, of light. The discussion is based in part on Scotians (2001) and NSVV (2003). See also Van Den Beld (2003) and Westerlaken et al. (2003).

The first thing to note is that each of the two effects is directly related to the fact that they use separate neural pathways. The image forming pathway is the well-known optical nerve that is discussed in detail in sec. 8.1.5. It connects the eye to the visual cortex. The non-image forming effects are transmitted by the retinohypothalamic nerve tract – or RHT – that, as the name suggest, connects the retina to the hypothalamus. See Figure 4.5.1.

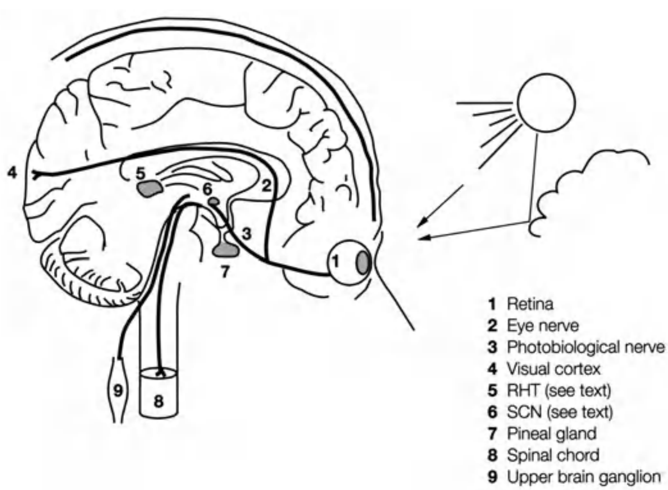

Figure 4.5.1: *The nerve tracts in the eye-brain system. After NSVV, 2003, figure 4.1.*

As is described in sec. 10.1.5a, the hypothalamus, together with the thalamus, are parts of the brain that are located near the brain stem. The hypothalamus has many functions, like e.g. the organization of the bodily hormonal control and of the circadian rhythms that are discussed in sec. 4.5.3 (Gregory, ed., 1987, p. 531). Also, some of the more elaborate instinctive behaviour seems to be related to activities of the hypothalamus and the thalamus (Frijda, 1988). More recently, it is assumed that the biological rhythms are not so much governed by the hypothalamus as such, but by the suprachiasmic nucleus, or SCN, that actually is a part of the hypothalamus (NSVV, 2003, p. 17-18; Brainard, 1995).

It is interesting to note that the spectral sensitivity curve of the non-image forming effects is essentially different from the two that are related to the image forming effect, viz. the photopic V_λ-curve and the scotopic V_λ'-curve. One might say that here is a non-image forming V_λ-curve. This is depicted in Figure 4.5.2.

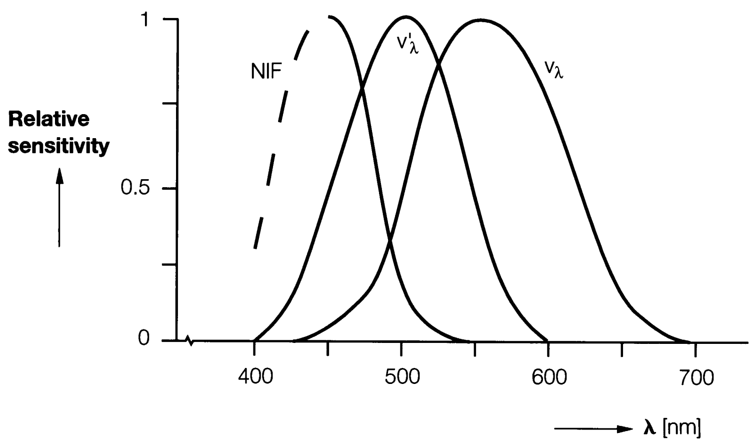

Figure 4.5.2: The relative spectral sensitivity curves for NIF effects, scotopic and photopic vision. After NSVV, 2003, figure 6.1.

The photopic and scotopic sensitivity curves are discussed in detail in sec. 8.3.4a. "It is not precisely known, how the signal that is transmitted by the RHT is processed in the SCN. The research covers not only molecular and physiological aspects, but also evolutionary and cognitive aspects" (NSVV, 2003, p. 18). Details are given in Hankins & Lucas (2002). What is known, however, is that signals are sent from the SCN towards the pineal gland, where the hormone melatonin is produced (Gregory, ed., 1987, p. 530). This hormone is also known as the 'sleep hormone' (NSVV, 2003, p. 19). The pineal gland produces not only melatonin, the sleep hormone, but also the adrenocorticotrope hormone ACTH, which, in its turn, triggers the production of cortisol in the cortex of the adrenal (NSVV, 2003, p. 21). Cortisol is the stress hormone (NSVV, 2003, p. 19). Cortisol and melatonin act as antagonists: the first triggers action, and the second triggers rest. Both are produced under the influence of non-image forming light from the retina via the pineal gland. So it is likely that, in natural conditions, the two will be synchronized, although not necessarily in phase. This synchronizing effect is called the biological clock. In view of the large influence of ocular light, it is to be expected that, also in natural conditions, the biological clock will show a 24-hour period – which is in fact the case. A long list of diurnal rhythms can be made, the most important being:

- sleeping patterns;
- food patterns;
- vigilance;
- tiredness and sleepiness.

(NSVV, 2003, p. 21; see also Wetterberg ed., 1993).

4.5.2 Influence of light on the biorhythm

The importance of biorhythms for animals is discussed briefly in sec. 4.4.1. See also De Molenaar et al. (1997) and De Rudder (1952). The 24-hour-economy causes a considerable disruption of the day-and-night rhythm: at present, about 15% of the professionally working population works in night shifts (Schoutens, 2001, p. 29). In the end, the consequences for the health of shift workers can be quite severe: it has been reported that people who work always in night shifts, live on the average five to six years shorter that the rest of the population (Schoutens, 2001, p. 28). It seems that it is desirable to experience the daylight directly for the stabilization of the day-and-night rhythm. It is, however, not a matter of the light level only. As an example, it is well-known that people who work in windowless rooms without any daylight penetration, suffer more from bad moods, lack of concentration and lower levels of attention (Schoutens, 2001, p. 30). Another health aspect is also reported: injuries heal faster by holding them in front of an LED array (Drolette, 2000). As LED's usually do not emit much UV-radiation, that radiation does not seem to have much influence.

In 2000, a comprehensive study was published in the Netherlands that discussed the impact of outdoor lighting on man and nature (Anon., 2000). We have already mentioned this study several times. Because it was published by the Health Council of the Netherlands, emphasis was on the influence of light pollution on the health of individual human beings. As mentioned earlier, some parts of that report are quoted here with permission (Anon, 2000, Section 4.1., Impact of outdoor lighting on health). It should be noted that several points have been added and that some small editorial changes have been made.

As mentioned in an earlier part of this section, outdoor lighting may disrupt the biological rhythms, or biorhythm, both the day-night rhythm (the biological clock) and the seasonal rhythm (the biological calendar). Details are given by Molenaar et al. (1997). Experimental research with laboratory animals that can be used as a model for human beings, such as rats, has provided a great deal of knowledge about biological rhythms and the effect of light on the neuro-endocrine system. As mentioned in sec. 4.5.1, light has been demonstrated to control the day-night rhythm in the secretion of melatonin, which in turn affects the sleeping-waking rhythm, the movement rhythm and brain activity (see Anon., 2000, chapter 3 and De Molenaar et al., 1997). Also, disturbances in the day-night rhythm can have clearly noticeable physical and psychological effects, such as jet lag and the effects of shift work.

As with other mammals, man also has a genetically determined biological clock and even a biological calender. Research has shown that under isolated, constant conditions, human beings have a day-night rhythm that is comparable with the rhythm of other mammals (Wever, 1979). The rhythm is also adapted to the specific length of the day and night in northern regions, for example. The rhythm is also only affected by exposure to intense light of over 2000 lux. This finding formed the basis for using light therapy for people suffering from winter depression that is discussed in more detail in sec. 4.5.3. However, still little is known about the mechanism that forms the basis for seasonal affective disorders of this kind and the way light therapy works. For a summary of the research into light therapy see Wirz-Justice (1993). See also NSVV (2003), Schoutens (1999; 2001), Van Den Beld (2003) and Westerlaken et al. (2003). The 24-hour economy will also result in an increase in shift work. It is hoped that experimental research into influences on the biological clock will provide indications for solving problems experienced by workers when disturbances of the day-night rhythm occur (Van Dam, 1999). Research over the past ten years into human biorhythm has also examined the role of the seasonal rhythm in relation to the physiology, biochemistry and behaviour of man (Aschoff, 1981; Lacost & Wirz-Justice, 1989).

It seems obvious to assume that a disturbance of the day-night rhythm and seasonal rhythm of humans would have a detrimental effect, just as it does with other mammals. That effect will generally be less severe in humans, as they have not followed the normal day-night rhythm since the invention of artificial light. One possible way that artificial light may affect human health is through stress. Stress occurs if something is at stake that is important at the time for an individual's well-being in terms of important objectives and values (Lazarus & Folkman, 1984). An individual may experience stress, and over time an impact on health, from a disturbance of the environment by artificial light during the evening and night, depending on how much the person considers this to be a nuisance (Pijnenburg et al., 1991). The combined exposure to other stress factors in the environment may increase this indirect effect of artificial lighting.

In research by the municipal health authority into the effect of the assimilation lighting used in greenhouse horticulture on the residents in the area around Venlo in the Netherlands where greenhouse horticulture is growing rapidly, questionnaires were used to survey the impact on health. Residents in the area reported complaints such as anxiety dreams in children, sleep disturbance, depression and feelings of oppression. None of these health complaints could be related to the light from the greenhouses (Grit & Bomers, 1992; Pijnenburg et al., 1991). No psychological or biological variables were measured in the surrounding residents. That is an omission, because measurements of that kind would provide a more objective indication of the occurrence of stress as a result of a disturbance of the day-night rhythm by light from greenhouses.

4.5.3 Phototherapy

The most beneficial aspect of light for health seems to be the use of light to counteract seasonal depressions. This is usually termed ‘phototherapy’. It should not be confused with the much older use of UV-radiation in health care. It has been reported that in Central Europe, about 15% of the population suffers from a mild form of seasonal dependent depressions and 4% from a severe form (Lusche, 2001). A detailed study which includes a comprehensive literature survey, lists the main advantages of phototherapy compared to drug treatment (Fisch et al., 1997). The best results were obtained when the illumination at eye level is between 2 500 and 10 000 lux in a therapy session of at least six weeks for one hour per day (Fisch et al., 1997, p. 574; 575). The way light therapy works, as well as the main negative side-effects, are discussed by Fisch et al. (1998).

Many details are published in NSVV (2003), as well as in a preview of that report presented by Schoutens (1999). “In the Netherlands, with about 16 million inhabitants, about 450 000 people suffer from the serious ‘winter depression’ (Seasonal Affective Disorder SAD) and about 1,2 million from the milder form of ‘winter blues’ (Subsyndromal Seasonal Affective Disorder SSAD)” (Schoutens, 1999, p. 2). “About 11% have serious or milder problems to adapt their sleeping rhythm to changes of the seasons” (Schoutens, 1999, p. 3). “ Apart from counteracting winter depression and correcting sleeping rhythm disturbances, light therapy might improve the condition of patients who suffer from Alzheimer disease. This disease is a.o. characterised by atrophy of the cells that regulate the day-night rhythm. It is estimated than about 15% of Alzheimer patients suffer from the resulting disturbance of the sleeping rhythm” (Schoutens, 1999, p. 5). “Also more common disturbances in the sleeping rhythm may be treated successfully with light therapy, both the ‘early’ as the ‘late’ sleepers (the Advanced Sleep Phase Syndrome ASPS and the Delayed Sleep Phase Syndrome DSPS respectively). The correction resulting from light therapy is particularly useful for those – almost completely – blind people who have some rudimentary sense of light and dark” (Schoutens, 1999, p. 5). “In most industrialised countries, about 15% of professional workers have hours different from ‘nine-to-five’ (shift workers). Working predominantly or exclusively in night shifts usually causes severe disturbances in the biological clock, leading to increase in accident involvement, in cardiovascular diseases and will, as mentioned earlier, lead to a shortening of about five to six years in the life expectancy. Light therapy helps to reduce these negative effects of shift work” (Schoutens, 1999, p. 6). “In cases of severe ‘jet lag’, light therapy is found to allow to set back (or forward) the biological clock by as much as 12 hours in three days” (Schoutens, 1999, p. 7).

Additional information about some of these issues is given in Kerkhof (1999). “In ‘dark’ Minnesota, about 1 in 10 people suffer from winter depression, whereas in ‘sunny’ Florida the number is about 6 in 100 000” (Kerkhof, 1999, p. 1). “In the Southern Hemisphere, winter depression occurs in ‘their’ winter, i.e. in June and July” (Kerkhof, 1999, p. 1). “When sufferers from winter depression are treated by means of light therapy for at least two hours each day with a level 5 or 6 times that of normal living room levels, after a few days a clear improvement takes place, whereas after a week almost all patients are free from complaints" (Kerkhof, 1999, p. 1-2). "Light therapy reinforces the synchronization of the 24-hour rhythm" (Kerkhof, 1999, p. 2).

In all discussions about the benefits of light therapy it is suggested – but not stated – that the 'summer' regime is the best regime for humans, and maybe also for many animals and plants; the 'winter' regime is inferior. It is sometimes suggested that, as far as human beings are concerned, this may have to do with the fact that humans – at least modern humans – stem from the subtropical regions of the world, and migrated later to hotter or colder climates. It may seem that the preferences as regards light conditions are somehow 'frozen' into our genetic pattern. There seem to be some anthropological data to support this suggestion.

What is clear, though, is the fact that many seasonal disturbances and illnesses may be treated successfully by light therapy. This is undoubtedly another positive effect of lighting. Although light therapy is mostly applied indoors, there are possibilities that it might lead to light pollution, as many people might tend to believe that light is always 'good' under all circumstances, and thus 'more light is always better'. In the sections 4.5.4 to 4.5.7, the public health aspects of lighting that is excessive or not-appropriate are discussed in detail. Just as in other aspects of lighting, like street lighting or other forms of outdoor lighting, it is the improvement in lighting quality that is the best way to counteract light pollution.

4.5.4 Nuisance caused by outdoor lighting

In the Netherlands, research was carried out on the nuisance created for surrounding residents in relation to two uses of outdoor lighting, viz. assimilation lighting in greenhouses (Van Bergem-Jansen & Vos, 1991) and tennis court lighting (Van Bergem-Jansen et al. 1996). The research into the nuisance caused by assimilation lighting was a follow-up study to the research conducted in the greenhouse horticulture area around Venlo (see sec. 4.5.3; Grit & Bomers, 1992; Pijnenburg et al., 1991) and concerned ten locations in the West of the Netherlands. 391 surrounding residents were included in the study. The research was commissioned by the Ministry VROM. The physiological effects were not considered in this study. The research used statistical analyses to discover linear relationships between an objective exposure level and the percentage of people who were annoyed by various types of nuisances. This should make it possible to use the 'exposure-effect relations' – a variety of the well-known dose-effect relation – to determine limits for the percentage of people experiencing annoyance. The research into tennis court lighting included 12 residential areas with 120 surrounding residents. This research was commissioned by the Environmental Policy Appeals Consultancy (BAMB).

Questionnaires were used to determine the occurrence of nuisance. People were asked about how often they noticed the lighting, either directly or the sky glow, the perceived strength and the annoyance they experienced. The questionnaire also contained questions on various aspects of perception and behaviour. It covered matters like difficulty getting to sleep, closing the curtains, being distracted or irritated, sitting in other rooms, comparisons with the nuisance created by other sources of light, the degree of indifference, or even the feeling of safety that the outdoor lighting gave, and so forth.

4.5.5 Nuisance caused by assimilation lighting

Research into annoyance from assimilation lighting shows that the glow above greenhouses that is visible in residential areas causes the most annoyance: around 3% of residents consider the illumination of their homes or gardens as 'annoying' or 'very annoying'. 2% consider the direct view of the greenhouse lighting from the home as 'annoying' or 'very annoying'. Around 10% of people experience the visible glow around their homes as 'annoying' or 'very annoying' (Vos & Van Bergem-Jansen, 1995). The degree of annoyance caused by the glow decreased when the night sky was naturally lighter. Around 15% of people who prefer to walk outside, considered the direct view of the greenhouse lighting as 'annoying' or 'very annoying'. No questions were asked about the nuisance of glare while walking. It is striking that the percentage of walkers experiencing annoyance is greater than the percentage of people annoyed by the direct view of the greenhouse lighting from their homes. Walkers apparently prefer walking in the dark during the evening. This finding is in contrast to the experience – as is explained in sec. 2.5.3 and 12.1.4 – that pedestrians prefer lighted areas for reasons of personal security. Probably, walkers walk only in areas where they feel inherently safe. It is also striking that a third of those questioned did not agree with the following statement in the questionnaire: "It doesn't really bother me that it's practically no longer ever completely dark here in the evening and in the night". Nevertheless, only 3% would like to submit a complaint.

The research did subscribe to the conclusion from previous German research that the illuminance on a vertical plane provides an objective measure for the exposure (Assmann et al., 1987; Hartmann, 1984; Hartmann et al., 1984). This measure was subsequently adopted by CIE as the main criterion for intrusive light (CIE, 2003; Schreuder, 2001a). In the study it was found by measurement or by calculation, that the vertical illuminance varied from 0,003 lux to 2 lux. However, a clear relationship was not found between the degree of exposure and the percentage of people annoyed by various types of light nuisance. Therefore, nuisance limits could not be derived from these studies. More details are given in sec. 15.4.3.

The original Venlo study of Pijnenburg et al. (1991) gave slightly higher percentages of people who are disturbed by the lighting of greenhouses than Van Bergem-Jansen & Vos (1991). See Table 4.5.1.

Distance (m)	Percentage disturbed
< 200	48
200-1000	11
1000-4000	7

Table 4.5.1: *Percentage of people, disturbed by greenhouse lighting. After Pijnenburg et al., 1991, fig 1.*

As quoted earlier, that report concludes as follows: "The intensity of the light emitted by greenhouses is not high enough to cause by humans any influence on the circadian rhythm. The only way assimilation lighting can influence human health is via stress. It depends on the stress level whether the health will be influenced. Before stress may occur, the lighting must be considered as annoying" (Pijnenburg et al., 1991, p. 17).

4.5.6 Nuisance caused tennis court lighting

For tennis court lighting, it was found that zero to 10% of the surrounding residents considered the illumination of their homes as 'annoying' to 'very annoying'. The answer depends on the vertical illuminance (Van Bergem-Jansen et al., 1996). Between 0 and 5% considered the illumination of their gardens as 'annoying' to 'very annoying'. Lighting generally appears to cause less of a nuisance if the contrast with the background lighting or surrounding brightness is less. However, it is difficult to verify in the Netherlands this impression, because there is not sufficient variation in the surrounding brightness in and around urban areas.

In contrast to assimilation lighting, the glow visible above tennis courts caused little, if any, annoyance. In assimilation lighting, the brightness of the glow is about a factor of ten higher. The majority of surrounding residents was fairly indifferent to the fact that it was no longer completely dark in the evening. Some people even saw benefits in the presence of a sports field.

It was concluded from this research that the nuisance limits recommended by CIE did not need to be adjusted (CIE, 2003). This agrees with the limits recommended by NSVV (1999). They are used in the more recent publications in this area as well (NSVV, 2003, b,c,d). The recommendations agree also with earlier studies that were made in the context of the NSVV (Folles, 1979; Schreuder, 1979). See also Bergmann (1994), Forcolini (1993) and Schreuder (2001a). In Chapter 6 of this book, details are given about the limiting values of the light intensity and luminance that are relevant for different applications of outdoor lighting, a.o. sport lighting.

The recommendations set up by the NSVV in 1999 were the basis of the first part of legislation in the Netherlands regarding light pollution (Anon., 1998). In the section about 'lighting' it is stated that sport lighting must be extinguished between 23.00 h and 07.00 h (Anon., 1998, sec. 1.5). In the Note of Explanation (a formal part of the legislation) it is indicated in the section on lighting that "At present there is no norm but recommendations of NSVV are in preparation" (Anon., 1998, sec. 1.5.2). The recommendations have since been published (NSVV, 1999). See also NSVV (2003, b,c,d).

4.5.7 Light nuisance and the general population

(a) A nation-wide survey

The studies mentioned earlier only examined specific types of nuisance among a limited group of people in the immediately surrounding residential area. In 1995, a random survey was conducted among around 4000 inhabitants of the Netherlands that could be regarded as representative of the country's entire population (Anon., 1995). People were asked about the nuisance caused by various disturbing environmental factors, which, besides various sources of outdoor lighting, included noise, smells, vibrations, and dust/soot/smoke. Outdoor lighting proved to be the least annoying factor in comparison with the others; only 4% of the population – or rather, of the respondents – experience a serious nuisance caused by light. By way of comparison: 40% experience a serious nuisance from noise. The main source of light nuisance are headlights from road traffic (2%), followed by street lighting and outdoor lighting, which together account for 2%.

(b) Visual performance

A study from Pennsylvania University is quoted where just under 500 children between 2 and 16 years of age were screened on myopia. From those who slept always in the dark, 10% was myopic; from those who had a night lamp, it was 34%, and from those who slept under the full lighting it was 50%. It is suggested that the "the increase of the background luminance as a result of industrialization and urbanization is responsible for the increase of myopia over the last two centuries". Further support for this suggestion is not given in this survey article (Anon., 1999a).

(c) Urban ecology

In a German study, a comprehensive survey has reported measures for urban planning to promote living and working in harmony with the environment ('urban ecology'). The measures are restricted to the protection of the free space, waste disposal, and to the protection of clear water and air (Anon., 1995, p. 6, 7). It is striking that measures for noise reduction are not included. It is probably a little less surprising, however, that measures to reduce light pollution – both sky glow and light trespass – are not dealt with. This is a further point that is considered in sec. 15.2, where the aspects of public and political awareness are discussed.

(d) A Petition concerning the artificial light

The British Astronomical Association BAA has a very active Campaign for Dark Skies. In 1994, a letter was sent to the European Commission EC (Mizon, 1994). The letter contains as an annex a draft petition: "To the President of the European Parliament and the Petitions Committee. A Petition concerning the adverse effects of stray artificial light upon the night sky, and the need to for the European environmental authorities to take action to preserve our view of the heavens. The British Government's Department of the Environment does not consider that regulatory action is necessary on stray light, contrary to such EC regulations as 89/364/EEC on the efficient use of electricity and 91/565/EEC on the promotion of energy efficiency in the European Community. The Department's often repeated assertion that light pollution is not a matter for regulation but for public education will mean the increasingly rapid disappearance of the normal nighttime environment, both terrestrial and celestial, increased trespass of light as a nuisance to neighboring properties and further energy waste from lighting" (Mizon, 1994). It is striking that the British Government did not consider at that time the nighttime environment and therefore the overall landscape quality in the country, as worth-while to protect vigorously, nor that energy conservation should be promoted in all possible occasions; also it is striking that the world of the amateur astronomers has very little faith in public education. If this is the case, one wonders why the same people and organizations pay so much attention to enhance the public awareness!

(e) Addiction

Addiction is a very wide-spread condition of the human mind. Although it is customary to restrict the concept of addition primarily to the use of alcohol and drugs, with a detour into smoking and sex, the symptoms of addiction may be observed in a wide variety of human behaviour aspects. This is the reason that we will devote a few words to this condition, even if it may seem rather far away from the main subject of this book – the restriction of light pollution. We will use the book of Richardson as a guidance (Richardson, 1997).

In that book, addiction is treated almost exclusively in relation to alcohol and drugs. It is felt that many of the considerations apply equally well to other forms of addictions. Only the term 'substance' should be widened accordingly (Richardson, 1997, p. 130). A deeper psychological study may suggest that even the 'fight against light pollution' may, under circumstances, be classified as a 'substance' – be it a non-chemical substance (Schreuder, 1973, sec 3.2.4). A crucial concept in the discussion on addiction is the continuum of substance use from low to high. It increases along the following steps: abstinence > experimental > social > abuse > addiction or dependency.

These terms mean:

- abstinence: one chooses to abstain totally for a variety of reasons;
- experimental: to see how they affect you;
- social (or recreational): do it at a party and not feel any compulsion to do it again;
- abuse: to alter your thinking or feeling;
- addiction or dependency (here treated as synonyms):

"Addictions are progressive, they get worse over time" (Richardson, 1997, p. 135).

They result in loss of control that becomes apparent by:

- increase (or decrease) of tolerance;

- emotional or physical withdrawal (in case of stopping the use);
- obsessive thought, compulsive behaviour:
  - obsessive thought: constantly thinking about it. "The obsession takes on a life of its own and becomes the set-up for the compulsion" (Richardson, 1997, p. 135);
  - compulsive behaviour occurs when you repeat the same behaviour over and over. (Richardson, 1997, p. 136).

A few notes may be added here:

(1) The author seems to imply, without actually stating it, that compulsive behaviour is not functional any more, even not for the addicted, and that the compulsive behaviour might switch to other areas of life;

(2) One may use the description of Van Essen: "Either you have it or it's got you" (Van Essen, 1965, 1970);

(3) The World Health Organization WHO makes a difference between addiction and dependency;

(4) And finally it should be kept in mind that there is a close link between addiction – notably to alcohol and drugs – and the aggressive and violent behaviour that is discussed in secs. 12.1.2 and 12.1.3.

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5 Light pollution and astronomy

All astronomical observations are essentially an observation of contrast. Any stray light causes a veil, reducing all contrasts. Sky glow is disability glare. This hold for all sources. Diffraction makes even point sources into surface sources. The decrease in the limiting magnitude as a result of the veiling luminance is expressed in the 'sky glow formula'. Over the years, many measurements of light pollution have been made regarding the distribution in place and time, both local and regional. Satellite observations made it possible that in 2001 'The First World Atlas of the Artificial Night Sky Brightness' was published. It is found that about two-thirds of the world population is subject to light pollution. For 25% of the world population, only the brighter stars can be seen, but not the Milky Way. For 85% of the population in the Netherlands, the artificial light exceeds that of the full moon, and in only 3% of the area of the country, the artificial brightness is less than the natural brightness. The Atlas is based on measurements that are made by the Defense Meteorological Satellite Program (DMSP). In spite of considerable efforts to avoid it, sky glow did increase considerably on a global scale over the last few years. At present, it seems safe to expect that the levels of light pollution at most locations in the world are increasing and that they will go on increasing for the foreseeable future. A rate of increase is difficult to guess but it might seem that 3% per year will not be too far off. It should be noted that 3% per year means a doubling in 23 years.

5.1 Interference with astronomical observation

5.1.1 Contrast observation

In sec. 1.2.1 and 3.3, it is explained that in outdoor lighting, always part of the light goes upwards, resulting in what is commonly known as 'sky glow'. To understand the effect of the diffuse sky glow on astronomical observation, one must realise that all observation, both visual, photographic and electronic, of light emitting objects is essentially an observation of contrast. Why this is so is explained in a further part of this section. When the luminance of an object is called L_0 and the luminance of its background, against which the object must be observed, is called L_b, the contrast C is conventionally defined as:

$$C = \frac{L_o - L_b}{L_b} \quad [5.1.1]$$

The overall stray light causes a light veil that extends over the field of observation. This veil has a luminance as well, that will be called L_v. The veiling luminance has to be added to all luminances in the field of observation. All contrasts will be reduced, as can be shown as follows:

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{L_o - L_b}{L_b + L_v} \quad [5.1.2]$$

As the nominator stays the same and the denominator always is greater, thus:

$$C' < C \quad [5.1.3]$$

This is, of course, the way lighting engineers assess the influence of disability glare (Adrian, 1961, 1993; CIE, 1976; Schreuder, 1998, Vos, 1963, 1983, 1999, 2003, Vos & Padmos, 1983: Vos et al., 1976). The sky glow is in effect a sort of disability glare (Schreuder, 1997). Disability glare effects are discussed in detail in sec. 9.2.2.

5.1.2 The sky glow formula

When the object to be observed is a star, one might suppose that its observed luminance equals the intrinsic luminance of its surface. The intrinsic luminance of a surface is the luminance as it would be observed from nearby, without any influence of the media between the source and the meter; in other words, its 'true' luminance. For a star, one may assume an intrinsic luminance about equal to that of the Sun, this being, as an average over the full disk, about 10^9 cd/m^2 (Budding, 1993, p. 85). The intrinsic luminance of the source is therefore is much, much higher than L_v.

However, while a distant star is a close geometric approximation to a 'point source', its image in the instrument with which the observations are made is not a point at all. The image can never be smaller than a certain limiting size, even with excellent 'diffraction limited' optics (Kuchling, 1995, sec. 26.2.6; Longhurst, 1964). For the naked eye, which is quite far from being diffraction limited, the minimum diameter of any visual object is equivalent to almost a minute of arc (Vos et al., 1976; Schreuder, 1998, Chapter 7). This means that for the naked eye, L_o is not very large. Thus, even for very good observers and excellent conditions, the limit for detection with the naked eye is about the sixth magnitude, as was found already by Hipparchus in 120 BC (after Sterken & Manfroid, 1992, p. 23). See also Schmidt (2002; 2002a). The limit for detection of stars with the naked eye is discussed in detail in sec. 14.2.2a (Schaefer, 1993, 2003). The limiting magnitude follows from the definition of (difference in) magnitude:

$$m = 2.5 \log(I_1 / I_2) \quad [5.1.4]$$

where I_1 and I_2 are the luminous intensities of the two stars that are compared. See for details Sterken & Manfroid (1992), Weigert & Wendker (1989), Broglino et al. (2000) and Fellin et al. (2000). When assessing the influence of the sky glow, the smallest luminance for the most favorable conditions is L_{o1} and under sky glow conditions L_{o2}. The background luminance is L_b and L_v respectively. With $L_v = a \cdot L_b$, and according to [5.1.1] and [5.1.2], for observation at the threshold of the contrast sensitivity, C equals C':

$$C = C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{L_o - L_b}{L_b + L_v} \qquad [5.1.5]$$

When L_b is small compared to L_{o1} and L_{o2}, L_b may be disregarded in the nominators. The formula [5.1.5] becomes:

$$(a + 1) = \frac{1}{L_{o1} / L_{o2}} \qquad [5.1.6]$$

When inserting L_{o1} and L_{o2} for I_1 and I_2 in formula [5.1.4], one gets

$$m = -2.5 \log(a + 1) \qquad [5.1.7]$$

with m the increase in the threshold, or the decrease in the limiting magnitude as a result of the veiling luminance. This formula is sometimes called the 'sky glow formula' (CIE, 1997).

Another, mathematically more strict, derivation is given in Fellin et al. (2000). They have presented a relation that allows to determine the increase of the threshold magnitude for just visible stars as a result of lighting parameters:

$$dm = -2.5 \log \frac{1 + R_n}{r(1 - R_n)} \qquad [5.1.8]$$

with:
dm: the increase of the threshold magnitude for just visible stars;
R_n: the total upward flux of a whole town;
r: area average of the reflection factor.
(after Fellin et al., 2000, equation 9).

5.1.3 Walker's Law

As has been mentioned already several times in this book, light trespass is a matter of major concern for the astronomers, presenting itself in the form of a 'sky glow' in the vicinity of large urban or industrial concentrations. The luminance of the sky glow can conveniently be expressed by 'Walker's Law' (Garstang, 1991, p. 62; see also Walker, 1970, 1973, 1991). According to Garstang (1991, p. 57, equation 1), the relation between the sky brightness and the distance to the city that is the source of the sky glow, can be written as:

$$I = C \cdot P \cdot d^{-2.5} \qquad [5.1.9]$$

in which:
I: the sky brightness as measured in the direction of the source under an elevation of 45 degrees;
d: the distance;
P: the population of the city;
C: a factor that depends on the units that are used, on the luminous flux per inhabitant, and on other factors, like the reflectivity of the ground.

It is interesting to note that the exponent of the distance is 2,5, and not 2 as for the inverse square law that is discussed in sec. 14.1.5d. One might assume that the absorption of light in the atmosphere plays a role here.

Another point to note is that the formula, as given here, includes the population of the city and the luminous flux per inhabitant. The formula would be more generally applicable, if these two were replaced by the total luminous flux of the source; it that way, the formula could be used for all sorts of sources of sky glow, and not only for cities. Furthermore, the luminous flux per inhabitant, sometimes called the 'Walker number', but also sometimes the 'Garstang number', is not a constant, as is explained in secs. 5.3.3 and 13.3.3. The value of 1000 lumen per capita is only a crude approximation.

Walker's Law is established for cities in the South-West of the USA (Walker, 1973; Crawford, 1983, 1985; Turnrose, 1974). It seems to be applicable for other locations as well (Fisher & Turner, 1977; Diaz-Castro 1993, 1998; Sanchez Beitia, 1984). Surveys of the problems of sky glow and of the remedies against it are given in Anon. (1985, 1985a) and IAU/CIE (1980) and also in the special issue of Vistas In Astronomy (Anon, 1985b).

5.2 Light pollution today

5.2.1 Distribution in place and time of light pollution

Over the years, many measurements of light pollution have been made. The number of the measurements and their quality seems, however, rather meager in view of the importance to restrict light pollution for optical astronomy. In this section, an overview of the most relevant measurements is given. As will be seen, most local measurements refer to observatory sites; the regional measurements are used to influence the decision making process as regards lighting ordinances and regulations, whereas the global measurements are used to promote the idea of a 'clear night', or starry night. In sec. 5.4, the changes of light pollution over time will be discussed.

In 1997, a comprehensive survey of the diffuse night sky brightness was published (Leinert et al., 1997). A short section is included on light pollution; this section gives no more information than that what has been discussed, in more detail, in this section. The survey is interesting, because it gives an overview of other components of the diffuse night sky brightness, such as tropospheric scattering, zodiacal light, integrated starlight, diffuse galactic light, and extragalactic background light. The survey also contains detailed information about the relevant brightness units, and their respective conversion factors, as well as the relevant coordinate transformations. The natural background radiation and its components are discussed in sec. 3.1. Further details on conversion factors and conversion tables are given in sec. 14.3.2.

5.2.2 Local measurements of light pollution

As stated earlier, most local measurements of light pollution refer to observatory sites.

(a) *Mount Hamilton, USA*
It was found that since 1948, light pollution did increase at a rate of 0,065 magnitude per year. In 1978, the background in the V-region – the spectral region of yellow light; see sec. 14.2.3 – was 20,1 mag. per square arcsecond, in 1991 it was about 1,6 magnitudes brighter than the natural background (Walker, 1991, p. 53)

(b) *The Guillermo Haro observatory, Mexico*
The sky brightness was in the V-region in 1994: 20,5 mag. per square arcsecond, in 1997: 20,0 mag. per square arcsecond (Carrasco et al., 1998, table 1).

(c) *Kottamia Observatory, Egypt*
The increase over the natural background in the yellow region was 0,25 mag. per square arcsecond (Nawar et al., 1998, p. 153, referring to Massey et al, 1990, for the measuring method). The same paper lists a number of older measurements; see Table 5.2.1.

Observatory	**Year**	**Increase in V-region** (mag. per square arcsecond)
Kottamia	1995	21,05
Lick	1973	20,37
Mount Palomar	1966	21,67
San Pedro Martir	1970	21,65
Junipero Serra	1971	21,71

Table 5.2.1: *Light pollution for several observatories. After Nawar et al., 1998, table 3.*

(d) An IAU survey of observatories

A survey under members of IAU Commission 50 yielded about 40 answers (Isobe, 1998). That number was disappointing low in view of the importance of light pollution reduction for optical astronomy. The answers were analyzed in terms of preferred ALCoR-zone (see Murdin, 1997) and also in terms of distance to a city and of the population nearby. These analyses did not yield much further insight. The relation between the sky brightness and the location of the observatory did show, however, a clear trend. As was to be expected, the more remote the location, the lower the sky brightness. See Table 5.2.2.

Location	**Number of answers**	**Sky brightness** (mag. per square arcsecond)
city centre	1	16,0
in a city	5	17 to 18
suburb	5	18 to 20 (one value at 16)
country-side	10	19 to 22
mountain-side	19	20 to 23

Table 5.2.2: *The relation between observatory location and sky brightness. After Isobe, 1998, Figure 4.*

(e) Three observatories in the USA

For three observatories in the USA, the value of the light pollution was measured (Luginbuhl, 2001). The light pollution is indicated for the V-region and is expressed in magnitudes over the natural background. The data are given in Table 5.2.3.

Observatory	**Year**	**Light pollution**	**Reference**
Kitt Peak	1987	0,07	Pilachowski et al, 1989
Mt Hopkins	1996	0,49	Caldwell et al, 1999
Flagstaff	1996	0,45	Luginbuhl, 2001a

Table 5.2.3: *Light pollution for observatories in the USA. After Luginbuhl, 2001, Table 1.*

(f) Mont Megantic observatory

At the Mont Megantic observatory in East Canada, the light pollution level in the 1970s amounted to about 25% of the natural background. Towards 2000 it was 50% (Dutil, 2001, p. 135).

(g) La Palma, Canary Islands

Several measurements were made over the years of the light pollution at the Observatory on the island of La Palma, Canary Islands. Some results have been mentioned already. In 1984, measurements were made, from which it was concluded that the Walker Law, which is discussed in sec. 5.1.3, also holds for locations outside the American South-West where it was originally conceived (Sanchez Beitia, 1984; see also CIE, 1997, chapter 3; Schreuder, 2000). Other results are quoted by Diaz-Castro 1993, 1998, 2000).

(h) Cerro Tololo and Cerro Pachon, Chile

Over the course of the 11-year solar cycle, the natural background varies by 0,6 V-mag. per square arcsecond, from 21,3 to 21,9 V-mag. per square arcsecond (Smith, 2001, p. 40).

At Cerro Tololo and Cerro Pachon, the location of several of the major observatories in the world, it was in 2001 not possible to measure any artificial light pollution at elevations over 45 degrees, meaning that the artificial sky brightness in the zenith is less that 0,08 mag. per square arcsecond over the natural background (Smith, 2001, p. 41).

5.2.3 Regional measurements of light pollution

(a) Measurements in the Netherlands

In the Netherlands, just as elsewhere, light pollution is getting more attention, particularly from amateur astronomers and nature lovers. Big cities, industrial areas, sports stadia, airport facilities and – in the Netherlands the main source of light pollution – the greenhouses create a 'sky glow' that stretches over most of the night sky. In view of the dense population combined with the high level of affluence, the situation is more serious than in most other countries. As has been mentioned in sec. 4.2.2.2.a, it is sometimes stated that the Netherlands are in the top-three of the most light-polluted countries of the world (Cinzano et al., 2001; Schmidt, 2002). The measurements made in the Netherlands are discussed in detail in Schreuder (2001a). This section is based on that publication.

The first group of measurements was a photographic survey made in 1992. Photographic surveys are made by inviting a large number of amateur observers, not necessarily amateur astronomers, to take pictures with a normal camera in a fixed position, i.e. on a tripod, and with a normal slide-film of the zenith-area in their own neighborhood. The method has been developed in Japan (Isobe, 1995; Isobe & Kosai, 1994, 1998; Kosai & Isobe, 1991). The results are reported in Schreuder (1994). They are summarized here (sec. 14.6.2d).

Some results are given in Table 5.2.4, where the average values that are measured at one moment in time (7 February 1992, between 20.00 h and 22.00 h local time) for about 100 locations over the Netherlands are listed. The individual values did range from 20,97 to 17,2 mag. per square arcsecond. The average value for the 9 postal code areas is given. The postal code areas 2, 3, and 4 correspond to the densely populated, industrialized region in the West of the Netherlands, the areas 5, 7, 8, and 9 correspond to the agricultural, less densely populated area of the North and South-West, and the areas 1 and 6 have a more mixed character.

Part of the material was measured by Dr S. Isobe at the National Astronomical Observatory of Japan in Osawa, Mitaka, Tokyo, using a microdensitometer and measuring one particular star in all exposures (Capella). The method is the same as used in the Japanese surveys (Kosai & Isobe, 1991; Kosai et al., 1993). The data were given for individual exposures in mag. per square arcsecond. Because they cannot be averaged as such, they are converted into luminance terms. The converted values per post code are included in Table 5.2.4.

In the context of the 'dark night of 5 April 1997' a star counting exercise was made (sec. 14.6.2c). A large number of volunteers made an estimation of the weakest star they could see. This method is described in Kosai & Isobe (1991). More detail are given in Schreuder (1999, 1999a, 2001a). In total, 136 observations spread over 89 locations within the Netherlands were used. The areas measures about 20 degrees ($2 \cdot 10°$). A toilet paper roll was used to define the area of observation. The sky area was centered around the 'rectangle' of the Big Dipper (Ursa Major). The better of the two eyes was used. Within that area, there are about 10 stars brighter than magnitude 5, the usual value given for the threshold for normal good eyes, untrained observers, a clear sky, and no light pollution. See for details secs. 5.1.2 and 14.2.2a.

The results for the post code areas are included in Table 5.2.4. In the 'worst' post code area, the sky is about 2,5 times as bright as in the 'best' area. The individual observations are, of course, much wider apart. The lowest value in the measurements is 0,564 mcd/m^2, whereas the highest is 6,12 mcd/m^2 – more than a factor of ten! As explained earlier, the postal code areas 2, 3, and 4 correspond to the densely populated, industrialized region in the West of the Netherlands, the areas 5, 7, 8, and 9 correspond to the agricultural, less densely populated area of the North and South-West, and the areas 1 and 6 have a more mixed character.

The three sets of data are collected in Table 5.2.4, all converted into luminance values.

'Dark night' data			**Schreuder data**		**Isobe data**	
Post code area	**Luminance** (mcd/m^2)	**Ranking**	**Luminance** (mcd/m^2)	**Ranking**	**Luminance** (mcd/m^2)	**Ranking**
1	2,50	5	1,71	7	0,35	6
2	3,19	1	2,68	1	8,01	1
3	2,70	4	2,68	2	1,68	2
4	3,04	2	2,00	4		
5	1,25	9	2,22	3	1,41	3
6	2,86	3	1,78	5	0,52	5
7	1,43	8	1,78	6	1,01	4
8	1,83	6	1,55	9		
9	1,79	7	1,71	8		
average	**2,059**		**1,811**		**2,164**	

Table 5.2.4: *Comparison of the three sets of data, each ranked from 'bad' to 'good'. The average (non-weighted) values are added.*

Inspection of Table 5.2.4 shows that there is a certain similarity between the three sets of data. The average values are of the same order of magnitude; that suggests that all three methods are likely to give useful information. There is no clear sign of the fact that the light pollution did increase considerably – at least according to subjective experiences – in the years between 1992 and 1997. Clumping the data even further in 'industrial', 'mixed' and 'agricultural' areas (post code areas 2, 3, and 4; the areas 1 and 6, and the areas 5, 7, 8, and 9 respectively) does not seem to reduce the differences between the three data sets. See Table 5.2.5.

Area	'Dark Night' data	Schreuder data	Isobe data
industrial	2,98	2,45	4,85
mixed	2,68	1,75	0,44
agricultural	1,18	1,82	1,21

Table 5.2.5: *Comparison of the three sets of data, average luminance for three areas. Luminance in mcd/m^2.*

The data permitted to investigate the way the light pollution decreases during the night. It was found that during the night, as an average over all posts, the luminance dropped to about 33% of the evening value. See Table 5.2.6.

Time	Luminance (mcd/m^2)
before 22.00	1,15
22.00-22.30	0,71
22.30-23.00	0,65
23.00-23.30	0,88
23.30-24.00	0,47
after 24.00	0,38

Table 5.2.6: *Decrease of light pollution during the night.*

As a conclusion, it may be stated that the light pollution as a whole is a serious problem in the Netherlands. The values found in these test are, systematically, considerably higher than the natural background luminance. In most areas the sky luminance is often ten times as high. One does not need, of course, measurements for this statement: even the most cursory glances outdoors will conform this. In order to find a base for regulatory measures or for legislation, a more detailed, quantified, picture is required. First attempts for a nationwide cartography of nighttime artificial light are described in Schmidt (2002, 2002a).

(b) Measurements in Japan

In Japan, the situation is similar to that in the Netherlands: Japan is a densely populated, affluent and highly industrialized country where light pollution is a major problem, not only for astronomers but for the general public as well.

Most of the earlier large-scale survey measurements of light pollution were made in Japan. The two major survey measuring methods, viz.: star counting and photographic surveys, were developed in Japan and applied on a large scale. The results of these very valuable studies are summarized in Isobe (1995, 1997); Isobe & Kosai (1994, 1998); Kosai & Isobe (1991) and Kosai et al (1992, 1993, 1993a). Details of the methods are given in secs. 14.6.2c and 14.6.2d.

A contour map of Japan giving the degrees of light pollution was presented in Isobe & Kosai (1994, figure A1.1). The contour map is based on data collected with the photographic survey method that is described in detail in Isobe (1995); Isobe & Kosai (1994, 1998) and Kosai & Isobe (1991). See also Schreuder (1994). A satellite photo of the same area is given in that publication (Isobe & Kosai, 1994, figure A1.2). There is a striking similarity between the two. The serious conditions in Japan are directly clear from the contour map: there are many regions where the threshold sky brightness is higher than 17 mag. per square arcsecond; also, there are many regions between 17 and 19 and still more between 19 and 21. "Fortunately, there are still some zones which have brightnesses fainter than 21 mag. per square arcsecond". (Isobe & Kosai, 1994, p. 155). For the details of the study, reference is made to Kosai et al., 1992, 1993a. More recent results of the same programme are given in Isobe & Kosai (1994).

Similar data but now from satellite observations are given for a number of Japanese cities in Isobe & Hamamura (1998). Here, emphasis is placed on the economic loss as a result of the light that is emitted upwards. See also Isobe (1995). In sec. 3.3.3, this type of assessments is discussed, where in most cases the reflected light is included in the analysis. Now, reflected light is mostly 'used', and to consider it as an economic loss is not always correct. This aspect is explained in sec. 1.2.1c. In sec. 12.4.4, details are given about the difficult question of how to deal with the reflected light.

Another survey of the light pollution situation in Japan is described in Kosai & Isobe (1991). Using normal $7 \cdot 50$ binoculars ('field glasses'), the limiting magnitudes of stars within a specific sky region were determined. The method is explained in sec. 14.6.2c. The survey was really nation-wide: observations were made at 106 sites. The limiting magnitudes varied from 10,3 to 5,1 magnitude. (Kosai & Isobe, 1991, Table 1).

(c) Measurements in Italy

In Italy, a number of measurements were made. In part, they were the outset of what was later to become 'The First World Atlas of the Artificial Night Sky Brightness' (Cinzano et al., 2001a). These measurements were made by Cinzano and his colleagues, using the satellite observations of the American Defence Meteorological Satellite Program

(DMSP). See e.g. Cinzano, 1994, Cinzano et al., 1999. We will discuss the details in the next section.

A recent Italian paper gives a comparison between the light pollution of two Italian towns (Fellin et al., 2000). As the comparison is based on calculations and not on direct observations, the value of the paper is more of a theoretical nature. Details are given in secs. 3.3.3 and 15.5.3.

(d) *Measurements in Belgium*

Using 231 satellite images made between October 1994 and March 1995 by the DMSP satellites, a contour map of the Flanders region of Belgium was made (Vandewalle et al., 2001). The data are presented only in a qualitative way, depicting light pollution concentrations near the big cities (Vandewalle et al., 2001, Figure 3).

(e) *Measurements in the UK*

In the UK, the results of more recent satellite measurements have been made public on the internet. Details are quoted from Anon. (2003). As most conclusions refer to the increase in light pollution over the last few years, these data collections are discussed in more detail in sec. 5.4.

5.3 'The first world atlas of the artificial night sky brightness'

5.3.1 Publicity impact

Cinzano and his colleagues have spent the last decade in establishing of 'The First World Atlas of the Artificial Night Sky Brightness'. This atlas will be published in the near future; a preprint is already available (Cinzano et al., 2001a). It is difficult to overestimate the importance of this endeavour; the wide-spread attention in the scientific press as well as in publications for the general public is therefore fully justified. A few examples: Cinzano (1994); Cinzano et al. (1999, 2000, 2001, 2001a).

Some of the conclusions are neatly summarized by Beekman (2001). It is found that about two-thirds of the world population is subject to light pollution. This is supposed to be the case when the airglow is more than 10% of the natural background radiation. For 93% of the population in the USA and for 90% of the population in Europe, the sky never gets darker than corresponds with a half-moon at 15 degrees elevation. For 25% of the world population, the sky never gets darker than corresponds to the 'nautical twilight' (the sun between 6 and 12 degrees below the horizon). In such cases, only the brighter stars can be seen, but not the Milky Way.

Similar results from the Cinzano-studies are given by Schmidt (2002). Focussing on the Netherlands, it is found that the upward light emitted by a rather big city like Amsterdam (about 700 000 inhabitants) extends over an area with a radius of about 100 km (Schmidt, 2002, p. 157). As is mentioned earlier, for 85% of the population in the Netherlands, the artificial light exceeds that of the full moon, and in only 3% of the area of the country is the artificial brightness less than the natural brightness. The Netherlands has the dubious honour to belong to the top-three of the most 'light polluted' countries of the world (Schmidt, 2002, p. 157; Schmidt, 2002a).

The doom-scenario that is sketched by Crawford (1991, 1992, 1994, 1998); Murdin (1993, 1994); Percy (1998, 1999), seems to be close to reality. If a halt is not called to the progress of light pollution, astronomy as a science will come to a grinding stop. What is more, the ordinary people will loose their main contact with the cosmos; as is explained in sec. 1.1.2, the main way to have, as a mortal, contact with the cosmos is to be able to contemplate the dark, starry night sky. The sun-drenched daytime is interesting as a symbol of life, of fertility even, but the sun blots out all the stars. In this way, one might consider the sunlight as the ultimate light pollution!

5.3.2 The technical basis of the Atlas

As is explained in great detail in Cinzano et al. (2000), the Atlas is based on measurements that are made on a continuous basis by the Defense Meteorological Satellite Program (DMSP). In the description of the technical aspects, extensive use is made of this publication more in particular of the Chapters 2 and 4 (Cinzano et al., 2000). The predecessor of the Atlas was the image produced by Sullivan (1989, 1991). These images had a considerable impact, but because they were based on analogue pictures, they could not be used digitally in a quantitative way. This became possible when the DMSP data could be treated digitally (Elvidge et al., 1997, 1997a,b).

US Air Force DMSP satellites are in low-altitude polar orbits at 830 km with a period of 101 minutes. The observations are made by means of an oscillating scan radiometer, at night supported by a photomultiplier tube. It is essentially a line-scan system (the Optical Linescan System OLS). The sensitivity of the system is, including amplification, 10^{-10} W cm^{-2} sr^{-1} m^{-6}, corresponding to a luminance of 0,2 mcd/m^2 (Elvidge et al., 1999). The scan swaths are 3000 km wide. Normally, the OLS operates at high gain settings at 60 dB. These are not suitable to measure lighting installations at the surface as they tend to be saturated. In eight nights in March 1996 and on ten nights each in January and February 1997, measurements were made at a lower gain at 24 dB. In the end, it was possible to detect a minimum luminance of 4 kcd/km^2, or in more common units, about 4 mcd/m^2 (Cinzano et al., 2000, p. 643).

5.3.3 Results

The first set of results refer to the relation between the upward flux and the population for a large number of cities in Italy, France, Germany, Spain and Greece. The data suggest that he relation is nearly proportional, the higher populations being somewhat underrated. The spread is, however, considerable. The normalization of the set seems somewhat arbitrary. The unity is "normalized, for display purpose, to the average flux of a city of about 100 000 inhabitants in the same country" Cinzano et al. (2000, p. 643). In this way it might seem that the idiosyncrasies between countries in light usage are compensated to a certain extent. It is not possible, however, to give absolute values for the population relationship. The data of Cinzano et al. (2000, Figure 2) are converted into Table 5.3.1.

Population ($\cdot 10^3$)	Relative upward flux low	average	high
2	2	7	20
5	1,3	10	25
10	4	17	21
20	10,5	25	80
50	20	60	230
100	70	110	160
200	105	300	300
500	600	800	1000
1000	600	1000	1000
20000	2000	2000	2000

Table 5.3.1: *Relation between population and the upward flux for European cities (after Cinzano et al., 2000, Figure 2). The 'average' corresponds to a visually determined correlation curve.*

The data are, in spite of some inaccuracies as reported by Cinzano et al. (2000, p. 643), in good agreement with several other sets of data. Cinzano et al. (2000) quote the results of the measurements of Walker (1977) where, however, a considerably smaller exponent (of only 0,8) was found. See also Walker (1973), Schreuder (1986, 1987) and CIE (1997). Garstang states, referring to the same Walker data: "Some indications were obtained that a law with an exponent of 0,8 might be a better approximation, but the uncertainties were such that it probably suffices to take an exponent equal to unity. This may be called the luminosity relation" (Garstang, 1991, p. 57. See also Garstang, 1991a). From this, it follows that there must also be a good agreement with the 'model' of Garstang because the Garstang-model is based on the same experimental data. The 'Garstang model' that results in the statement that one finds 1000 lumen per capita, is described in some detail in several papers by Garstang; hence the term 'Garstang number'. A survey is given in Cinzano et al., 2000. A summary is given in Garstang (1991). In that paper, also other relationships between population and flux are discussed, like e.g. Berry (1976). In view of the limited experimental data that are involved, the applicability is, however, more limited than is generally assumed. So did Schreuder find all sorts of values between about 50 to over 2000 lumen per capita (Schreuder, 1986; 1991). Furthermore, there are some indications that modern lighting techniques combined with the proliferation of the 24-hour economy, brought the values closer to 2000 lumen per capita. However, on the basis of limited practical experience it is stated in sec. 13.2.3, that, probably, the Garstang number of 1000 lumen per capita is the best number to use for rule-of-thumb assessments of light pollution. In short, the lumen-per-capita rule does not seem firmly fixed on experimental data.

5.3.4 Upward emission

"The normalized emission function, the sum of the direct emission from fixtures and the reflected emission from lighted surfaces, is not known. In this paper it is assumed that all land areas have the same normalized emission function" (Cinzano et al., 2000, p. 646). For the average normalized emission function, the city emission function of Garstang (1986) is used. In view of the way the Atlas is used, it seems to be justified to use the model. In some respects, the model is very sophisticated, but when it should be applied in the actual design of outdoor lighting installations, it seems that there are, in other aspects, some approximations that do not always reflect the complicated nature of the light emission from cities. At present, it is not fully clear where the problems are, let alone what the solutions might be, but one area might be the way the light is reflected by a composite surface and also the distinction between 'used' and 'useless' reflected light. Further study is still required. An outset is given by Gillet & Rombauts (2001, 2003) and Laporte & Gillet (2003). We will come back to this item in sec. 12.4.6.

For the application of satellite data for actual lighting design it seems that more detailed data sets are required. An example of such detailed sets is given by Isobe & Kosai (1998). As mentioned earlier, nation-wide contour maps of the whole of Japan have been given. In addition, for two cities, much more detailed data are given. For Nagoya (2 million inhabitants) the relation between the sky brightness and the distance to the city centre is given. It seems that for a large area up to some 5 km radius, the sky brightness is almost constant. Between 5 and 15 km it is halved, and after 15 km it is rapidly reduced to about 1% of the brightness at the centre. From this, it might be assumed that the city measures some 25 km in diameter (Isobe & Kosai, 1998, fig 6; curve for 1 million inhabitants). For Tajimi city (100 000 inhabitants) a detailed contour map is given (Isobe & Kosai, 1998, fig 7). Based on a large number earth-based observations, it is shown that the sky brightness diminishes smoothly from over 19,0 mag. per square arcsecond in the centre, to about 21 mag. per square arcsecond in the outskirts. This detailed data are needed to improve the actual lighting scheme of cities.

5.3.5 The spread-function of the light pollution

One of the most crucial results of the satellite measurements for the practical lighting design is the spread function of the emitted light. With this, we mean the distance from a source where the effect of the source is still noticeable. In this respect, there are two effects to take into account. The first is the 'light blob' directly over the source, like e.g. a big city, which is often easily visible from a great distance. As the blob is the result of the light emitted almost vertically and scattered in the atmosphere, it can not be higher than the thickness of the atmosphere. If we take that as being about 8 km, above which the atmospheric pressure is too low to cause much scatter, the elevation of the top of the blob will be at 50 km distance about 9 degrees and about 4,5 degrees at 100 km. Because few astronomical observations are made at smaller elevations than some 15 degrees, this blob represents 'horizon pollution' but it is no threat to astronomical observations (Schreuder, 2000). Details are given in sec. 3.3.4.

The second aspect is probably more important. Light emitted by a source at near-horizontal elevations may travel far through the atmosphere and be scattered downward right above observation places, even at a considerable distance from the source. The Atlas suggests that this distance may be up to 100 km; see e.g. the light halo around the drilling platforms in the North Sea as depicted in Cinzano et al. (2000, Figure 13). As mentioned earlier, it is found that the upward light emitted by a big city could indeed extend over distance of about 100 km (Schmidt, 2002, p. 157). This finding is essential to the warning that emanates from the publication of the Atlas. The farther reaches of this light halo are rather weak, corresponding to an increase of the night sky brightness of only a few percent over the natural background radiation. Nevertheless, it was found that, due to this wide scattering of the light, a considerable part of the world population is severely hindered in observing the starry night (sec. 5.3.1; Beekman, 2001). This means in a more practical sense that the reduction of this wide, rather faint, haze must be the first priority of the lighting engineers when planning outdoor installations. We will come back to these priorities in sec. 11.2. It seems that stray light emitted by outdoor luminaires in a direction close to the horizon is more harmful than the light emitted straight upwards. Thus, it is important for lighting designers, as is explained earlier as well, to have a good, and generally accepted, classification system for outdoor lighting luminaires. We will come back to this classification in sec. 7.1.4. In view of the severe consequences that the light haze may have on the actual lighting design, it is important to consider in more detail the origin and the extent of this haze. These points have been mentioned already in sec. 3.3.4.

There is one thing that is not fully clarified. It is not completely clear in how far the scatter of light in the optics of the satellite detector systems is accounted for. Each optical system is subject to such scatter. In the human visual system, this is called disability glare; it is explained in detail in sec. 9.2.2. In applied optics, this effect is described in terms of the point-spread function. No optical system is fully free of this form of light scatter. The problem is that it is not possible to distinguish, on the base of satellite pictures made in space alone, the effects of the light halo, that is mentioned earlier in this section, from the effects of the point-spread function.

The degree in which this haze may obstruct astronomical observations depend on two things. The first are the physical characteristics of the atmosphere related to its transmission of light towards the locations above the observatory, and the light scattering function to send the light down. In sec. 1.2.1b, the relation between light pollution and air pollution is briefly indicated. The second is the way, more in particular the angular distribution, of the emission of the light source.

In the Atlas, a number of assumptions are made regarding the characteristics of the atmosphere, including the presence of absorbing and scattering aerosols. Cinzano et al. (2000, pp. 646-647) have given a number of mathematical relations that describe these characteristics. Reference is made to the work of McClatchey et al. (1978) and Garstang (1991a). It is assumed that the quoted relationships are adequately based on experimental proof: "Details on assumptions can be found in the quoted papers" (Cinzano et al., 2000, p. 645). Improvement still seems possible: "More detailed atmospheric models could be used whenever available" (Cinzano et al., 2000, p. 646). However, there are no reasons to believe that any improvement could easily be made, nor – more important – that there really is a need for further precision in this matter. It seems, therefore, fully justified to proceed in the way as has been done in the establishment of the Atlas.

In view of its great importance for the practical lighting design, it seems to be wise to pay close attention to the second aspect, related to the angular distribution of the emission of the light source. As has been mentioned several times already, when considering a city – or any other outdoor lighting installation for that matter – as a light source and a possible source for light pollution, one has to take into account that part of the light that is emitted directly upwards by the luminaires, whereas another part – usually by far the greatest part – is reflected by a variety of surfaces before it is emitted upwards. One might argue that all the light that is emitted directly upwards by the luminaires, is, as explained in sec. 1.2.1, spill light. It is, however, as already stated several times, definitely wrong to consider all reflected light as spill light as well. In preparing the Atlas, again here a model proposed by Garstang has been used (Garstang, 1986) and another, proposed by Cinzano (2000). In these models, the emission is considered to be the sum-total of the direct and the indirect light. The reflected light is approximated by a diffuse, 'Lambertian' function. This might be true in an obstacle-free surrounding, but in a city where buildings, trees, and other obstacles block off part of the light, it is not certain at all. Further study is still required. See sec. 5.3.4. In sec. 12.4.6, the results of the studies from Gillet & Rombauts (2001, 2003) and Laporte & Gillet (2003) are discussed.

The direct light component is derived from the Garstang model (Garstang, 1989). The city light emission function is normalised by means of a procedure that is described in Cinzano (2000, 2000a). The results agree well with the values that are derived from direct satellite measurements, even when the rather indirect way these measurements were made, is taken into account. "We have checked these functions by studying the relation between the upward flux and the distance from the satellite nadir" (Cinzano et al., 2000, p. 646). The results agree also with the measurements published by Cinzano & Diaz Castro (2000).

Again here, it seems to be justified to proceed in the way as has been done in the establishment of the Atlas. However, when dealing with the actual design of outdoor lighting, it would be better if one could use the actual, direct measurements of the 'light distribution' of cities or of other large outdoor lighting installations. It might seem that such direct measurements could be derived from the fly-over of a satellite or maybe even of a high-flying airplane. This is certainly a matter that deserves further attention – in spite of the large value of the Atlas!

5.4 Increase in sky glow

As has been indicated several times already, not many systematic studies about the extent of the light pollution in practice have been made, in spite of the fact that urban sky glow is one of the major limiting factors for astronomical observations. What is more, in spite of considerable efforts to avoid it, sky glow did increase considerably on a global scale over the last few years, and again, this increase has not been well documented. It is the main aim of one of the projects that did originate in the Netherlands from Ministry of VROM, that was discussed in some detail in sec. 4.2.2.2. The basis was the outcome of a national conference 'Working together for darkness' (Anon. 2000). The Ministry of VROM decided to set up a measuring system to monitor the changes in the light pollution of the Netherlands. As is mentioned in sec. 5.2.3a, the first step is to establish nationwide cartography of nighttime artificial light. A proposal has been made in (Schmidt, 2002, 2002a).

Although several papers have been published recently, most of them are qualitative in nature (Crawford, 1994). Other publications do not address the problem in general, but focus on specific locations. We will discuss a few of them, to serve as an example and to give an indication of the order of magnitude involved.

For the promotion of quality lighting, it is very important, however, to have general, modern, world-wide data. Only when such data are available, is there a chance to influence the politicians who in the last instance have the power to make laws and to set up regulations. If the data do not exist, or are not convincing, the economic pressure of advertisements, of land use and of industrial product promotion will be too strong to protect the night. A major first step has been made by the publication of the atlas, that is discussed in some detail in the preceding section. See Cinzano (2002) and Cinzano et al. (2001). However, the Atlas is based on measurements made during a short time within one year (eight nights in March 1996 and ten nights each in January and February 1997; Cinzano et al., 2000, p. 642). So the Atlas, in its present form, cannot give any indication about the trends of changes in the levels of light pollution. For this, a new set of observations is needed.

For some time, it was not clear whether budget constraints would allow new satellite observations. However, very recently, new data are made public on the internet. Details are quoted from Anon. (2003). A draft map for the Netherlands has been made already. The UK internet site gives the following comments: "The land area of England experiencing severe light pollution grew by 17% between 1993 and 2000. Over the same period, the rural areas where there are truly dark skies and unimpeded views of the night sky in all its majesty and mystery shrank by 27%. On average, the light shining upwards at night from each square kilometre in England rose by 24% over those seven years." (quoted in Anon., 2003). This means an annual growth of just over 3%. That is in line with the other data that are given in this section. These numbers resulted in a parliamentary enquiry commission. See also sec. 15.5.1.

In further parts of this section, a survey of the most important publications is given that can give some insight in the changes – i.e. the increase – of light pollution over the years. When needed, 'astronomical' photometry is converted into 'light-technical' photometry. The conversion is discussed in sec. 14.3.2.

Mice & Foltz (2000) described detailed measurements at two major US observatories (Kitt Peak and Mount Hopkins) in 1988 and 1998. They conclude: "The zenith sky brightness increased only modestly by 0,1-0,2 mag. per square arcsecond". This still means, according to the usual approximations, an increase of 10% to 20% in sky luminance. On Kitt Peak, at lower elevations the increase was larger, from 0,2-0,35 mag. per square arcsecond in directions away from the city of Tucson, to about 0,5 mag. per square arcsecond in the direction of Tucson (Mice & Foltz, 2000, p. 572). So, even at the best protected sites in the US and probably in the world, the sky luminance increases with several percentage points per year.

Isobe & Hamamura (1998) describe the increase for a number of Japanese cities over recent years. The data are summarized in Table 5.4.1. It should be noted that these measurements cannot be generalized easily. It is not known in which way the five cities were chosen, so it is not known whether they may be considered to represent Japan as a whole. Also the process to take the average of relative increases of relative values, does not yield more than a rough indication only. Nevertheless, the result is still important: for the five cities there seems to be an increase of about 10% per year in the upwards emitted light.

City	Year	Index	Year	Index	Rel. increase	Rel. increase per year
Akita	1993	1300	1996	2000	0,54	0,135
Shizuoka	1993	2900	1996	3300	0,14	0,034
Hiroshima	1993	4650	1996	5200	0,12	0,029
Tokushima	1994	5000	1996	8600	0,72	0,24
Matsuyama	1993	2650	1996	3450	0,30	0,075
Average						**0,103**

Table 5.4.1: *Increase in ejected city light for a number of Japanese cities over recent years. Based on data from Isobe & Hamamura, 1998, figures 6 - 10.*

Other Japanese data are collected by means of the global method using photo cameras as described by Isobe & Kosai (1994). The measurements show in general a trend of a considerable increase in the sky brightness with a noticeable exception of the years of the Gulf War where many energy saving measures were taken in Japan – showing that those measures are quite feasible (Isobe & Kosai, 1998, p. 178; Table 1). Photometric measurements described in the same paper show for the Tokyo area a dramatic increase of the sky brightness. It was 20,5 mag. per square arcsecond in 1958; 19,5 in 1978 and 17,6 in 1998 (Isobe & Kosai, 1998, p. 178). According to the usual conversions, these values correspond to 0,99; 1,49 and $14{,}6 \cdot 10^{-3}$ cd/m^2.

Carrasco et al (1998) describe the sky glow situation at a major observatory in Mexico. Between May 1994 and January 1997, the increase in sky brightness, as an average over four spectral bands, corresponded with about 0,4 mag. over a period of 32 months. According to the approximations given earlier, this would mean an increase of about 40% in luminance, or of about 15% per year. Again here a word of caution. The measurements were made with a different aim, so also here it is dangerous to generalize the results. Still, the increase in sky brightness is remarkable.

As a part of his many and outstanding efforts to reduce the impact of light pollution, spanning several decades, Garstang has described what has happened at the famous Mount Wilson observatory (Garstang, 2000). As all astronomers know, the Mount Wilson observatory is located not far from the centre of Los Angeles, California. For his calculations, he mostly uses his model that is based on a constant installed luminous flux of 1000 lumen per capita (Garstang, 1989, 1991). When he included the effect of changing over the years from incandescent to mercury to high-pressure sodium lamps, the result suggested an extra increase in sky brightness. The extra increase was about 30% in the V-band and about 11% in the B-band. These bands represent different spectral regions. They are explained in sec 14.2.3g. The total increase between 1980 and 1990 of the sky brightness as a result of the population growth in the Los Angeles area, combined with the excess increase as a result of changes in the lighting technology is 41% and 43% in the two bands (Garstang, 2000). In another paper, Garstang gave a slightly different estimation of what happened over the years at Mount Wilson (Garstang, 2000a). According to his calculations, the background radiation in 1980 was 510 nL, and in 1990 620 nL an increase of over 21% (Garstang, 2000a, Figure 1). Again a considerable increase over just a decade. The sky background at sunspot minimum is given as 50 nL. In ISO units, the figures are 1,63 cd/m^2, 1,98 cd/m^2 and 0,16 cd/m^2 respectively. It should be noted that what is described by Garstang as 'changes in the lighting technology', actually means an increase in the Garstang number. See Garstang (2004) for more recent data.

There seem to be locations where the light pollution does not increase in any appreciable degree. For the AURA observatory in Chile, it is estimated that, even in a worst case scenario, the artificial sky brightness will, in the year 2020, be only 0,1 mag. above natural minimum background, which is about 21,9 mag. per square arcsecond (or 58 nanolambert). This estimate is published by Smith (2001, p. 47), quoting Walker & Smith (1999).

As a conclusion it seems safe to expect that the levels of light pollution on most locations in the world are increasing and that they will go on increasing in the foreseeable future. A rate of increase is difficult to guess but it might seem that 3% per year will not be too far off. It should be noted that 3% per year means a doubling in 23 years. It is suggested that the level of light pollution in a country is closely related to the population density as well as to the affluence, expressed in the per capita GNP (Cinzano et al., 2001a). In most countries, the population density is increasing, often very steeply. It is difficult to make predictions about the GNP, so it will not clear what will happen with the light pollution. Again, the 3% increase seems not to be too far off. This would suggest some sort of direct relation between the per capita GNP and the Garstang number. This sort of relations are the subject of the investigations that are described by Petrakis (2003). See sec. 14.6.6.

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6 Limiting values for light pollution

At present, there are several national and international organizations that have set up standards and recommendations for the limiting values for light pollution, expressed in photometric and sometimes in geometric terms.
A number of these sets of recommendations are discussed in this chapter. What is presented in this chapter is, of course, only a sample of the many sets of recommendations that exist. It should be noted, however, that most recommendations are not expressed in photometric or geometric terms. In another section, we give what is in our view the best set of recommendations.

6.1 Zoning and curfew

(a) *Zoning*

In sec. 3.4.1, we have discussed the zoning method. The outset is that, as indicated in that section, the consequences of light pollution are not equally severe at all places in the world; this implies that the light intrusion restriction measures do not need to be equally strict for all places. For this, 'the world' it divided into zones. Zoning may serve as a frame of reference for anti-pollution legislation and regulation. Legislation and regulations, aimed at a reduction of light pollution, are discussed in detail in Chapter 15 of this book.

As is explained in sec. 3.4.1, CIE has proposed a Zoning System for general purposes (CIE, 1997, 2003). The system is closely related to the system of zoning that is in use in many countries. The zones are characterized by their Zone rating (E1 ... E4). See also CIE (1993) and Pollard (1997). A description is given in Table 6.1.1. This material is also presented in Table 3.4.2.

Zone	Surroundings	Lighting environment	Examples
E1	natural	intrinsically dark	national parks or protected sites
E2	rural	low district brightness	agricultural or residential rural areas
E3	suburban	medium district brightness	industrial or residential suburbs
E4	urban	high district brightness	town centres and commercial areas

Table 6.1.1: *Description of the environmental zones, after CIE, 2003, table 2.1.*

As is explained in sec. 3.4.1, in most cases the CIE zoning system is sufficiently detailed for most practical lighting design purposes. Still, the specific lighting design aspects of installations near astronomical observatories, as well as the operation of the observatories, may call for a more detailed zoning system, where one or more of the CIE zones are split up in sub-zones, based on the ALCoR system (Murdin, 1997; Schreuder, 1994, 1997, 1998). The description of the environmental sub-zones is given in secs. 3.4.1 and 7.1.1. The sub-zones are summarized in Table 6.1.2. Sometimes, as is mentioned in sec. 4.2.2.1g, the operation or the management of national parks or nature reserves may require an even further subdivision. These further division has usually no consequences for the lighting design nor for its operation. So, for lighting purposes, the CIE zones, if needed supplemented by the sub-zones, are sufficient. This material is also presented in Table 3.4.3.

Environmental zones	Examples sub-zones
E1	Areas with intrinsically dark landscapes
E1a	– nature preserves
E1b	– national parks
E1c	– areas of outstanding natural beauty, protected landscapes
E2	Areas of low district brightness: rural agricultural areas, village residential areas
E3	Areas of middle district brightness
E3a	– sub-urban residential areas
E3b	– urban residential areas
E4	Areas of high district brightness
E4a	– urban areas having mixed residential, industrial and commercial land use with considerable nighttime activity.
E4b	– city and metropolitan areas having mixed recreational and commercial land use with high nighttime activity

Table 6.1.2: *Description of the environmental sub-zones (Based on Schreuder, 1994).*

(b) Curfew

Similar to the location aspects, the consequences of light pollution are not equally severe at all times of the day and night; this implies that the light intrusion restriction measures do not need to be equally stringent at all times. Consequently, the concept of 'curfew' has been introduced. The period of darkness is subdivided in the 'evening' and the 'night'. 'Dawn' usually is not considered separately, but considered as a part of the night. In general terms it is recommended to operate after 'curfew' only the light that is directly related to safety and security and to switch off the rest (CIE, 1995, 1997, 2003; NSVV, 1990, 1999, 2003, 2003a,b).

6.2 CIE proposals for light pollution limits

6.2.1 CIE Guidelines for minimizing sky glow

In 1997, CIE published 'Guidelines for minimizing sky glow' (CIE, 1997). This publication was not the first CIE activity in this area. In 1978, CIE prepared, in co-operation with IAU, recommendations about the identification and protection of existing and potential observatory sites (Anon., 1978). Subsequently, it was published jointly by CIE and IAU under the title "Guidelines for minimizing urban sky glow near astronomical observatories" (CIE, 1980). This report was reproduced as Appendix 4.1. in McNally, ed. (1994).

The scope of the CIE report was "to give general guidance for lighting designers and also policy makers about the ways the interference by light of astronomical observations can be reduced or even avoided. The report gives guidance for the design of lighting installations and lighting equipment. The report gives suggestions that will result in a reduction of the sky glow. It should be noted that sky glow does not depend exclusively on the lighting design. It also depends on the atmospheric conditions (humidity, aerosols, clouds, haze, atmospheric pollution etc.). The recommendations given in the report are expressed in photometric terms, where the amount of light emitted above the horizontal plane is given as a proportion of the lamp lumens according to the design of the luminaire or of the luminaire luminous flux in practical situations" (CIE, 1997, sec. 1).

In the CIE document, the recommendations for the limitation of sky glow are presented (CIE, 1997, sec. 9). They are given as the maximum permissible value of ULR (the Upward Light Ratio – expressed as a percentage of the luminous flux of the luminaire in the position according to its design) for each of the four Environmental Zones. This limit applies to each individual luminaire in that zone. The values have been included subsequently in a more recent CIE publication (CIE, 2003). See Table 6.2.1.

Zone rating	ULR (%)	Astronomical activities
E1	0	observatories of (inter)national standing
E2	0 – 5	postgraduate and academic studies
E3	0 – 15	undergraduate studies, amateur observations
E4	0 – 25	casual sky viewing

Table 6.2.1: *Recommendations for the limitation of sky glow. After CIE, 1997, Table 2.*

The light pollution in a point in a specific zone – the 'reference point', e.g. astronomical observatories, natural parks etc. – is determined not only by the lighting in that zone, but also by the lighting in neighbouring zones, as well as by the dimensions of these zones. The CIE document gives recommendations for the minimum distance between a zone borderline and the reference point (CIE, 1997, sec. 9). See Table 6.2.2. As is mentioned in the CIE document, the values quoted in this table are derived from practical experience in a limited number of case studies. Future verification is desirable.

Zone rating of reference point	Zone rating surrounding zones distance (km) to borderline of surrounding zones		
	E1-E2	E2-E3	E3-E4
E1	1	10	100
E2		1	10
E3			1
E4		no limits	

Table 6.2.2: *Minimum distance (in km) between the zone borderlines and the reference point. After CIE, 1997, Table 3.*

One remark must be made concerning the ULR as given in Table 2 of the CIE Guidelines, reproduced here as Table 6.2.1. In that table, a value of 0 (zero) is required for zone E1 for observatories of national or international standing, or for national parks or protected sites in intrinsically dark areas. Zero, of course, is difficult to reach because of tolerances in fabrication and installation of luminaires.

An ULR value of zero is not in agreement with the need for visual or optical guidance. This subject was studied in detail by De Boer and his collaborators; see e.g. De Boer (1967, p. 19-20 and sec. 2.7) and Van Bommel & De Boer (1980, p. 148). See also Schreuder (1998 secs. 9.1.2 and 10.1.2). Also, some 'sparkle' is desirable, particularly in residential lighting with a decorative function (Schreuder, 2001, 2001a). Finally, an ULR value of zero is not very useful because the surfaces to be lit, will reflect always a considerable amount of light. Thus, it does not make much difference whether the ULR is exactly zero or 'almost' zero. The difficult matter of the influence of small amounts of light that are emitted just over the horizon, are discussed in detail in secs. 3.3.4, 12.4.4, 12.4.5 and 14.1.8b.

When dealing with such small quantities, it is essential to mention also measuring tolerances. See also sec. 14.5.3d. It is generally accepted that in field measurements, the following measuring system tolerances may be reached:

- Horizontal illuminance: < 3%;
- Road luminances: < 10%;
- Point luminances: < 15%;
- Veiling luminances: < 25%.

These values are quoted from CEN (1998). They agree with DIN (1998) and in general terms as well with CIE Publication No. 69 (CIE, 1986) and with the NSVV publication on photometric measurements in road lighting (NSVV, 2003c). See Schreuder (2001b, sec. 12.6).

For laboratory measurements, the measurements are usually more accurate. The measurement of the Upward Light Ratio is essentially a measurement of the luminous intensity and that equals the measurement of the illuminance. CIE suggested a tolerance of 2%, which seems rather strict but still feasible (CIE, 2000). This is in reasonable agreement with the official laboratory tolerances that are accepted in Spain. Diaz-Castro (2000) quotes a value of ± 0,03%, which corresponds for a luminaire with 2% upward flux to the actual value between 1,97% and 2,03%. It its turn, this corresponds to about 1,5%.

Based on these considerations, a small value of ULR is permitted in many ordinances. The Italian standard UNI 10819 tolerates 1% for the "ratio between the nominal upward flux emitted from the lighting equipment and the total luminous flux" (Zitelli et al., 2001, p. 115). See also UNI (1999) and Fellin et al. (2000). Details on these ordinances and regulations are discussed in detail in sec. 15.5.3a.

6.2.2 CIE Guide on the limitation of obtrusive light

For many years, the CIE Technical Committee TC 5.12 on Obtrusive Light worked on a report on the limitation of the effect of obtrusive light from outdoor lighting installations. The report has been be published in 2003 (CIE, 2003).

The report contains, as has been indicated already, the final version of the CIE proposal for environmental lighting zones, as given in Table 6.1.1. Further, the report contains proposals of limiting values for a number of lighting situations regarding the vertical illuminance on properties (see Table 6.2.3), for the maximum values for intensities of luminaires (see Table 6.2.4), for glare (see Table 6.2.5), and for the maximum luminance of surfaces like advertisement signs (see Table 6.2.6). For the maximum values of Upward Light Ratio, reference is made to the existing CIE Guidelines for minimizing sky glow, more in particular to the table 2 of that report, reproduced here in Table 6.2.1. (CIE, 1997, Table 2).

We will summarize the main recommendations of the obtrusive light report here.

Light Technical Parameter	**Application Conditions**	**Environmental Zones** E1	E2	E3	E4
Illuminance	Pre-curfew	2	5	10	25
vertical (lux)	Post-curfew	0*	1	2	5

Table 6.2.3: *Maximum values of vertical illuminance on properties.*

*) for road lighting 1 lux (after CIE, 2003, Table 2.2)

Light Technical Parameter	Application Conditions	Environmental Zones E1	E2	E3	E4
Luminous intensity (cd)	Pre-curfew	2500	7500	10 000	25 000
	Post-curfew	0*	500	1000	2500

Table 6.2.4: *Maximum values for intensities of luminaires in designated directions.*

*) for road lighting 500 cd (after CIE, 2003, Table 2.3)

Light Technical Parameter	Road classification No road lighting	M5	M4/M3	M2/M1
Threshold increment adaptation	15%	15%	15%	15%
Luminance (cd/m^2)	0,1	1	2	5

Table 6.2.5: *Maximum values of threshold increment from non-road lighting installations (after CIE, 2003, Table 2.4).*

Light Technical Parameter	Environmental Zones E1	E2	E3	E4
Building facade luminance (cd/m^2)	0	5	10	25
Sign luminance (cd/m^2)	50	400	800	1000

Table 6.2.6: *Maximum permitted values of average surface luminance (after CIE, 2003, Table 2.6).*

Some additional notes will be made. The threshold increment TI is, as is explained in sec. 9.2.2f, the criterion adopted by CIE to characterize the disability glare in road lighting (CEN, 1998; CIE, 1976, 1977, 1995; Schreuder, 1998; Van Bommel & De Boer, 1980). The recommendations have, to a certain extent, a 'didactic' value: "It would be fine if all installations would comply" (Pollard, 2002).

The recommendations relate to new installations. It is not completely clear whether the recommendations are valid for all outdoor lighting, including flood lighting and self-luminous advertisement signs, or only for more traditional road and area lighting.

There might be a need for special arrangements including dispensation rules for temporary installations like fairs, exhibitions etc. Also, when the recommendations would in the future be converted into standards or norms, an introductory period for new installations as well as a replacement period for existing installations are needed.

6.2.3 Extension of the CIE guidelines for minimizing sky glow

(a) Proposals under consideration

The CIE report of 1997 contained, as is mentioned earlier, three sets of requirements in order to quantify the permissible light emission of lighting installations:

(1) The zoning principle, which defines where different activities may take place;
(2) The time-restriction principle ('curfew'), which defines when the different activities may take place;
(3) The amount of light emitted above the horizontal plane, expressed as a proportion of the lamp lumens according to the design of the luminaire – the Upward Light Ratio ULR.

These three requirements are sufficient to decide whether a particular type of luminaire can or cannot be used at a specific time in a specific zone. They do not give, however, information for the designer about the requirements for the design of new lighting installations or for the refurbishing of existing installations. Nor do they give any further information for local authorities to decide whether a certain installation may be used at a specific time in a specific zone. For these purposes, another set of requirements is needed, which should be added as an extra point (4) to the three points mentioned earlier:

(4) The total flux of all installations for specific zones must be established.

In the years 2000 and 2001, several proposals for the extension of the CIE guidelines for minimizing sky glow have been discussed. Although a final decision has not yet been made, it seems to be useful to discuss briefly a number of these proposals at this place. The main reason to do so is that these proposals, even although they have not yet been adopted, have made a distinctive contribution to the recommendations that are given in Chapter 7 of this book.

(b) Sub-zones

The first proposal we will discuss here is to introduce the Environmental Sub-zones as discussed earlier in Table 6.1.2. It is necessary to split up each sub-zone in an urban and a rural area. Not all possible combinations will be found in practice.

(c) Upward Light Ratio ULR

The next proposal we will discuss here relates to the Upward Light Ratio (ULR). Introducing urban and rural sub-zones allows a much finer distinction as regards ULR-requirements. A proposal was given for road and area lighting only. Combined with this proposal, a suggestion was given about the light distribution of the luminaires and about the colour of the light of the lamps for the different areas of application. Further proposals according to these lines are discussed in Chapter 7 of this book.

(d) *The Maximum Installed Lumen per unit Area*

The ULR considers only the relative upward flux per luminaire. For the design of lighting installations, as well as for their appraisal, the absolute value of the upward emission must be known. It is not enough that the requirements of the relative upward flux are fulfilled. Also the size – the lumen output – of the lamp in the luminaire and the total number of lamps that contribute to the sky glow, must be taken into account. For this, the Maximum Installed Lumen per unit Area might be a helpful criterion. In sec. 7.3.2e, a proposal is made as regards the limiting values for the Maximum Installed Lumen per unit Area for different zones.

(e) *The distance relations for zoning*

As has been explained in CIE (1997), the sky glow in the reference point is determined not only by the lighting in that zone but also by the lighting in neighbouring zones, as well as by the dimensions of these zones. It has been proposed to consider the fact that the minimum sky glow is a major consideration for the selection of sites for astronomical observatories. Therefore, it is recommended to select a site for an astronomical observatory where the interference by light is a low as possible. This is of particular interest to major astronomical observatories in sparsely populated countries or regions. For the selection procedures the recommended minimum distance between the reference point and the borderlines of surrounding zones is given in Table 6.2.6.a and b. In these tables, a distinction is made for observatories near small towns or major cities with a typical population of under 50 000 inhabitants or over 100 000 inhabitants respectively. These numbers serve as examples only. This distinction is relevant in particular for observatories in sparsely populated regions.

Zone rating of reference point	**Zone rating surrounding zones recommended values of the distance** (km) **to borderline of surrounding zones**		
	E1-E2	**E2-E3**	**E3-E4**
E1	5	25	100
E2		5	25
E3			5
E4		no limits	

Table 6.2.6a: *Recommended values of the minimum distance (in km) between the zone borderlines and the reference point for small towns (see text).*

Zone rating of reference point	Zone rating surrounding zones recommended values of the distance (km) to borderline of surrounding zones E1-E2	E2-E3	E3-E4
E1	10	50	150
E2		10	50
E3			10
E4		no limits	

Table 6.2.6b: *Recommended values of the minimum distance (in km) between the zone borderlines and the reference point for big cities (see text).*

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7 Recommendations

This chapter gives the summary of the recommendations about photometric and geometric requirements to restrict the negative effects of light pollution, as well as the counter-measures that are available at present or in the near future to put in effect these requirements. It should be stressed that the recommendations given in this Chapter, usually are in broad agreement with those of CIE, either in report or in draft form. Some of the data are based on the draft recommendations prepared in the Netherlands. This draft is prepared to supplement, and in part replace the first part of these general rules.
The recommendations given here often go much further. In this way, they might be a contribution to future recommendations and standards of CIE or other national or international organizations. The countermeasures against light pollution are discussed in detail in Chapter 1 of this book. In this chapter, all recommendations are indicated in italics.

7.1 General recommendations

7.1.1 Zoning

In sec. 6.1a, the details are given of the environmental zones that are introduced by CIE (CIE, 1997, 2003). The zones are repeated here in Table 7.1.1.

Zone	Surroundings	Lighting environment	Examples
E1	natural	intrinsically dark	national parks or protected sites
E2	rural	low district brightness	agricultural or residential rural areas
E3	suburban	medium district brightness	industrial or residential suburbs
E4	urban	high district brightness	town centres and commercial areas

Table 7.1.1: *Description of the environmental zones, adapted from CIE, 2003, table 2.1.*

As has been explained in sec. 6.1a, often a more detailed zoning system is called for. The description of the environmental sub-zones is repeated her in Table 7.1.2, based on the ALCoR system, proposed by Murdin (1997). As is explained in sec. 6.2.3b, in the ALCoR-system, some CIE zones are split up in sub-zones. See also Schreuder (1994, 1997).

Environmental zones	Examples sub-zones
E1	Areas with intrinsically dark landscapes
E1a	– nature preserves
E1b	– national parks
E1c	– areas of outstanding natural beauty, protected landscapes
E2	Areas of low district brightness: rural agricultural areas, village residential areas
E3	Areas of middle district brightness
E3a	– sub-urban residential areas
E3b	– urban residential areas
E4	Areas of high district brightness
E4a	– urban areas having mixed residential, industrial and commercial land use with considerable nighttime activity.
E4b	– city and metropolitan areas having mixed recreational and commercial land use with high nighttime activity

Table 7.1.2: *Description of the environmental sub-zones.*

Recommendations:

- *As regards zoning, it is recommended to use the zones, and if needed, the sub-zones as given in Tables 7.1.1. and 7.1.2.*

7.1.2 Curfew

As has been explained in sec. 6.1b, the consequences of light pollution are not equally severe at all times of the day and night; this implies that the light intrusion restriction measures do not need to be equally stringent at all times. To accommodate this idea, the concept of 'curfew' is introduced, introducing the 'evening regime' and the 'night regime' (CIE 1997, 2003).

Usually, the evening and night regimes are describes as follows:

- the evening regime covers the time period from sunset (or a fixed time after sunset, e.g. 15 or 30 minutes) until 23.00 h;
- the night regime covers the time period from 23.00 h until sunrise (or a fixed time before sunrise, e.g. 15 or 30 minutes) the next day;
- local authorities may extend the evening regime on certain evenings (e.g. Saturday) until 24.00 h.

Because national, local and climatological circumstances may influence the optimal times, a more flexible definition is defined.

Recommendations:
- *It is recommended to define the time of transition from the evening regime to the night regime at midnight;*
- *It is recommended to define the end-time of the night regime at sunrise;*
- *It is recommended to introduce in national, regional or local regulations the rules for allowing exceptions to these recommendations.*

7.1.3 Subdivisions

In sec. 3.2, a victim matrix, or an user's matrix, is introduced. This matrix is repeated here in Table 7.1.3.

Victims	Lighting for: sports	industry	floodlight	roads	advertizing	greenhouse-lighting
residents	X	X	X	X	X	X
astronomers	X	X	X	X		X
life in nature	X	X	X	X	X	X
road users	X		X		X	X
shipping	X	X			X	

Table 7.1.3: *The 'victims' matrix. The relevant areas are marked by X.*

As is explained in sec. 3.2, the term 'industry' is supposed to include 'general area lighting' as well, whereas the requirements are usually the same as for 'sport lighting'.

Recommendations:
- *It is recommended to use the 'user's matrix' as a survey of the area of light pollution;*
- *It is recommended to use the same requirements for the following lighting areas: industrial lighting; general area lighting and sport lighting.*

7.1.4 Classification of luminaires

(a) Use of luminaire classifications

One of the most important characteristics of any outdoor lighting installation is the light distribution – or luminous intensity distribution – of the luminaires. A classification system of luminaires is helpful in the determination of the type of luminaire that can be applied in a specific lighting installation. For practical lighting design, it is useful to have a detailed luminaire classification system. The luminaire classes can easily be added to the product information of each luminaire type. Such classifications allow the designer to select, in an early stage of the design, an appropriate luminaire, or maybe several appropriate luminaires. The actual design calculations can be made with those luminaires, avoiding the extra work of doing the calculations with other luminaires that, in a later stage, prove to be not appropriate for the particular design.

Systematic, comprehensive classification systems for luminaires are not common. In interior lighting, specific luminaire types are suggested for specific areas of application, but the designation is usually qualitative, e.g. in the form of sketches (Anon., 1993, Table 4.1, p. 160-161). As regards outdoor lighting, only for road lighting several classification systems are in use; they will be described in sec. 12.4.1b. For other area of application, the situation is similar to that of indoor lighting. Often, recommendations are given to use, or not to use, specific luminaire types, but usually again in a qualitative way, e.g. in the form of sketches (ILE, 1994). Undoubtedly these qualitative designations are useful, but a careful quantitative lighting design needs more.

None of the existing classifications gives specific, quantitative information about the influence of the luminaire on the light pollution, nor on the degree the specific luminaire can contribute to the reduction of light pollution. For this reason, a specific 'low light pollution luminaire classification' is proposed in this section. The proposed classification will be differentiated for specific areas of outdoor lighting applications.

(b) Road lighting

In Table 7.1.4 a proposed system of luminaire classification for road lighting is introduced. this system is based on a number of earlier classification systems that are explained in detail in sec 12.4.1b. See e.g. CIE (1977); NSVV (1957, 2002); Pimenta (2002); Schreuder (1998, sec. 7.3) and Van Bommel & De Boer (1980, p. 103). Also, several proposals for some other systems that are not yet published, have been taken into account.

The recommended system has the following characteristics:

(1) The upward light emission is divided in two angular areas:
 - from the zenith, downward to 15° above the horizon, designated as U_1;
 - from 15° above the horizon to the horizontal direction, designated as U_2.

(2) The downward light emission is divided in four angular areas:
 - straight in the horizontal direction. Theoretically this is, of course, not an angular area. The direction will be designated as I_{90}, or, when appropriate, as D_1;
 - from the horizontal direction down to 15° below the horizon, designated as D_2. The area might, when appropriate, be designated as I_{80};
 - between the directions 15° below the horizon and 45° below the horizon, designated as D_3;

- from the directions 45° below the horizon to the nadir (straight down under the luminaire), designated as D_4.

(3) All values apply to all lateral angles around the luminaire.
(4) All values are related to the rated (new) lamp lumens.
(5) All recommendations apply equally to open or closed luminaires, independent of the way the closure is made.

Note: The recommendations regarding the light colour of the lamps is discussed in sec. 7.1.5.

The system consists of six classes, designated as A to F. For each class, values of the different parameters are given. The recommended classification is given in Table 7.1.4. In this table, the CIE classification from 1977 is added for comparison as far as it is relevant (CIE, 1997).

Luminaire class	Photometric requirements for different angular areas U_1	U_2	I_{90} D_1	D_2 I_{80}	D_3	D_4	correspond to CIE class
A	0	0	0	10	30	100	n.r.
B	0	0	2	10	30	100	n.r.
C	0	2	10	30	100	n.r.	CO
D	0	5	30	50	n.r.	n.r.	SCO
E	10	10	50	100	n.r.	n.r.	SCO
F	20	20	100	n.r.	n.r.	n.r.	NCO

Table 7.1.4: *The recommended classification of road lighting luminaires.*

Note: n.r. means not relevant.

In sec. 3.4, four environmental zones and eight environmental sub-zones have been introduced. For each zone, one or more luminaire classes may be recommended. In Table 7.1.5, the luminaire classes are given for each zone or sub-zone. No distinction is made for pre-curfew and post-curfew regimes. The reason is, of course, that at the time of curfew the lighting may change, but not the luminaires. Neither is any distinction made for urban and rural conditions. The reason is, that usually the same luminaires are used.

Zone	Luminaire class					
	A	B	C	D	E	F
E1a	0	–	––	––	––	––
E1b	+	0	–	––	––	––
E1c	+	+	0	–	–	––
E2	0	+	+	0	–	––
E3a	0	0	0	+	0	0
E3b	0	0	0	+	0	0
E4a	–	0	+	++	+	+
E4b	–	–	+	++	++	+

Table 7.1.5: *Recommended luminaire class application for road lighting.*

It should be noted that the classification of Table 7.1.4 and Table 7.1.5 is relevant only for luminaires that are used in road lighting.

(c) General area lighting

The detailed classification system that has been presented for road lighting in the earlier part of this section is not suitable for general area lighting. For that type of lighting installations, a similar but somewhat simplified classification is proposed. In Table 7.1.6 a system of luminaire classification for general area lighting is introduced.

Class	I_{max}	**Maximum luminous intensity** (cd per 1000 lm) **angles with the downward vertical** (degrees)				
		80	**80-90**	**90**	**90-100**	**100-180**
full cut-off	< 50	0	0	0	0	0
cut-off	< 60	30	10	10	0	0
semi-cut-off	< 70	100	30	30	0	0

Table 7.1.6: *Classification of light distributions for general area lighting.*

It should be noted that, regarding the terms used in this table, 'full cut-off' has no CIE counterpart, and 'cut-off' and 'semi-cut-off' are similar to, but not identical with, the CIE 1977-classification (CIE, 1977).

In Table 7.1.7, the recommended luminaire classes are given for each zone or sub-zone. The maximum value of the Upward Light Ratio (ULR; in %) as well as the recommendations for pre-curfew and post-curfew regimes as well as those for urban and rural conditions are added.

Sub-zone	Maximum ULR (%) pre-curfew urban	rural	post-curfew	Light distribution (road and area lighting)
E1a	–	–	–	no lighting
E1b	+	1	0	full cut-off
E1c	+	3	0	full cut-off
E2	5	3	1	full cut-off
E3a	5	3	2	cut-off
E3b	10	5	5	cut-off
E4a	15	+	10	semi-cut-off
E4b	25	+	15	semi-cut-off

Table 7.1.7: *Requirements installations for general area lighting.*

Notes:
– no lighting; + not relevant; urban and rural refer to the general degree of urbanization (only relevant for zones E2 and E3 because E1 is always rural and E3 is always urban).

It should be noted that the classification of Table 7.1.6. and Table 7.1.7. is relevant only for luminaires that are used in general area lighting. This includes, as is explained earlier, industry lighting and sport lighting.

(d) Guidance lighting

In sec. 11.2.7, the importance in road traffic of visual guidance, or optical guidance is stressed. Before recommendation are discussed, it is necessary to explain the technical means to support the guidance. There are three principles to secure or improve of road traffic guidance:

(1) Passive road markings;
(2) Traditional road lighting;
(3) Active road markings.

All three can be applied during the day and at night. We will concentrate on the nighttime situation here, primarily because only then, the markers may contribute to light pollution, but also because during the day, optical guidance hardly ever is a problem, apart from exceptional weather conditions like e.g. snowfall, heavy rain and heavy fog (OECD, 1976).

Passive road markings are the traditional means to improve guidance on the road. There are three main types: plain road paints, retroreflective markings, either paints or thermoplasts, and raised pavement markers, often called 'cat's eyes'. All rely on the vehicle headlighting to be effective. (OECD, 1975; Schreuder, 1981). Vehicle headlighting is discussed in detail in sec 12.2. In order to have any effect at night, passive road markings need to be equipped with retroreflectors. Retroreflective materials are discussed in sec. 14.1.9.

One of the quality criteria of traditional road lighting is the degree to which the optical guidance is supported by the luminaires themselves. For this, the luminaires must emit some light just above and just below the horizon. This requires a careful design of the luminaires. If the luminous intensity is too low, the guidance is not adequate; if the luminous intensity is too high, glare and undue light pollution will be the result. The consequences of this are incorporated in the proposed classification for road lighting luminaires (sec. 7.4.1). Some design characteristics of luminaires are discussed in secs. 11.4 and 11.7.2.

The requirements for adequate optical guidance usually are restricted to qualitative remarks about the pattern of the light sources and the colour of the light (De Boer, 1967, sec. 2.7). Modern books mention optical guidance as a quality criterion hardly at all (Van Bommel & De Boer, 1980, p. 148; Hentschel, 1994, p. 185; Schreuder, 1998, p. 163). This might seem strange because from the driving task analysis point of view, optical guidance would be the most important quality requirement of road lighting (Schreuder, 1991; 1998, p. 150). The analysis of the driving task is discussed secs. 10.2 and 10.3. The quantitative requirements given by CIE are aimed at providing adequate optical guidance with a reasonable glare restriction (CIE, 1977). The CIE-requirements are discussed in sec. 6.2.1. More recent developments in luminaire design and in the considerations about the restriction of glare and of light pollution necessitate a more strict light intensity restriction near the horizon. Proposals for a more appropriate luminaire classification are given in sec. 7.4.1.

The draw-backs of passive road markings and of traditional road lighting as means to support optical guidance are clear: passive road markings require vehicle headlighting and therefore never can contribute to the guidance at a larger distance than the 'reach' of the low beams; traditional road lighting often causes too much glare and too much light pollution. Active road markings present a useful compromise. As is explained in sec. 11.1.1h, several alternatives have been investigated (Jongenotter et al., 2000). The most promising seems to be to provide the raised pavement markers that have been mentioned earlier, with lamps. At present, only semiconductor lamps or Light Emitting Diodes (LEDs) can fulfill the requirements regarding light intensity and colour, power consumption, lamp life and size. The essence is that they emit enough light to be clearly visible over a considerable distance – say a few hundred meters – and still they are so dim that they do not cause any glare or light pollution. As a matter of fact, in many cases the light pollution restriction was the first requirement to be met as they are often installed in areas that are 'light pollution sensitive' like natural parks etc. (Anon, 1997a; Schreuder, 1999).

The Province of Noord-Holland in the Netherlands has done most of the research in this field (Jongenotter et al., 2000). On the basis of this research, a proposal has been made for Guidelines for the design of installations for active markings (Anon., 2003). In Tables 7.1.8 and 7.1.9, proposals are given for quantitative recommendations for light elements for self-luminous raised pavement markers.

Lanes	Direction	Straight	Curvature, radius 150-600 m	under 150 m
2	2	3	6	12
1	1	6	12	24
2	1	12	24	24

Table 7.1.8: *Aperture angles in degrees (two times 'half beam width'). After Anon., 2003, tables 5 and 6.*

Light conditions	Peak luminous intensity (cd)
dark; no straylight	0,5
distant lighting	1,0
in or near road lighting	2,0

Table 7.1.9: *Peak luminous intensity for different light conditions. After Anon., 2003, table 7.*

Notes:
- the values refer to all colours;
- it is assumed that the markers cannot be adjusted. If they are adjustable, the beams can sometimes be narrower;
- 'straight' includes curves with a curvature radius over 600 m;
- both beam width and luminous intensity vary considerably for products of different manufacturers.

Recommendations:
- *It is recommended to use for the luminaires for road lighting, the classification as given in Table 7.1.4;*
- *It is recommended to use luminaires for road lighting according the indications as given in Table 7.1.5;*
- *It is recommended to use for the luminaires for general area lighting, the classification as given in Table 7.1.6;*
- *It is recommended to use luminaires for general area lighting according the indications as given in Table 7.1.7;*
- *It is recommended to use equipment for guidance lighting according the indications as given in Tables 7.1.8 and 7.1.9.*

7.1.5 The colour of the light

As is explained in sec. 1.2.5, the use of monochromatic light sources such as e.g. low-pressure sodium lamps is generally considered as one of the most effective ways to reduce interference of outdoor lighting with astronomical observations (CIE, 1997, sec. 10). Astronomical observations are hardly affected by the monochromatic light emitted by these lamps (Budding, 1993; Sterken & Manfroid, 1992). Furthermore, they are the most efficient light sources available at present (Schreuder, 2001a; Van Bommel & De Boer, 1980). For roads and streets with a high crime risk, however, the monochromatic light is less suitable (Schreuder, 1998, 2000). As one cannot see any colours, prevention and solution of crimes is more difficult. Also, the monochromatic light of low-pressure sodium-vapour lamps is not in line with amenity and comfort considerations, nor does it help to avoid the more subjective fear for crime (Painter, 1999; Schreuder, 2001). Details are given in secs. 12.1.2 and 12.1.4.

On the basis of these considerations, Table 7.1.10 has been prepared.

CIE-zones	Road type	Recommended light sources	Light sources to be avoided
E1	all	low-pressure sodium	white light
E2	traffic	low-pressure sodium	white light
	residential	fluorescent	low-pressure sodium
E3	traffic	high-pressure sodium	
	residential	fluorescent	low-pressure sodium
E4	all	high-pressure sodium	low-pressure sodium

Table 7.1.10: *Recommendation of lamp type for different zones (after Schreuder, 2000a, Table 10).*

Note: In this Table, white light is understood to include fluorescent lamps, incandescent lamps, high-pressure sodium lamps and metal halide lamps.

Recommendations:

- *It is recommended to use lamp types according the indications as given in Table 7.1.10.*

7.2 Intrusive light

7.2.1 Recommendations regarding direct light intrusion – residents

In this section, recommendations are given that are relevant for those cases where the light falls directly into the living space of the 'victims' ('intrusive light'). These conditions are referred to under the heading 'residents' in the user's matrix that is introduced in secs. 3.2 and 7.1.3.

(a) Sports and general outdoor lighting

In Table 7.2.1, recommendations are given to avoid undue intrusive light from sports and general outdoor lighting, industry area lighting included.

Zone	E1	E2	E3	E4
illuminance (lux)				
evening	2	5	10	25
night	1	1	2	4
luminous intensity (cd)				
evening	2500	7500	10 000	25 000
night	0	500	1000	2500

Table 7.2.1: *Recommendations for intrusive light restriction from sports and general outdoor lighting. Based on NSVV, 1999, table 1.*

The first two lines of Table 7.2.1 relate to the illuminance on the plane of the facade of living quarters, particularly of bedroom windows. The following two lines of that table relate to the luminous intensity of fittings in the direction of the windows in those facades. It should be noted that the data of Table 7.2.1 have been originally established for the lighting of sport facilities (NSVV, 1999). They have been regarded as being relevant for area lighting as well (NSVV, 2003, table 1). They may be used for other types of outdoor lighting as well, like e.g. general outdoor area lighting and lighting for city beautification (Schreuder, 2001).

(b) *Floodlighting*

In Table 7.2.2, recommended limiting values for the luminance of facades to restrict undue light intrusion into the living space of neighboring residents. The disturbance is the result of the light from floodlighting equipment that is reflected by the illuminated facades into the living area of the residents. The values refer to the average of the facade area of the building under consideration. They are based on a draft for the recommendations of the Netherlands (NSVV, 2003, table 2).

Zone	E1	E2	E3	E4
evening and night	5	5	10	25

Table 7.2.2: *Recommendations for obtrusive light restriction for the luminance of facades (cd/m^2).*

(c) *Road lighting*

Road lighting is a major cause for disturbance by light intrusion for sub-urban and rural areas. In Table 7.2.3, recommended limiting values are given for the luminance of road lighting to restrict undue light intrusion into the living space of neighboring residents. In establishing this table, some data from the unpublished draft for the recommendations of the Netherlands has been used.

Zone	E1	E2	E3	E4
illuminance (lux)				
main roads				
evening + night	5	10	10	15
secondary roads				
evening + night	0	5	5	15
luminous intensity (cd)				
evening + night	200	400	400	1000

Table 7.2.3: *Recommendations for intrusive light restriction from road lighting.*

The first two line of Table 7.2.3 relate to the illuminance on the plane of the facade of living quarters, particularly bedrooms. The third line of that table relate to the luminous intensity of fittings in the direction of the windows in those facades. The recommendations in Table 7.2.3 show considerable differences from those given in Table 7.2.1, because the disturbance is related to the road type and thus to the road lighting class, but also to the general lighting conditions in the area and thus to the zone. The limiting values of the luminous intensity are much lower because road lighting fittings usually are much closer and much lower than the fittings for general area lighting. Finally, usually there is no distinction between evening and night time lighting.

(d) Advertizing signs

Advertizing signs ('billboards') proliferate heavily in industrialized countries; they often form a major problem in respect to light pollution. Three different aspects must be taken into account:

(1) The luminance of the sign;
(2) The illuminance on the facade, facing the sign;
(3) The luminous intensity of the fittings, belonging to the sign, in the direction of the facade, facing the sign.

In Table 7.2.4, recommendations are given to avoid undue intrusive light from advertizing signs. The data are based on (NSVV, 2003b).

Parameter	Conditions	Zone			
		E1	E2	E3	E4
L	all times	50	400	800	1000
E_v	day/evening	2	5	10	25
	night	1	1	2	5
I_f	day/evening	2500	7500	10 000	25 000
	night	0	500	1000	2500

Table 7.2.4: *Limits of photometric values (NSVV, 2003b, tables 1 and 2).*

Notes to Table 7.2.4:
L: maximum average luminance of sign over the entire surface area of the sign, irrespective of its colour and size (cd/m^2);
E_v: illuminance on facade facing the signs (lux);
I_f: luminous intensity of fittings (each fitting; cd);
day/evening: 07:00-23:00h;
night: 23:00-07:00 h.

It is recommended to avoid advertising signs in the zones E1 and E2. As regards the signs themselves, no distinction is made between 'evening' and 'night time' conditions, because it is not feasible to have special night-time signs. It they are too much of a pollutant, they should be switched off entirely or in part. It might be noted that the values given in Table 7.2.4 deviate sometimes considerably from those that are proposed by other organizations.

(e) Greenhouses

Although greenhouses are the greatest contributors to light pollution in the Netherlands, at present there are no recommendations for the restriction of light intrusion from these establishments. As has been explained in sec. 15.4.3e, the present regulations in the Netherlands are aimed mainly to protect the farming in adjoining greenhouses and further to reduce the hindrance for those people living close-by, usually the neighbouring farmers-greenhouse owners (Anon., 2000). As is explained in secs. 4.5.5 and 4.5.6, also residents and pedestrians at larger distances, may experience nuisance when confronted with greenhouse lighting (Vos & Van Bergem-Jansen, 1991). About 10% of residents experienced the visible glow around their homes as 'annoying' or 'very annoying' and so did about 15 percent of pedestrians. The distance was usually several hundreds of meters. As is explained in sec. 4.5.5, an earlier study gave slightly higher percentages of people who are disturbed by the lighting of greenhouses (Pijnenburg et al., 1991). Maybe this has to do with the distance to the greenhouse complexes in the different study areas.

Although legal requirements are still lacking, the fact that greenhouses are amongst the greatest contributors to light pollution, makes recommendations indispensable. In Table 7.2.5, recommended limiting values for the light emission of greenhouses are given. They are based on the following considerations: it was found that there is a, usually weak, correlation between the dose and the effect, that is between the amount of light and the degree of annoyance (Vos & Van Bergem-Jansen, 1991). The tests were made for the following intervals:
(1) Direct light (glare) between 0,003 and 2 lux;
(2) Room intrusion between 0,1 and 2 lux;
(3) Sky glow between 0,09 and 0,67 cd/m^2.

The results of that study suggest, however, that the influence of the surroundings is often larger than that of the dose. This suggestion allowed the introduction of different environmental zones in the recommendation. As these recommendations are not based on direct experimental results, the values given in Table 7.2.5 might, as a result of specifically aimed research, be in need of future amendments.

Zone[1]	E1		E2		E3		E4	
'regime'	d	n	d	n	d	n	d	n
direct light (glare)[2]								
illuminance (lux)	*	*	0,03	–	0,03	–	1	0,03
room intrusion[3,4]								
illuminance (lux)	*	*	5	–	10	–	25	4
sky glow[5]								
luminance (cd/m^2)	*	*	0,05	–	0,15	–	0,5	0,15

Table 7.2.5: *Recommendations for light emission for greenhouses.*

Notes to Table 7.2.5:

1) It is assumed that greenhouses will not be allowed in the zone E1; it is assumed that greenhouse lighting in the zones E2 and E3 must be extinguished in the 'night' regime;
2) Folles (1979) gives 0,03 lux as the limit for glare (Vos & Van Bergem-Jansen, 1991 p. 36);
3) The values are, as far as is relevant, equal to those given earlier for sport and general area lighting as given in secs 7.1.4b and 7.1.4c. See also NSVV (1999, 2003, 2003a,b);
4) Assmann et al. (1987) give 1 lux as the limit for light intrusion (Vos & Van Bergem-Jansen, 1991 p. 35);
5) The sky glow limits given here refer to residents and pedestrians, not to astronomical observatories. These are discussed in sec. 7.3.

(f) Traffic participants

Compared to residents, traffic participants will have quite different requirements as regards the limiting values of intrusive light. The main reason is that road vehicles (cars etc.) carry their own lights. It should be noted that, as has been decided in the way the light pollution problems are approached in this book, the annoyance for road traffic users is that from all outdoor lighting with the explicit exception of road lighting. The reason is that 'victims' have been defined as those people who have nothing to do with the lighting under discussion. Road lighting is, however, installed with the specific aim to assist the traffic participants in the fulfillment of their driving task.

In Table 7.2.6, recommendations are given to avoid undue light pollution effects from outdoor lighting installations for traffic participants, more in particular for car drivers.

Parameter	Road classification			
	No road lighting	M5	M4/M3	M2/M1
Equivalent adaptation luminance (cd/m^2)	0,1	1	2	5
Threshold increment	15%	15%	15%	15%

Table 7.2.6: *Maximum values of threshold increment from non-road lighting installations.*

In Table 7.2.6, the road classification is according to CIE (1995). See also CEN (2002) and NSVV (2002). The more recent recommendations for road lighting are discussed in sec. 11.7.2e. The 'equivalent adaptation luminance' is the luminance that is to be used in assessing the Threshold Increment (TI). TI is defined in CIE (1976); see also Schreuder (1998) and sec. 9.2.2f. It should be noted that the TI cannot be calculated according the CIE method for irregular lighting installations. It is suggested to apply in those cases the limiting values for the luminous intensity that are given in Table 7.2.1.

(g) *Decorative lighting*

As has been explained in sec. 2.4, decorative lighting has a function of its own. Many forms of decorative lighting have a crucial role in city beautification. Because there are so many forms of decorative lighting, it is not possible to establish strict requirements that must be fulfilled for all those forms.

In Table 7.2.7, recommendations are given to avoid undue light pollution effects from decorative lighting. The table is assumed to be valid for most forms of decorative lighting, including Christmas tree types of lighting, artificial candles, lighting of fountains, laser beam displays etc. Because of this, the recommendations are restricted to notifications where and when the decorative lighting should not be permitted to be used.

Zone[1]	**E1**		**E2**		**E3**		**E4**	
'regime'	**d**	**n**	**d**	**n**	**d**	**n**	**d**	**n**
operation of decorative lighting[2]	*	*	disp	-	reg	-	reg	reg

Table 7.2.7: *Recommendations for the use of decorative lighting.*

Notes to Table 7.2.7:
1) It is assumed that decorative lighting will not be allowed in the zone E1; it is assumed that decorative lighting in the zones E2 and E3 must be extinguished in the 'night' regime;
2) Reg: on a regular base; disp: by way of dispensation only (e.g. for special occasions like e.g. Christmas, festivals, national holidays or Royal birthdays etc.).

7.2.2 Summary of recommendations

It is recommended to use the following tables for the designated areas of application:
- *Table 7.2.1. for sports and general outdoor lighting*
- *Table 7.2.2. for floodlighting*
- *Table 7.2.3. for road lighting*
- *Table 7.2.4. for advertising signs*
- *Table 7.2.5. for greenhouses*
- *Table 7.2.6. for non-road lighting installations for traffic* participants
- *Table 7.2.7. for decorative lighting.*

7.3 Recommendations to restrict the interference by light of astronomical observations

7.3.1 Direct light

In the foregoing sections of this chapter, we have discussed the requirements to be imposed onto outdoor lighting installations to reduce the amount of light intrusion. These requirements have been defined in term of 'the amount of light that enters into bedroom windows'. The relate, however, also to the direct light that may enter the premisses of astronomical observatories. Without any restriction, the requirements are valid to avoid undue interference by outdoor lighting installations for astronomical observations.

7.3.2 Sky glow

(a) Disability effects

It is explained in sec. 5.1.1, that the major interference by light of astronomical observations is the result of the sky glow that usually is present above cities and above other major outdoor lighting installations. It extends over a large part of the sky and it reduces all contrasts in the field of view in the same way as the veiling luminance that interferes with visual observations when observers are subjected to disability glare. The contrast reduction is discussed in sec. 5.1.1; the disability effects of glare are described in detail in sec. 9.2.2. See also Adrian (1961, 1993); CIE (2002); De Boer (1951; 1967); Stiles & Crawford (1937); Schreuder (1998); Van Bommel & De Boer (1980) and Vos (1963, 1983, 1999, 2003).

(b) CIE guidelines

The 'Guidelines for minimizing sky glow', published by CIE, are discussed in sec. 6.2.1 (CIE, 1997). In sec 6.2.3, it is indicated that these guidelines need, in at least three aspects, to be supplemented:

(1) To amend the requirements regarding the amount of light that is emitted by the lighting luminaires above the horizontal plane (the Upward Light Ratio ULR);
(2) To establish requirements regarding the total flux of all installations for specific zones (the Maximum Installed Lumen per unit Area);
(3) To amend the requirements regarding the minimum distance between the zone borderlines and the reference point.

(c) The Upward Light Ratio

In Table 7.3.1, recommendations regarding the Upward Light Ratio ULR (in %) for road lighting and for general area lighting are given for different sub-zones.

Sub-zone	Maximum ULR (%) pre-curfew urban	rural	post-curfew
E1a	–	–	–
E1b	*	1	0
E1c	*	3	0
E2	5	3	1
E3a	5	3	2
E3b	10	5	5
E4a	15	*	10
E4b	25	*	10

Table 7.3.1: *Requirements for ULR (in %) for road and area lighting.*

Notes to Table 7.3.1:

1) – means: no lighting; * means: not relevant; urban and rural refer to the general degree of urbanization (only relevant for zones E2 and E3 because E1 is always rural and E4 is always urban);
2) for all numbers given in Table 7.3.1, a value of 0,1% of ULR is allowed for production and measuring tolerances.

It should be noted that the values recommended here are more strict than those of CIE (1997, 2003). The reason is that light pollution is still a major problem in most countries of the world. It should also be noted that many luminaires can easily agree to the required values as given in Table 7.3.1, but many cannot at all. Many of the luminaires that are very popular today, have ULR-values up to 30 % or even up to 50 %. See for this e.g. Pollard (1993, Chart 1), where values for common luminaires between 0% and 50% are quoted.

(d) Urban sky glow

In sec. 14.3.6, the relation between the photometry as it is used in astronomy and in lighting engineering it discussed. In sec. 14.3.2, the following conversion factor is defined: "a luminance of $3{,}2 \cdot 10^{-6}$ cd/m^2 corresponds to 26,33 mag. per square arcsecond" (after Crawford, 1997, Table III). Astronomical photometry is discussed in detail in Crawford (1997). See also Budding (1993); Sterken & Manfroid, (1992) and Weigert & Wendker, (1989). In sec. 3.1, it has been explained that the influence of sky glow is assessed by comparing its luminance to the luminance of the sky under the most favourable earth-bound observation conditions, which is assumed to be the natural background radiation. This natural background radiation was found to amount to about 21,6 mag. per square arcsecond and the corresponding sky luminance amounts to $3{,}52 \cdot 10^{-4}$ cd/m^2.

Based on the correspondence between the astronomical and the lighting engineering photometry, the luminance values for different degrees of sky glow that are equivalent to specific values of the natural background radiation can be assessed. See Table 7.3.2.

Mag. arcsec^2	Mag. diff	log diff	r (%)	Luminance (10^{-4} cd/m^2)
21,6	0	0	0	3,52
21,5	0,1	0,04	10	3,88
21,4	0,2	0,08	20	4,23
21,1	0,5	0,2	60	5,64
20,7	0,9	0,36	120	7,79
20,6	1	0,4	150	8,81
20,1	1,5	0,6	300	14,1
19,6	2	0,8	530	22,2
18,6	3	1,2	1480	55,7
17,6	4	1,6	3880	140
16,6	5	2	9900	352

Table 7.3.2: *Luminance values compared to natural background for different degrees of sky glow. See also sec. 14.3.6.*

Using this correspondence, tentative recommendations have been set up regarding the detailed limitation of sky glow for different (sub-)zones. See Table 7.3.3. This table is based on data from Schreuder (1994, 1997).

Zone	Sky glow after curfew delta-mag	before curfew delta-L	after curfew delta-L
E1a	0,1	0,1	0
E1b	0,2	0,2	0,1
E1c	0,4	0,5	0,2
E2	0,7	1,0	0,5
E3a	1	1,5	0,8
E3b	2	5,3	2,5
E4a	3	14,8	7,5
E4b	4	38,8	19

Table 7.3.3: *Detailed suggestions for the limitation of sky glow.*

Notes to Table 7.3.3:
1) delta-mag: decrease in magnitude of 'limit stars' resulting from sky glow;
2) delta-L corresponding increase in sky luminance (in 10^{-4} cd/m^2).

(e) the Maximum Installed Lumen per unit Area

In Table 7.3.4, recommendations regarding the Upward Light Ratio ULR (in %) are given for different sub-zones. The recommendations refer to the total of all outdoor lighting installations. The recommendations are expressed in lumens per m^2. It should be noted that the dimension is the same as that for lux; the values given in Table 7.3.4. refer, however, to installed lamp lumens in new conditions and therefore cannot be measured with a luxmeter.

Sub-zone	Maximum installed outdoor lighting (lumen per m^2) pre-curfew	post-curfew
E1a	0,02	0
E1b	0,06	0
E1c	0,18	0
E2	0,75	0,15
E3a	3	0,8
E3b	12	2
E4a	50	20
E4b	150	30

Table 7.3.4: *Recommended values for the Maximum Installed Lumen per unit Area for all outdoor lighting installations for different sub-zones; in lumen per m^2.*

(f) *Distance*

As is explained in sec. 6.2.3e, the sky glow in the reference point is determined not only by the lighting in that zone but also by the lighting in neighboring zones, as well as by the dimensions of these zones (CIE, 1997). Because sky glow is a major consideration for the selection of sites for astronomical observatories, it is recommended to select a site for an astronomical observatory where the interference by light is a low as possible. See also sec. 14.6.4. For the selection of a site for a world-class observatory, the zones should be as wide as possible. This is particularly valid for countries or regions where distances are large and the population is scarce or non-existent (Batten, ed., 2001; Schreuder, 2001b). For the operation of existing observatories, the size of the nearby cities is important. Therefore, a distinction has been made for two cases: one of observatories near small towns (up to 50 000 inhabitants) and for observatories near large cities (half a million inhabitants or more).

In Table 7.3.5, recommendations are given regarding the minimum distance between zone borderlines and the reference point for thinly populated countries or regions. These recommendations are primarily aimed at the selection of sites for world-class observatories.

Zone rating of reference point	Zone rating surrounding zones recommended values of the distance (km) to borderline of surrounding zones		
	E1-E2	E2-E3	E3-E4
E1	5	25	100
E2		5	25
E3			5
E4		no limits	

Table 7.3.5: *Recommended values of the minimum distance (in km) between the zone borderlines and the reference point for the selection of sites for world-class observatories.*

In Table 7.3.6, recommendations are given regarding the minimum distance between zone borderlines and the reference point for observatories near small towns. These recommendations are primarily aimed at the operation of major existing observatories.

Zone rating of reference point	Zone rating surrounding zones recommended values of the distance (km) to borderline of surrounding zones		
	E1-E2	E2-E3	E3-E4
E1	1	10	100
E2		1	10
E3			1
E4		no limits	

Table 7.3.6: *Minimum distance (in km) between the zone borderlines and the reference point for the operation of major existing observatories. Based on data of CIE (1997, table 3).*

In Table 7.3.7, recommendations are given regarding the minimum distance between zone borderlines and the reference point for observatories near large cities. These recommendations are primarily aimed at:
(1) The operation of existing observatories;
(2) Observations by amateur astronomers;
(3) Education in astronomy.

Zone of reference point	Surrounding zones recommended values of the distance (km) to borderline of surrounding zones E1-E2	E2-E3	E3-E4
E1	1	5	10
E2		1	5
E3			1
E4		no limits	

Table 7.3.7: *Minimum permissible distance (in km) between the zone borderlines and the reference point for the operation of observatories for amateur astronomers and for education in astronomy. Based on data from UNI (1999).*

(g) *Summary of recommendations*

Recommendations:

- *It is recommended to use for the restriction of the direct light the data given in Table 7.2.1;*
- *It is recommended to use for the requirements for ULR the data given in Table 7.3.1;*
- *It is recommended to limit sky glow for different zones according to the data given in Table 7.3.3;*
- *It is recommended to use for the requirements for the Maximum Installed Lumen per unit Area for all outdoor lighting installations the data given in Table 7.3.4;*
- *It is recommended to use for the requirements for the minimum distance between the zone borderlines and the reference point for the selection of sites for world-class observatories the data given in Table 7.3.5;*
- *It is recommended to use for the requirements for the minimum distance between the zone borderlines and the reference point for the operation of major existing observatories the data given in Table 7.3.6;*
- *It is recommended to use for the requirements for the minimum distance between the zone borderlines and the reference point for the operation of observatories for amateur astronomers and for education in astronomy the data as given in Table 7.3.7.*

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8 Vision and visibility

When we look at the role of vision in society, it seems that we meet a paradox. On the one hand, vision is an essential element in modern society. The activities of daily life are geared to the fact that human beings are essentially 'seeing beings', more in particular 'daytime seeing beings'. On the other hand, it is clear that blind people can cope well, and can lead an almost normal life. The paradox is not a real one. Even a casual inspection shows that on the one hand almost all manual activities – as well as their derivatives, machine activities – require a high visual information input, whereas on the other hand, communication between human beings require only little visual information, that, additionally, can be replaced almost completely by auditory or other sensory means. It goes without saying, however, that matters like visibility, its tools, and its obstructions, are essentially of a visual nature. They are simply defined in this way. Therefore, we will devote several chapters to matters of visibility. This chapter deals with vision as well as with the different aspects of colour vision and colorimetry. The next chapter deals with visual performance. In further chapters, matters like the tools – illumination – and the obstructions – light pollution – will be discussed in detail.

8.1 The anatomy and physiology of the human visual system

8.1.1 The overall anatomy

The human visual system, as well as that of animals, is very complicated. The traditional ideas about the anatomy have been discussed in detail in textbooks like e.g. Davies, ed., (1969). See also Gregory (1965) and more in particular Hubel (1990). A complete but concise survey of almost all aspects of vision is given by Gregory, ed. (1987). That book is from 1987, so one might not find the most recent developments in it. A further draw-back is that the book is organised as an encyclopedia, listing the concepts alphabetically. Furthermore, the whole 'mind' is discussed in over 850 pages in small, two-column print. All this leads to the fact that in this volume it is sometimes hard to find the item one is looking for. At the other hand, it may be recommended as the best overview in not-too-difficult language which exists at present. We will give a very brief overview of the matter here, based on Schreuder (1998, Chapter 6; 2001). In its turn, that discussion is based on a several modern treatises of the human visual system (Crick, 1994; Greenfield, 1997; 2000; Hentschel, 1994 and others). What is presented here may be regarded as being in agreement with the present state of knowledge.

The human visual system consists of five major elements:
(1) The optical elements of the eye;
(2) The retina and the photoreceptors;
(3) The nerve cells (neurons) in the eye;
(4) The visual nerve tracts;
(5) The brain, notably the visual cortex.
Of these, (1), (2) and (3) are within the eye-ball, whereas (4) and (5) are located within the skull. In Figure 8.1.1, a broad sketch of these parts is given.

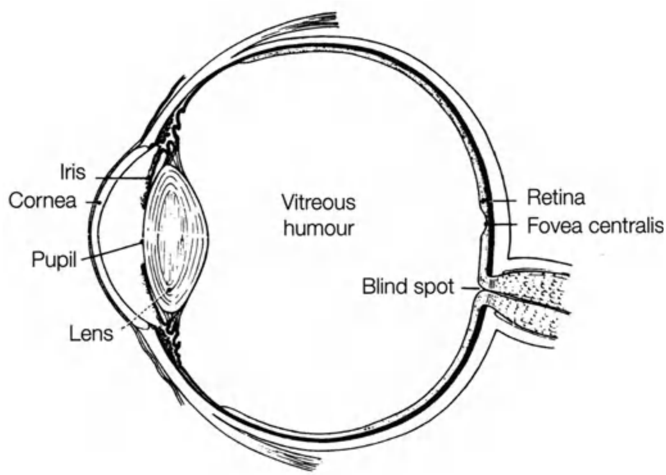

Figure 8.1.1: *The elements of the human visual system (after Schreuder, 1998, Figure 6.1.1).*

The eye-ball is, as the word says, an almost spherical organ of about 25 mm diameter (Hentschel, 1994, Table 1.1). In its front are the cornea, the iris and the eye lens; at its rear, the retina. The rest is filled with transparent fluids; the vitreous body (See Gregory, ed., 1987, p. 248, figure 1). We will discuss the different parts very briefly here.

8.1.2 The optical elements

The optical elements make an optical image of the exterior world on the retina. The optical elements of the eye are:
(1) The cornea, which forms the outer layer of the eye;
(2) The eye lens;
(3) The iris with its opening, the pupil.

The optical image is made in the first instance by the cornea. Apart from being the outermost layer of the eye, it is also the main refractive element of just over 43 diopters (Hentschel, 1994, Table 1.1). The role of the lens is mainly to adjunct the focal length of the optical system, allowing sharp images of objects at different distances. Its focal length corresponds – depending on the state of accommodation – from about 20 to just over 30 diopters (Hentschel, 1994, Table 1.1). A diopter is the reciprocal of the focal length in metres. When people get older, the lens looses most of its flexibility; older people cannot focus easily on nearby objects. They cannot accommodate easily any more (Stilma, 1995). They suffer from presbyopia and they need reading glasses – "their arms get too short!". The diminishing accommodation depth is given in Figure 8.1.2.

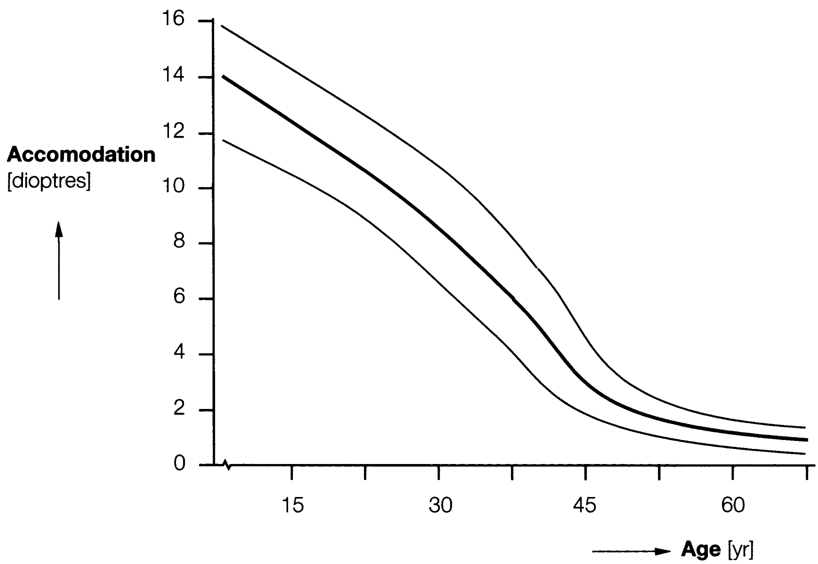

Figure 8.1.2: *Depth of accommodation versus age. After Schreuder, 1998, fig. 6.1.2.*

Just like all other optical devices, the eye shows aberrations. The theory of optical abberations is given in detail in the 'classic' treaty of Van Heel (1950). See also Feynman et al., 1977, Volume 1, Chapter 27). A simplified discussion is given in Kuchling (1995, Chapter 25). The main aberrations are the monochromatic aberrations and the heterochromatic aberrations. The monochromatic aberrations refer to those imaging errors that are not dependent upon the wavelength of the light. They result in images that are not sharp. The errors decrease when the pupil is smaller, when the receiving surface is curved, and when the perception is made along the optical axis of the system. The human visual system makes use of these conditions: when there is sufficient light, the pupil diameter is small, the retina is curved, and, the eye-ball being spherical, the optical axis can be aimed at the object looked at. In this way the monochromatic aberrations are kept to a minimum. The relation between the pupil diameter and the ambient light level (adaptation level) is given in Figure 8.1.3. It should be noted that, contrary to common belief, the changes in pupil diameter do not contribute much to the adaptation. The diameter may change from about 2,8 mm to about 7 mm, or about a factor 6 in area. Including the Stiles-Crawford-effect that takes the lower efficiency of the transmission through the lens edges into account, the ratio is even smaller (Helbig, 1972; Weale, 1961). See for further details Schreuder (1998, sec. 7.2.4). The numerical influence of the Stiles-Crawford-effect is given in Table 8.1.1.

Distance from centre of pupil (mm)	**Relative effectiveness** (%)
0	100
1	90
2	83
3	50
4	20

Table 8.1.1: *The effectiveness of rays entering the pupil at different points (approximated values, averages for the different directions). After Moon, 1961, figure 12.05, based on data of Stiles & Crawford, 1933.*

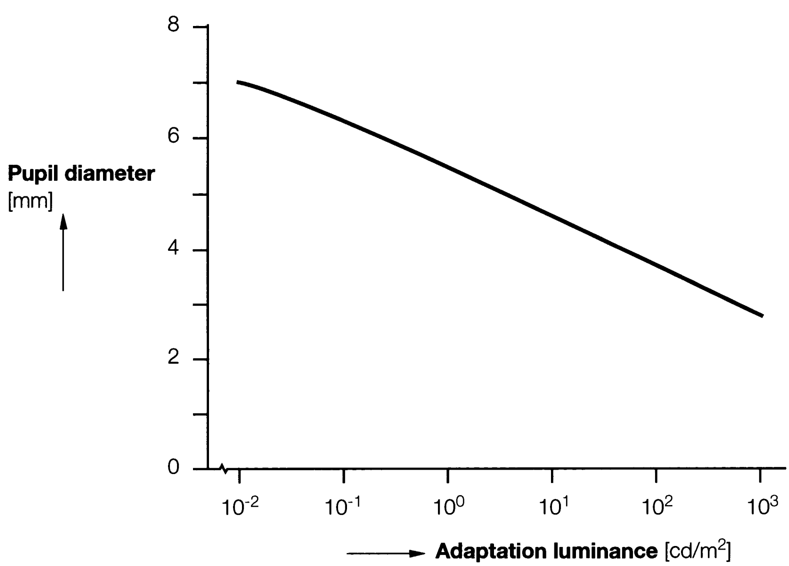

Figure 8.1.3: *The relation between the pupil diameter and the adaptation level. After Schreuder, 1998, figure 7.2.6. Based on data from Hartinger (1921).*

The other monochromatic aberrations will not be discussed here because they are not important in the considerations about light pollution. This contrary to the heterochromatic aberrations.

Heterochromatic aberrations result from the fact that the refractive index of optical media depends on the wavelength of the light. The refractive index for blue light, having a short wavelength, is higher than that for red light, having a longer wavelength. Thus, the focal length of an uncorrected lens, such as the eye-lens, for blue light is shorter than that for red light. The eye is myopic ('short sighted') for blue light and hypermetrope ('long sighted') for red light. See for details Mann & Pirie (1950); Schreuder (1998) and Stilma & Voorn, eds. (1995). On top of this, the apparent size of the image in blue light is usually smaller that in red light. The heterochromatic aberrations cannot be reduced by a reduction of the pupil diameter (Schreuder, 1998, sec. 6.1.2). They can, however, be reduced or even completely eliminated when monochromatic light is used. As the word says, monochromatic light contains only one single wavelength.

As is explained in sec. 11.3.4, low-pressure sodium lamps are essentially monochromatic. In many respects these lamps prove to be superior to other light sources. This superiority has two aspects. The lack of heterochromatic aberrations results in a better visual performance (Van Bommel & De Boer, 1980, p. 59). Also, visual comfort is often considered as being superior to that of the greenish-white light that is emitted by – uncorrected or colour-corrected – high-pressure mercury lamps (De Boer, 1951; De Boer & Van Heemskerck Veeckens, 1955; Schreuder 1967). For this reason, these lamps have been applied in many countries for road lighting, particularly for traffic route lighting (De Boer, 1967; NSVV, 1957). High-pressure mercury lamps, either uncorrected or corrected, are gradually being phased out. In industrialized countries, they are almost completely replaced – in new installations at least – by high-pressure sodium lamps. This is done for the reasons of economy that are discussed in detail in sec. 11.3, as well as for environmental reason, because mercury is one of the most dangerous heavy metals that are a direct threat to health. As is explained in sec. 11.3.4, both high-pressure mercury lamps and high-pressure sodium lamps have an emission spectrum with many lines and bands, so that their spectrum is almost a continuum. In the time of De Boer, they both would classify as 'white'. Nowadays, however, the designation 'white' is restricted to metal halide lamps and fluorescent tubes, that approach real white very closely. The lamps types are described in secs. 11.3.6 and 11.3.5 respectively; what is the meaning of 'real white' is discussed in sec. 8.3.8. Recent investigations did show that the white light of fluorescent tubes and metal halide lamps is preferred over the 'whitish' light of high-pressure mercury or high-pressure sodium lamps. See sec. 8.3.1.

Coming back to low-pressure sodium lamps, they emit the maximum of the light in two spectral lines at a wavelength of 589,0 nm and 589,6 nm (Moon, 1961, p. 80). These lines are so close together that for practical purposes, low-pressure sodium lamps may be regarded as being monochromatic with a wavelength of 589 nm (Hentschel, 1994, p. 137). As is explained in sec. 8.2.2, this wavelength is close to the wavelength of 555 nm where the maximum of the spectral sensitivity of the light adapted eye may be found, or, as it is usually called, in photopic vision (Moon, 1961, p. 412; Schreuder, 1998, p. 44). This implies that the 'efficiency' of the light is high; this is expressed in the fact that the efficacy of low-pressure sodium lamps is high as well. Values up to 200 lumen/Watt for the lamps themselves are quoted (Van Bommel & De Boer, 1980, p. 93; Schreuder, 1998, table 13.3.1). When the ballast is included, the efficacy becomes lower, but still can reach 150 lm/W (Hentschel, 1994, table 5.9). In sec. 11.3.2, it is explained in detail how this compares to the efficacy of other light sources. In sec. 11.7.2, it is explained how this relates to the resulting road surface luminance when actual road lighting installations with different lamp types are compared. The actual installation efficiency of low-pressure sodium lamps is lower than one might expect when considering the lamp efficacy in isolation.

Monochromatic low-pressure sodium lamps have some disadvantages as well. In sec. 8.3.8, it is explained that the monochromatic character makes it impossible to recognise colours. The colour rendering is low – or even absent, as is often stated (Schreuder, 1998; sec. 7.4.4). This means that the general outlook of lighting installations that are equipped with low-pressure sodium lamps is unpleasant, sometimes called 'ghoulish'. Pedestrians and other people outdoors feel a lack of comfort and amenity (Schreuder, 1989, 1998; sec. 12.1.5). Furthermore, it is more difficult to recognise people and scenes than in white light, where the colour rendering is higher. In case of street crimes, the recognition of criminals is more difficult, making crime prevention and crime fighting less effective (Painter, 1999; Schreuder, 1998, 2000; sec. 12.1.2). As has been indicated in sec. 12.1.4, it is usually suggested to use 'white' light for residential areas as well as for regions with a high crime rate. As has been explained in secs. 1.2.5, 4.3 and 4.4, it is generally accepted that low-pressure sodium lamps are most beneficial for astronomical observations, as well as for nature preservation more in general (CIE, 1997; NSVV, 1999).

8.1.3 The retina and the photoreceptors

The photoreceptors in the retina collect the incoming light and convert the energy into electrical pulses. This process is rather complicated and it is even today not completely understood. We refer here again to a number of excellent books, some elementary and others rather advanced, where the interested reader may find the details: Crick (1989, 1994); Damasio (1994); Dennett (1993); Edelman (1992); Greenfield (1997, 2000); Hentschel (1994, sec. 1.2-1.4); Hubel (1990). An overview of almost all aspects of vision is given in Gregory, ed. (1987). Details of the organization of the visual system are given in Gregory, ed. (1987, p. 798-804).

Basically, a light quantum that is absorbed by a photoreceptor will, as a result of the energy transfer related to this absorption, change the structure of one of the molecules of the so-called 'visual pigments'. A concise description is given by Gregory, ed. (1987, p. 153). It is a process similar to ionization: one or more electrons are 'kicked out' of the molecule. After recombination, an electrical pulse may be generated. This simplified description is based on Hentschel (1994, p. 11).

As indicated above, the energy of the incident light, the stimulus, results in the creation of electric pulses, called 'spikes'. The frequency in which spikes are fired is proportional to the intensity of the incident light. See Figure 8.1.4.

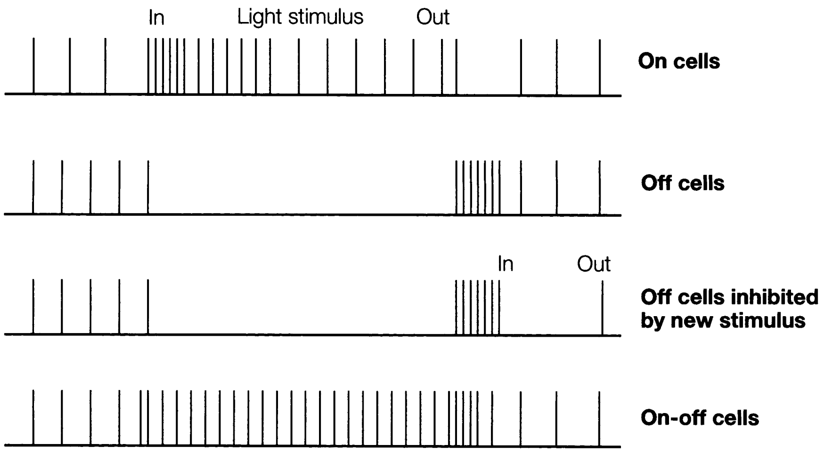

Figure 8.1.4: *Examples of bursts in so-called 'on' and 'off' receptors (After Schreuder, 1998, Figure 6.15, based on data from Hentschel, 1994, fig. 1.10).*

The processes involved are quite complicated. The whole chapter devoted by Hubel to these phenomena is in itself only a summary (Hubel, 1990, Chapter 3).

The electric pulses are, after a sort of pre-processing in the ganglion cells, transferred to the optical nerve that transmits them from the eye towards the visual cortex, the part of the brain were in a completely unknown fashion, the electric pulses are converted into a conscious experience called 'seeing'. Although some neuro-scientists – and others – pretend otherwise, the process is at present almost completely unknown (Greenfield, 1997, 2000).

8.1.4 Cones and rods

One will find in the normal human retina, as well as in that of many, but definitely not in all other animals, two main types of photoreceptors. They are commonly known as cones and rods. These names seem to stem from their overall shape, although one needs quite a lot of phantasy to see it!

The overall anatomy of cones and rods is similar; their operation, however, shows very important differences:

(1) The sensitivity of rods is much greater than that of the cones. We will come back to this point in sec. 9.1.3, where the adaptation is discussed;
(2) The rod system is not capable to discern colours, whereas the cone system, because of the interconnection of at least three different types of cones, can differentiate

between different colours. We will come back to this point in sec. 8.3.2, where the colour vision and its aberrations are discussed;

(3) The peak of the spectral sensitivity curve of rods is shifted towards the blue end of the spectrum compared to that of the cones. We will come back to this point in sec. 8.3.4, where the 'Purkinje shift' is discussed;

(4) The spatial distribution over the retina differs very considerably. The cones are mainly concentrated in the fovea centralis, whereas the rods are absent in the fovea centralis, but are abundant in the periphery. We will come back to this point in secs. 8.2.3c and 9.1.4, where the spatial distribution and the visual acuity are discussed.

8.1.5 The optical nerve and the brain

The physiology of the optical nerve and of the brain are exceedingly complicated. As the details are not particularly relevant for the study regarding light pollution, we will deal with it only in summary form. As is mentioned earlier, many details can be found in the standard books of Crick (1989, 1994), Damasio (1994), Dennett (1993), Edelman (1992), or Greenfield (1997, 2000). The short discussion presented here is based on Hubel (1990, chapter 4); Hentschel (1994, sec. 1.4) and Schreuder (1998, sec. 6.4).

(a) Neurones

Neurones are the building blocks of the nervous system. Neuro-physiological research has explained much during the last couple of decades, but many unanswered questions remain.

The anatomy of the neurones is reasonably well-known. See e.g. the section on brain development in Gregory, ed. (1987, p. 101-110). A neurone or nerve cell is a single cell, just like any other cell in the body. Its special characteristic is, however, a 'spur', the axon. The axons are extremely thin, measuring usually between 10^{-3} and 10^{-4} mm but often very long – up to one metre in length. Both ends of the cell, at the one side the cell body and at the other side the axon, have smaller protuberances, the dendrites. The dendrites play an essential role in the transmission of the electric pulses that are discussed in secs. 8.1.3 and 8.1.4. These pulses carry the information that must be transferred by the nerve system. Nerve cells form chains. The dendrites of the axon of one cell are in close contact with the dendrites on the cell body of the next cell. The transmission in the cell is along the axon. The transmission from one cell to the next is another very complicated process that is described in detail by Crick (1989), Edelman (1992), and Hubel (1990). In the last decade after 1990, the picture became more complete, but not more clear (Greenfield, 2000, Appendix).

The place where the dendrites of one cell meet the dendrites of the next cell is called the synapse. At the synapse, the two cells are near but they are not in contact. They are separated by an extremely narrow gap of about $25 \cdot 10^{-6}$ mm: the synaptic gap. At the 'sending' side of the synapse, the energy of the electric pulse is transformed into the chemical energy of the neurotransmitter. This chemical substance seems to cross the synaptic gap. At the other end, the 'receiving' end, the chemical energy is transformed back into electric energy in the next cell. In that cell, an electric pulse is created that is transferred along the dendrites and the axon to the next cell. In this way, the information can the transferred along the chain of nerve cells. This process is described by Hubel (1990, Chapter 2), where it is added that most of the process is "not understood" (Hubel, 1990, p. 20).

(b) Nerve tracts

Neurones are usually bundled into nerve tracts. The nerve tract, relevant for vision, is the eye-nerve or nervus opticus. It starts at the retina and runs right through the skull towards the visual cortex that is located at the rear end of the brain. The 'visual pathways' are described in Gregory, ed. (1987, p. 800, figure 1). A schematic picture is given in Figure 8.1.5.

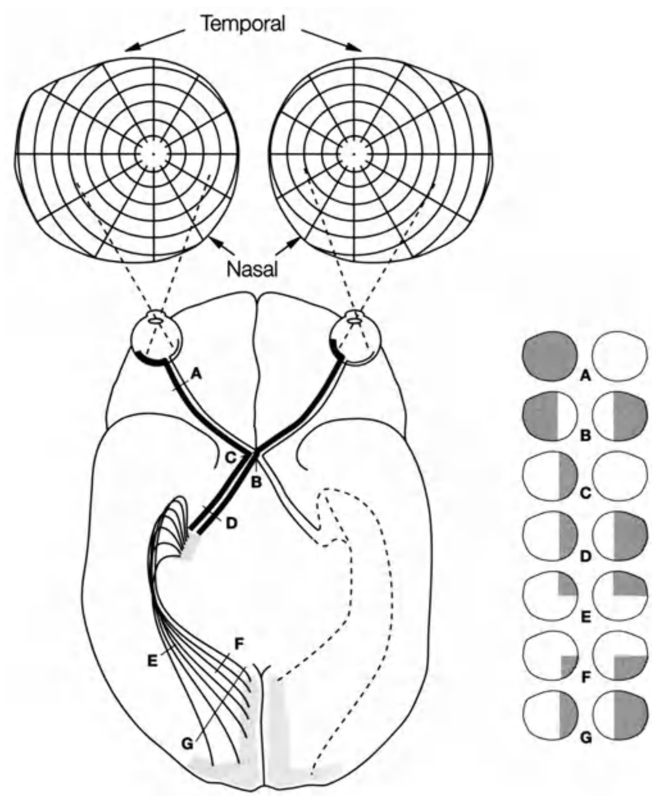

Figure 8.1.5: *The neural connections from the eye to the visual cortex. After Feynman et al. (1977, Vol 1, Figure 36-4).*

A clear overview is given by Voorn (1995) in the introductory chapter of the work on ophthalmology by Stilma & Voorn, eds. (1995), a standard textbook in the Netherlands. The brief description given here is based to a large degree on Hentschel (1994, p. 14-15).

(c) *The visual cortex*

The optical nerve ends in the cortex. The cortex is the outermost layer of the large brain (main brain or cerebrum; Greenfield, 1997, p. 6). It is only a few millimeters thick and it lays directly under the skull. Generally speaking, certain bodily or mental functions are linked to certain areas in the cortex. The brain functions related to vision are located in the rear part of the cortex. This section is therefore called the visual cortex.

The allocation of functions to areas can be demonstrated by measuring the blood supply to certain brain parts when the function is activated. The method is called a PET-scan (Positron Emission Tomography). See Bergsma, 1997 (p. 92; 106). In this way, it is possible to see an increased blood flow to specific brain areas when e.g. an arm is moved. These cortical parts might therefore be allocated to movements or to arms. At the one hand, some of these allocations are very specific. So, speaking words activates other brain sections than hearing words (Greenfield, 1997, figure 3; based on data from Posner & Raichle, 1994). In the past it was believed "that the brain can be divided into rigid compartments, each with a highly specific function" (Greenfield, 1997, p. 9). In the end, it was assumed that there were thirty-two different functions each with its own brain location (Greenfield, 1997, p. 11). Later, these ideas of the 18th century researcher Franz Gall, were refined in 1861 by Paul Broca and still later by distinguished researchers like Crick, Dennett and Edelman.

However, a more close look at human behaviour suggested that the allocation of functions to areas of the brain is far from specific. "The brain is made up of anatomically distinct regions, but these regions are not autonomous minibrains; rather, they constitute a cohesive and integrated system organised for the most part in a mysterious way" (Greenfield, 1997, p. 39). It might be better to speak of 'systems' (Damasio, 1994, p. 15). It is sometimes assumed that the visual cortex contains five different 'maps' of the visual field, called, without much phantasy V1, V2, V3, V4 and V5. A more refined analysis seems to reveal 32 different maps (Bergsma, 1997, p. 57). It is not immediately clear in which way this subdivision helps to clarify the visual process.

(d) *Vision*

As has been mentioned earlier, the optical nerve of both eyes come together in the chiasma opticum. Here, the information from the right hand side of both eyes is combined and so is the information from the left hand side of both eyes. The information from the right hand side of both eyes ends up at the left hand side of the cortex – because the optical image of the eyes is upside-down. The information from the left hand side of both eyes ends up at the right hand side of the cortex. Branches of the optical nerves go to those areas in the brain where the generation of associations is governed, but also to the brain stem where eye-movements are governed and to other brain sub-systems that govern muscle tonus. This in its turn relates to attention and awareness – two aspects that are mentioned in sec. 10.1.4b. Finally, the vegetative system can be influenced, that governs the more basic bodily functions like sleep, hunger, blood pressure and digestion. In this way, a wide variety of bodily and mental functions are directly or indirectly governed by the input from the photoreceptors. See also sec. 4.5.1, where the non-image forming aspects of the visual system are discussed.

The integration of the different visual aspects into 'seeing' is not straight-forward. We have indicated that allotting brain areas to functions does not give the answer. Until now, there seem to be no anatomically based grounds to designate one cortical region, that might serve as the centre where the information of all cortical parts that are involved in the visual process, comes together. "It even seems that the things that have been taken apart, never can be made to fit together again" (Bergsma, 1997, p. 61). This statement contradicts directly with the central idea of reductionism, where, under the assumption that 'the total equals the sum of the parts', it is assumed that studies of the parts reveal essential aspects of the total. A clear description of reductionism is given by Weinberg (1993). In spite of his enthusiasm, he makes it perfectly clear that the assumption of 'the total equals the sum of the parts' cannot to be made to fit to any living organism. One might even doubt whether it has any significance outside of some restricted areas of algebra.

This does not help much to find out what the conscious act of 'seeing' really means. Neurophysiology seems to point out the right direction, as has been assumed by many authors that have been quoted earlier in this section (Crick, 1989, 1984; Damasio, 1994; Dennett, 1993; Edelman, 1992). "The conscious picture of the surroundings is the result of the concerted efforts of all parts of the visual cortex made possible because the visual parts of the cortex not only are very precisely wired, but also have a diffusely operating network of neurones by which each part of the visual cortex stays in contact with all other parts" (Bergsma, 1997, p. 62). This 'diffusely operating network of neurones' suggest that a holistic approach might be more suitable. A more important suggestion is generated by this remark. It seems that we have cone to the end of the road; it seems that there are no further ways, open to the methods of natural sciences, to explain the forming of a conscious image out of the neuronal information in the brain. "A cohesive and integrated system is organised for the most part in a mysterious way" (Greenfield, 1997, p. 39).

It was mentioned earlier in this section that the information from the retina, in one way or another, influences many bodily and mental functions like e.g. attention and awareness, sleep, hunger, blood pressure, and digestion. One thing that astonishes is that most of these functions work perfectly well in people who are blind from birth. So the picture must be even more complicated. We refer again to sec. 4.5.1, where the non-image forming aspects of the visual system are discussed.

8.2 The functions of the human visual system

8.2.1 The sensitivity of the eye

In radiometry, the total power (in Watts) of the radiation is measured directly, e.g. by means of a bolometer (Budding, 1993; Hentschel, 1994, sec. 4.3.3.; Sterken & Manfroid, 1992, Weigert & Wendker, 1989). In photometry, the response of the human visual system must be taken into account. See also sec. 14.3.1.

As is explained in sec. 8.3.4, the sensitivity of the visual system to radiation is very large. Light quanta ('photons') that hit the photoreceptors will be absorbed; a part of the absorbed photons will give rise to specific photochemical reactions that are discussed in this section. Under optimal conditions, it is sufficient that within the time span of several milliseconds, three to four quanta hit one particular rod in order to cause a sensation of light (Weale, 1968, p. 27). For the cones, a much larger number of quanta is required.

The visual system is not equally sensitive to light of all wavelengths. Furthermore, the sensitivity depends on whether the rods or the cones, or possibly both, are active at the same time. Moreover, there are three types of cones, each with their own sensitivity. Details on this, and on the related colour vision, are discussed in sec. 8.3.2.

In spite of these complicating factors, it is possible to determine the sensitivity of the visual system as a whole for different wavelengths. The response to light of different wavelengths can be measured in different ways. A major problem in standardizing the eye sensitivity is, that each method gives different results. The methods themselves are not very relevant for the study of light pollution. We will refer for technical detail to the specialized literature (Helbig, 1972; Hentschel, 1994, sec. 4.2; Keitz, 1967; Walsh, 1985). More formal information is given in CIE (1924, 1932, 1978, 1989). See also Schreuder (1998, sec. 5.1.3). A detailed discussion on the standard visibility curve and of the problems involved, is given in Moon (1961, Appendix A).

Since the 1880s and 1890s, the proliferation of lamps – notably of gas lamps – required an international, time independent, reproducible standard against which the performance of lighting equipment could be measured and certified. In the beginning, normal light sources, like oil or gas lamps, operating under standardized conditions, were used (Barrows, 1938, Chapter II; Helbig, 1972). The most widely used source was the Hefner lamp (Barrows, 1938, p. 30). Later, a set of specially selected incandescent lamps was used (Barrows, 1938, p. 39). In the long run, they proved to be unsuccessful to serve as a primary standard, although they still are used on a large scale as secondary standards; see e.g. CIE (2002). It was decided that the eye sensitivity itself would serve as the standard, notwithstanding the problems we have already indicated. Additionally, there were problems with the definition of the standard observer; there always is a large inter-subject spread in psycho-physical study – no two persons are identical (Le Grand, 1956; Schober, 1960). Finally, the laboratory equipment of the time did not allow precise measurement of blue light. This fact turned out to have severe consequences for the day-to-day photometry of light sources: even in photopic photometry, blue emitting high-pressure mercury lamps were systematically underrated as regards their photometric performance, like e.g. the lamp efficacy that is explained in sec. 11.6.3. See Gall & Wuttke (1985).

8.2.2 Photopic vision; the V_λ-curve

In spite of all this, CIE defined in 1924 a 'standard observer'. It was designated as the "CIE Standard spectral luminous efficiency function V(lambda) for photopic vision" (CIE, 1924, p. 67; p. 232). See also Baer (1990, p. 14). In 1951, CIE defined also a 'standard observer for scotopic vision' (CIE, 1951, Vol 1, sec 4; Vol 3, p. 37).

The basis of this 'standard observer for photopic vision' was that the observer adapted fully to high levels of ambient luminances. Later, this was called 'daylight vision' or photopic vision. We will come back in sec. 8.2.3 to the important implications of this statement when we discuss the scotopic vision and mesopic vision. Another proviso is that the standard observer is defined doing the observations within a two-degree field. We will come back in secs. 8.2.3c and 8.2.3d to the important implications of this statement when we discuss the spatial distribution of rods and cones over the retina. In the definition of the standard observer, the average of 200 observers was used (Barrows, 1938, p. 2). Moon (1961, p. 49-50) gives more information about the way this standard observer was defined. It was found that in three different studies, the spread of the maximum sensitivity was considerable (Coblenz & Emerson, 1918; Gibson & Tyndall, 1923). "Because of this wide variation of perhaps 3 to 1 in the values of visibility obtained by different observers, it is advisable to standardize some kind of visibility curve for use in specifying the photometric quantities" (Moon, 1961, p. 51). This is exactly what CIE did later by adopting a 'standard visibility curve', based on the 1924 standard observer (CIE, 1932).

It is interesting to note the comments of Moon on this process (Moon, 1961, Appendix B). He begins to note that each concept in physics (it had been better if he had written 'experimental physics') "must be defined in terms of how it can be measured; concepts that cannot be directly related to measurable quantities are meaningless" (Moon, 1961, p. 536). "In general, we mean by any concept nothing more than a set of operations" (Moon, 1961, p. 536, quoting Bridgman, 1932, p. 5). A strange statement in view of the implications of the theoretical physics of the twentieth century, viz. quantum dynamics and the uncertainty principle. These have been described in many more recent popular books; see e.g. the 'classic' of Hawking (1988). Operations cannot be defined with infinite precision, nor can measurements. Moon seemed to be aware of this pitfall: "It would be unwise to claim that the operational method is the 'truth', whatever that may mean, or that it can be applied successfully everywhere. But in physics, its success has been so marked that its use hardly can be questioned" (Moon, 1961, p. 536). He continues: "From the operational standpoint, most of the photometric concepts as defined in the standard definitions are meaningless" (Moon, 1961, p. 537). Finally he states: "Specify a mathematical process by which the spectroradiometric curve is evaluated is in respect to the standard visibility curve. The resultant photometric quantities depend only upon the physical measurements entailed in the determination of the spectroradiometric curve, plus the subsequent arbitrary mathematical manipulation. *All photometric concepts therefore become purely physical concepts, quite independent of the observer*" (italics from Moon; Moon, 1961, p. 544).

In fact, this idea – although maybe implicit – was used when still later, the standard visibility curve was used to define the units of photometry. The CIE-system of photometry has been adopted by the Conference Générale des Poids et Mesures and later issued as an international ISO-standard. In the ISO-standard, the candela (abbreviated to cd) is the basic unity that links photometry to the other physical standards. It is added to the other basic quantities for length, time, mass, electric current, temperature and amount of matter. See e.g. Kuchling (1995, sec. 1.4). In 1967, the candela was defined as the luminous intensity emitted by a blackbody radiator with an area of 1/600 000 m^2, perpendicular to its surface at the temperature of solidifying platinum at a pressure of 101 325 Pa (CGPM, 1967, after Hentschel, 1994, p. 37). Even the most casual of readers would immediately detect that in this way, not the luminous intensity but the luminance has been defined (Schreuder, 1998, sec. 5.2.1). This and other considerations did lead to a new – and still valid – definition of the candela as the luminous intensity of a monochromatic source of radiation with a frequency of $540 \cdot 10^{12}$ Hz in a specified direction as the radiation with a radiometric intensity of 1/638 W/sr (CGPM, 1979, after Hentschel, 1994, p. 36-37). In sec. 14.1.4, we will come back to the precise definition of the steradian (sr) and its implications. The careful reader will note the equivalence of the photometric and radiometric radiations, as well as the conversion factor of 1/638. The numerical value of the conversion factor has to do with the 'area' that is included by the V_λ-curve that we will discuss later.

The 'Standard Visibility Curve' is usually presented in two ways:
(1) As a curve, depicting the relative sensitivity versus the wavelength. The curve, called the 'V_λ-curve', this is shown in Figure 8.2.1.
(2) As a table, giving the same relation. A shortened version is given in Table 8.2.1. CIE has produced a certified version of the table that gives the value of the sensitivity up to intervals of 1 nm (See Moon, 1961, Table X, based on Judd, 1931).

Wavelength (nm)	**Relative sensitivity**
400	0,0004
450	0,038
500	0,323
550	0,995
600	0,631
650	0,107
700	0,0041
750	0,00012

Table 8.2.1: *The relative sensitivity of the average normal eye in steps of 50 nm (based on data from Barrows, 1938, Table 1.1.).*

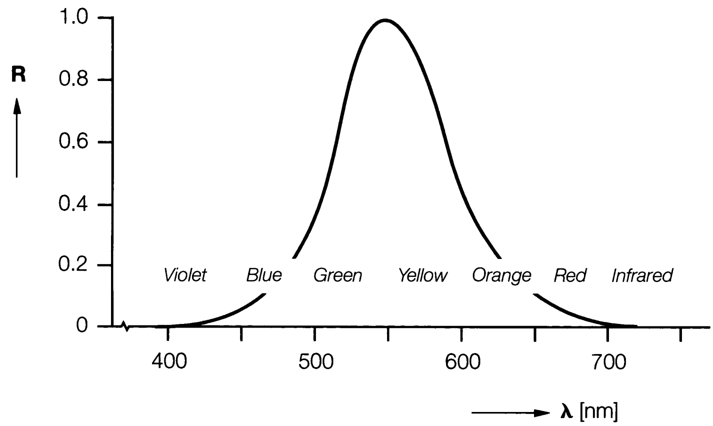

Figure 8.2.1: *The V_λ-curve (after Schreuder, 1998, figure 5.1.1).*

Note: as per definition, the sensitivity is set at unity for a wavelength of 556 nm.

In a symbolic way, the standard visibility curve is sometimes written as a function: V = f(λ). See e.g. Hentschel (1994. equation 2.44). As is to be expected, there is a third way to represent the Standard Visibility Curve. For this, a mathematical approximation is given in which V is given as a function of λ:

$$V = f(\lambda) \qquad [8.2.1]$$

An example of such a function is given by Baer (1990, p. 14). The function based on Mutzhas (1981). It is very complex and not very accurate. The average aberration is only 0,11% but at 550 nm, the aberration is +7,4%. Because there seems to be a misprint in the original publication, we do not reproduce the formula here. The reason that a function like this is not used often, is probably its complexity but also the fact that analytical representations did loose much of their interest as a result of the progress in numerical approximations by means of modern high-power computers.

There might, however, still be one area of interest of such formulae. The integral of the function would give directly the conversion from lightwatts into lumens. This seems still to be an area of much uncertainty. According to Moon, the conversion from 1 lightwatt yields 621 lumens. It is not correct to call this the 'mechanical equivalent of light' because light is not energy and cannot have a mechanical equivalent (Moon, 1961, p. 552-553). It should be noted that the constant has been changed – and thus was not very 'constant' – when a new definition of the candela was introduced in 1979. In that year, the 16me Conférence Générale des Poids et Mesures defined the 'candela' (cd) as the luminous intensity of a monochromatic source of radiation that emits in a certain direction (1/683) Watt per steradian at $540 \cdot 10^{12}$ Hz (Hentschel, 1994, p. 36). This automatically determines that one Watt corresponds to 683 lumen (Schreuder, 1998, p. 73). For the scotopic observer, the corresponding value is 1699, as given by Wyszecki & Stiles (1967). The value of 683 is sometimes called the radiometric equivalence.

It should be stressed that the presentations in graphical form (Figure 8.2.1) as well as that in table-form (Table 8.2.1) represent exactly the same data. One is therefore completely free to use the one or the other. Furthermore, it cannot be stressed strongly enough that the Standard Visibility Curve is the central issue that links the photometric units to the other physical units. It is therefore no surprise that one is very reluctant to include any corrections in the visibility curve, such as would be needed to correct the underrating of deep blue colours. Such a correction would have its repercussions, not only in the lighting industry, but in the whole structure of physical measurements and nomenclature. It would have specific repercussions for astronomy and astrophysics. To repeat it again, all photometry is based on the Standard Visibility Curve; it is therefore defined exclusively for photopic vision, for the standard observer, and for the two-degree field of observation. Any change in any of these assumptions would change the whole structure. Notably, the assumption that all photometry is based on photopic or daytime vision has severe consequences when we consider the visibility of objects at low ambient luminances. This point is discussed in detail sec. 8.3.4d.

8.2.3 Scotopic and mesopic vision

(a) Static and dynamic adaptation

The visual system can adapt its sensitivity to the ambient brightness. This effect is called adaptation. It has been shown that there are three aspects of adaptation:

(1) The changes in the pupil diameter. As is discussed in sec. 8.1.2, a small pupil opening will allow less light into the eye than a large pupil opening;
(2) The sensitivity adaptation of the receptors. As is discussed in sec. 8.3.4c, variations in the chemical composition of the visual pigments as well as the changes in the electric behaviour of the photoreceptors will change the sensitivity of the visual system;
(3) The switching on or off of the receptors. As is discussed sec. 8.1.4, there are two main classes of photoreceptors, viz. the rods and the cones. Their behaviour as well as their spatial distribution over the retina is different.

Adaptation is basically a dynamic process: it deals with the transition from one state of adaptation to another. These dynamic effects are discussed in detail in a further part of this section. Some aspects of adaptation need, however, be highlighted in order to explain the difference in operation of cones and rods. To begin with, we will introduce the 'state of adaptation'. In many cases, the changes in ambient brightness are slow, small or even absent. Under such circumstances, one may speak of 'the' state of adaptation.

(b) The state of adaptation

When the three aspects that were mentioned earlier are taken into account together at the same time, the resulting span of adaptation of the human visual system is astonishingly large. At the one extreme, the absolute threshold of visual perception, that is the lowest luminance that still can be distinguished from 'absolute' black, is about 10^{-6} cd/m^2. At the other extreme, the highest luminance where useful observations can be made near the condition of absolute glare, is about 10^4 cd/m^2 (Hentschel, 1994, p. 47; Schreuder, 1964). Light with much higher luminances may be observed, but the glare effects obstruct 'useful' observations, particularly because the after-images are predominant. It is interesting to note that even at those high luminance values, where most people will use sun-glasses, the amount of visual purple that is bleached out, is still small (Rushton, 1963; Rushton & Gubisch, 1966; Rushton & Westheimer, 1962). This might suggest that the visual system would be capable of observing much higher luminances. The role of the visual pigments on vision is explained in a further part of this section. There are only a few experiments that may support this suggestion (Schreuder, 1964). In extreme cases, damage to the eye can follow (Van Norren, 1995). To give an impression of the amount of visual pigment that is bleached at a specific adaptation luminance, some data from Rushton (1963) are depicted in Figure 8.2.2.

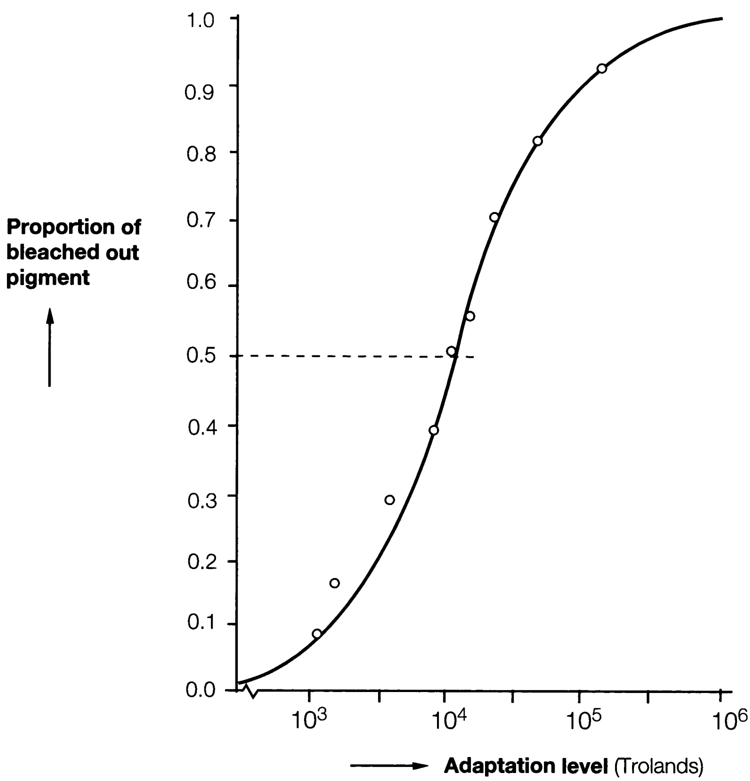

Figure 8.2.2: *The relation between the adaptation luminance (in Troland) and the percentage of bleached-out pigment according to Rushton, 1963. After Schreuder, 1998, Figure 7.2.7, based on Cornsweet, 1970.*

It should be noted that in Figure 8.2.2, the state of adaptation is quantified in Troland. The Troland is a measure that was often used in the past to quantify the retinal light impression, taking the pupil diameter into account. The retinal light impression is expressed in the illuminance of the plane of the pupil. In doing so, the pupil diameter must be taken into account. The relation is:

$$I_p = L_A \cdot A_p \qquad [8.2.2]$$

in which:
I_p: the pupil illuminance;
L_A: the adaptation luminance (in cd/m^2);
A_p: the area of the pupil opening (in mm^2).

In this complicated definition, de dimension of the Troland (Trol) is: cd $\cdot$ m^{-2} $\cdot$ mm^2 (after Baer, 1990, p. 18). One can only convert the state of adaptation, expressed in Troland, into the more common values of luminance (in cd/m^2) when the pupil diameter is known – which is usually not the case. Because the Stiles-Crawford-effect, that is discussed in sec. 8.1.2, is not taken into account, the non-ISO measure 'Troland' is not used often any more.

The overall range of adaptation of the human visual system is given in Figure 8.2.3.

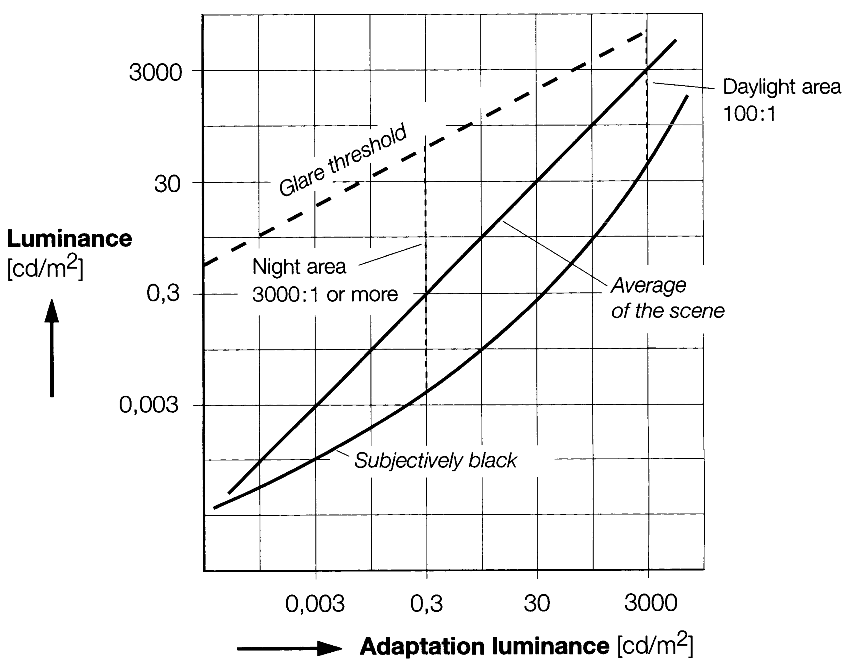

***Figure 8.2.3:** The scene and its limits of darkness and dazzle (After Schreuder, 1998, Figure 7.2.5).*

Table 8.2.2 may give an impression what these different luminance values in outdoor scenes really mean.

Luminance log (cd/m^2)	Examples	Visual performance
5		dazzle
4,5	sun on snow	glare
4		
3,5	average daylight	
3		good perception
2,5		
2	interior lighting	
1,5		
1	dusk	
0,5	main road lighting	reading possible
0	candle light	reading difficult
0,5	residential street lighting	
-1		colour perception impossible
-1.5	moonlight on snow	
-2		
-2,5	moonlit night	
-3		
-3,5	clear moonless night	only vague shapes
-4	starlight on snow	
-4,5	dark moonless night	
-5		only vague light impression
-5,5		
-6		perception threshold

Table 8.2.2: *Range of brightness (After Schreuder, 1998, Table 7.2.1, based on data from Hopkinson, 1969).*

Notes to Table 8.2.2:
- As has been indicated in sec. 3.1, it is customary to take, for the practical minimum of the natural background radiation, the value of 21,6 mag. per square arcsecond, corresponding to $3{,}52 \cdot 10^{-4}$ cd/m^2. This value refers to the sky, whereas the values of Table 8.2.2. refer to the ground;
- the glare terminology is not in complete agreement with the most recent proposals for a CIE-terminology as proposed by Vos (1999).

As can be seen from Figure 8.2.3, at any specific moment in time, the span of adaptation is much smaller, ranging from some 3000:1 in nighttime surroundings to about 100:1 in bright daylight. See also Noordzij et al. (1993).

(c) The spatial distribution of rods and cones

The human retina contains a very large number of receptors, approximately $1{,}2 \cdot 10^8$ rods and about $6 \cdot 10^6$ cones. The rods are distributed over the whole retina, except in the central area. This central area is called the fovea centralis, the macula or the yellow spot. In the fovea, where the rods are absent, the cones are very densely packed. As is explained in sec. 9.1.4, this is the reason that sharp seeing can be achieved only in the central are of the field of view – an area about 2 degrees in diameter. Seeing very dim stimuli can be, however, done best in the outer area or periphery of the field of view. This fact has been known for millennia in applied astronomy. Dim stars disappear from view when one tries to focus on them. The spatial distribution of the rods and cones over the retina is depicted in Figure 8.2.4.

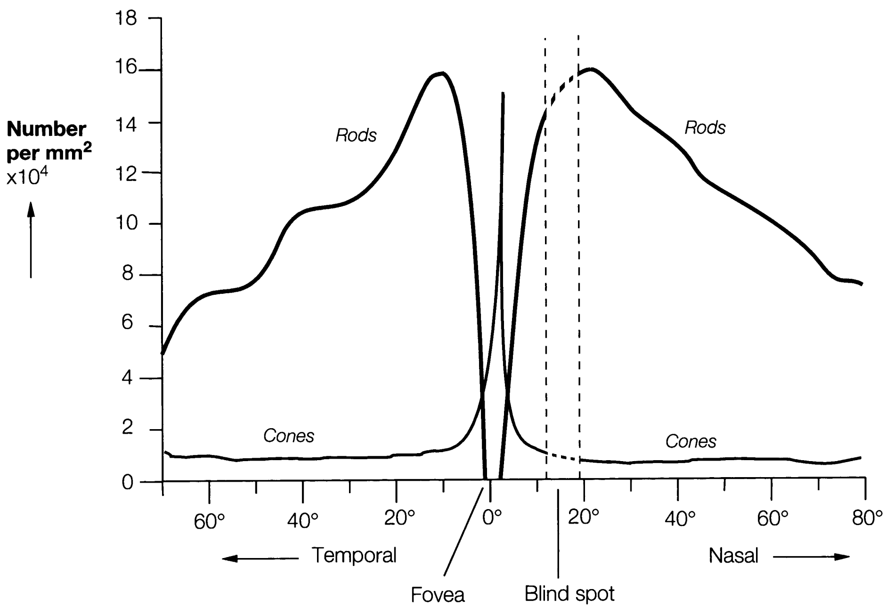

***Figure 8.2.4:** Spatial distribution of photoreceptors. After Schreuder, 1998, Figure 6.1.7. Based on Hentschel, 1994, fig. 1.6. Based on data from Osterberg (1935) and Pirenne (1972).*

As mentioned earlier, this results in the fact that the visual acuity is greatest in the fovea centralis and lowest in the far periphery. This is depicted in Figure 8.2.5.

(d) Scotopic and mesopic spectral sensitivity curves

As is explained in sec. 8.2.1, it is possible to represent the spectral sensitivity of the visual system in total in one curve, the V_λ-curve. This curve is valid only for photopic vision or day-time vision where only the cones are operational and the rods are inactive. The shape is essentially determined by the absorption characteristics of the visual pigments that are operational in the cones during daytime vision. Because the visual pigments that are operational during photopic vision are, chemically speaking, very similar to those that

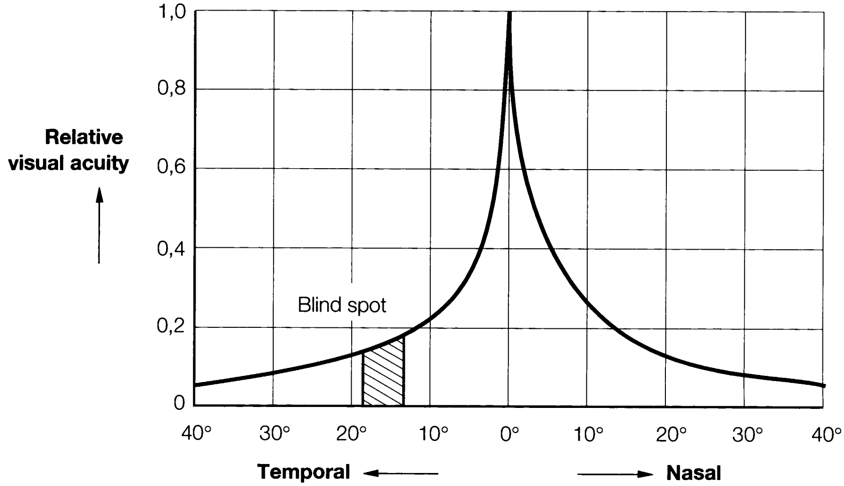

***Figure 8.2.5:** The relation between visual acuity and retinal location. After Schreuder, 1994, Figure 6.1.9. (After Hentschel, 1994, fig. 3.12; based on data from Wertheim (1894).*

are operational during scotopic vision, it is no wonder hat the spectral sensitivity curves of photopic vision and scotopic vision are very similar in shape.

In Figure 8.2.6, the two sensitivity curves are depicted together.

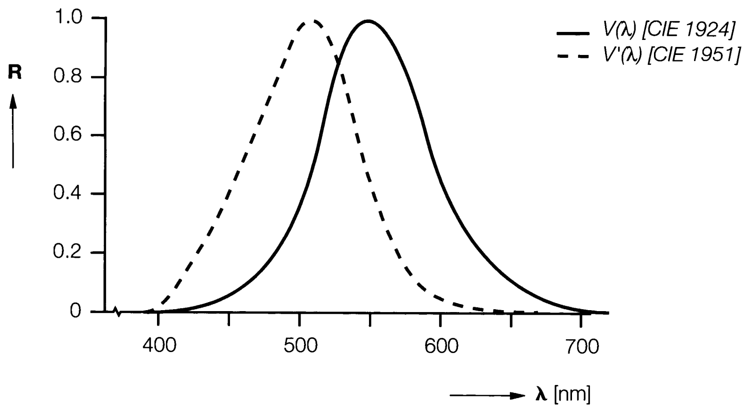

***Figure 8.2.6:** The spectral sensitivity curves for photopic and for scotopic vision, V_λ and V'_λ respectively. After Schreuder, 1998, Figure 5.1.2, based on Baer, 1990, fig 1.4.*

Notes to Figure 8.2.6:
- The two sensitivity curves are independently normalised to 100% for their maximum values;
- The drawn line for the photopic curve represents the measurements with a two-degree measuring field, the dashed line represents the measurements with a ten-degree measuring field. The discrepancy between the two curves is discussed in sec. 8.2.2;
- As is explained in sec. 4.5.1, the non-image forming effects of light follow their own spectral sensitivity curve, as is depicted in Figure 4.5.2.

There is not one single luminance value where photopic vision and scotopic vision meet. In contrary, there is a wide zone of transition zone between them. Because it is between photopic and scotopic vision, it usually called the zone of mesopic vision. The reason that the zone of mesopic vision does exist is because the activities of neither cones nor rods is simply switched 'on' or 'off'. There are reasons to believe that both cones and rods operate in all luminance conditions, but that their activity is not always apparent. This implies that there is no sharp borderline between the zones of photopic and mesopic vision, nor between the zones of mesopic and scotopic vision. Because there is no sharp criterion to determine whether one is in the zone of photopic or mesopic vision, or in the zone of mesopic or scotopic vision, the borders of the zone of mesopic vision that are used in literature, are somewhat arbitrary. It is often stated that the zone of scotopic vision begins at about 0,03 cd/m^2 (Baer, 1990, p. 41). Other data state that the zone of mesopic vision stretches from 10 cd/m^2 down to 10^{-3} cd/m^2 (Kokoschka, 1980, as referred to by Hentschel, 1994, p. 32). At another place, it is stated that the zone of mesopic vision stretches from 3 cd/m^2 down to 0,01 cd/m^2 (Hentschel, 1994, p. 47). Moon states that: "If the luminosity is above approximately 0,01 lumen/sq ft, vision is photopic; if it is below approximately 0,001 lumen/sq ft, the vision is scotopic" (Moon, 1961, p. 412). The zone of mesopic vision – called by Moon the Purkinje region – is only narrow – about one decade (Moon, 1961, p. 412). What it means in ISO-values is not clear: Moon used the unfamiliar term 'luminosity' which has, according to his own definition on p. 57, the dimension of illuminance. Now, the state of adaptation must be expressed in values of the luminance in cd/m^2 (or, indeed, in Troland). The illuminance can be converted into ISO values by using the standard conversion table as given in sec. 14.3.2a. See also e.g. De Boer, ed. (1967, p. 688, Appendix II). In this table, 1 footcandle or lumen per sq foot equals 10,76 lux. This would mean an illuminance of between 0,1067 to 0,01067 lux – rounded off between 0,1 and 0,01 lux. Assuming a reflection factor of 0,2 (a value commonly found in nature) the Moon-vales would correspond to luminances of 6,796 10^{-3} cd/m^2 to 6,796 10^{-4} cd/m^2 – rounded off again to 0,007 to 0,0007 cd/m^2. As can be seen immediately on the road, these values are far too low. Clearly, there is something wrong with the calculations of Moon. We give it here only to beware of experts! For decades, the book of Moon was the standard volume on lighting engineering all over the world.

In order to avoid this confusion, Schreuder has introduced the concept of 'high mesopic vision' (Schreuder, 1976, p. 28). Based on the practical experience available at that time, it was assumed that when the luminance is higher than 0,1 cd/m^2, the differences between high mesopic vision and photopic vision may be neglected. In other words, for practical – photometric and colorimetric – purposes, the lower limit of the zone of photopic vision may be put at 0,1 cd/m^2. Also it was found that on main road lighting, the luminance was almost never below that value (De Grijs, 1972; Westermann, 1967). And finally, it could be argued that even for motor vehicle headlamp lighting, the relevant areas of the road surface usually had a luminance higher than 0,1 cd/m^2 (Carlquist & Schreuder, 1969, fig. 3). So, at that time, it seemed to be justified to restrict lighting considerations to photopic vision and include high-mesopic vision in it. This point of view can be illustrated by Figure 8.2.7.

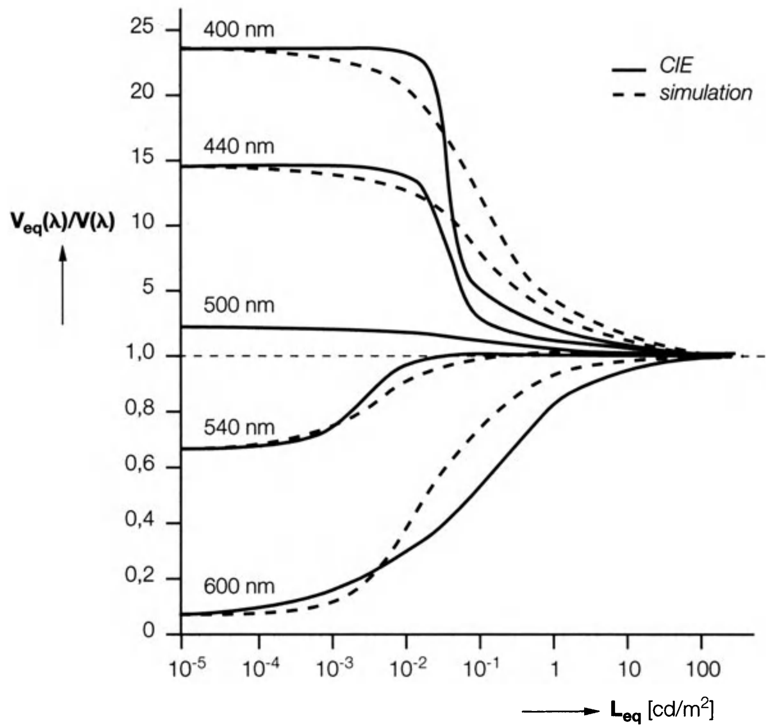

Figure 8.2.7: *The relative efficacy (V_{eq}/V) at various wavelengths as a function of the equivalent luminance (L_{eq}). After Schreuder, 1976, figure 3. Based on Cakir & Krochmann, 1971, fig. 1.*

In summary, it seems justified to follow the proposal of Hentschel for the limits of the zone of mesopic vision (Hentschel, 1994, p. 47). The upper limit is 3 cd/m^2 and the lower limit is at 0,01 cd/m^2. Also it seem justified to follow the proposal of Schreuder to introduce a zone of high-mesopic vision (Schreuder, 1976, p. 28). The zone of high-mesopic vision reaches from 3 cd/m^2 down to 0,1 cd/m^2. It is assumed that in this zone, photopic photometry and colorimetry are applicable. In sec. 8.3.5, it is pointed out, however, that, when considering light pollution, the last assumption might be in need of an amendment.

8.3 Colour vision and colorimetry

8.3.1 The importance of colour

Colours are important in daily life. In many trades and professions, colours are used to code products and equipment. There is a large literature of colour vision, on detection of colours, and on colour coding, as well as on the physiological and psychological principles that are relevant in the detection of colours. We will quote a few of the most recent CIE publications on this matter (CIE, 1975; 1983; 1986; 1994; 1996; 2001a, b).

First, however, a note on terminology. There are many different sets of terms in colorimetry, just as there are many different systems of colorimetry. Basically, they all include three concepts, that might be indicated in colloquial terms:
(1) The actual colour (red, green, yellow etc.);
(2) The saturation (strong or weak red; strong or weak green etc.);
(3) The lightness (bright or dark red; bright or dark green etc.).

In the Munsell-system, that is discussed in sec. 8.3.7h, the corresponding terms are 'hue'; 'chroma', and 'value' (Anon., 1993, p. 427; De Boer & Fischer, 1981, p. 90).

All standard works and textbooks on physiology, ophthalmology, psychology, and lighting engineering devote large chapters on colours and colour vision. It is, therefore, interesting to note that colour defective people, also those who can see no colours at all, can have an almost normal life. Missing the ability to see colours seems to have little or no consequences. So, maybe the ability to see colours is not that important at all.

However, those people who can see colours are very keen on using this ability. Colours are often considered to be the most important aspect of the surroundings. Surveys in lighted streets pointed out that many residents value a 'reasonable' colour impression above good visibility (Schreuder, 1989; Van Tilborg, 1991). It is difficult to think of architects or of fashion designers who would not put emphasis on the colour aspects of their creations.

A landscape without colours, like e.g. a hazy winter landscape in the snow, will evoke a peculiar emotion, just as most desert landscapes. And so does the really dark nights, where only nighttime vision is operational. So it seems that the ability to see colours is not essential for human life, but if we have the ability we will use it with fervour.

Another thing to note is that a considerable part of all paintings are made in black-and-white only; we usually call them 'drawings'. Also, for well over a century, all photographs, particularly those to which a large aesthetic value was attributed, were in black-and-white as well. As a matter of fact, black-and-white films are still being made! Here, we meet a striking phenomenon: when colours are not apparent, we are perfectly capable to fill them in. The essential condition is, however, that the observer must be able to recognise the setting. It is not difficult to determine the relevant colours in a black-and-white reproduction of a sea battle painted in the 18th century; it becomes harder to determine the colour of a cloth in a black-and-white reproduction of a Vermeer portrait and it is impossible to reconstruct the colours in a painting of Mondriaan from a black-and-white reproduction. Finally, most people wear sunglasses in overly bright daylight conditions. Almost all commercially available sunglasses distort the colour information presented to the wearer-sometimes to the extent that they are prohibited in traffic because the colour of traffic lights become invisible (Alferdinck, 1997; Schreuder, 1997). Apparently, people with colour-normal vision have the ability to fill in, from experience, the missing colour information in visual scenes. However, the fact that the actual visual information about the colour is missing or distorted, is, to them, perfectly clear.

These facts are highly relevant in view of our studies in the phenomena if light pollution and the possibilities to avoid or at least to reduce the adverse effects of it. On the one hand, human beings are perfectly capable to live and even to enjoy life without colours or without the 'true' colours. On the other hand, many people object vehemently against light pollution, particularly when it is 'coloured'. It would seem that the crucial factor is whether the person in question did choose for the absent or distorted colour impressions, or that they are exposed to it on the basis of the decision of someone else – e.g., the authorities. This is a well-known phenomenon; every mountain climber or long-distance runner, in fact anyone who participates in any sports, or who plays a musical instrument for that matter, will recognise the dilemma immediately. One suffers a lot at one's own free will, even sometimes until death follows. However, if the authorities would ever think to force people to do similar things, the world would cry out in indignation. Strangely enough, it seems that there are hardly any serious studies devoted to the phenomenon.

8.3.2 Colour vision physiology

As is explained in sec. 8.1.4, the photoreceptors in the human retina can be classified in rods that are operational only at low values of the adaptation luminance and cones that are operational only at high values of the adaptation luminance. Also it is mentioned that cones come in at least three different families, each family having its own visual pigment which results in a distinct spectral sensitivity curve for each family. The fact that there are three families of cones is the basis for colorimetry, discussed in sec. 8.3.6.

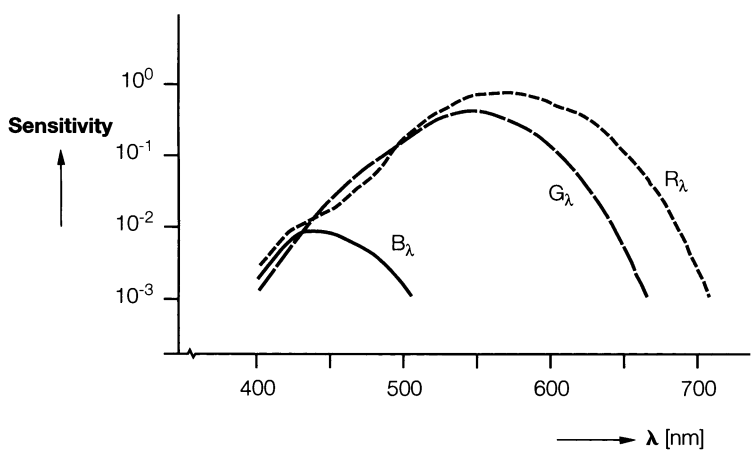

Figure 8.3.1a: *Sensitivity of different cones. Based on Walraven, 1981, p. 34.*

In sec. 8.3.3, the separate spectral sensitivity curves for each family are given. They can be determined by measuring the response of the total eye for people who have only one family of cones that functions properly: the protanopes, the deuteranopes, or the tritanopes. The pigments of these three families absorb primarily light of a particular colour. The cones of the protanopes absorb mainly yellow, the cones of the deuteranopes green, and the cones of the tritanopes blue. Therefore, the three families of cones are usually called the yellow cones, the green cones and the blue cones (Feynman et al., 1977, vol. I, p. 36-2; Walraven, 1981, p. 34). See Figure 8.3.1a.

The three families of cones are not connected directly to parts of the visual cortex. In fact, the way the visual signals travel from the retina towards the cortex is rather complicated. Here, we will follow the simplified explanation from Walraven (1981, p. 34). Some details from Feynman et al. (1977, vol. I, p. 36-2) are added.

As long as the cones are illuminated, they emit a continuous signal that varies in strength with the light intensity. The maximum value of the signal corresponds to about 0,05 volt. These graduated potentials can travel only over a short distance such as the thickness of the retina. These signals are propagated towards the ganglion cells, where they are converted into neuronal pulses. As is explained in sec. 8.1.3, these neuronal pulses are transmitted towards the cortex.

The role of the ganglion cells is two-fold. The first is the conversion of the graduated potentials into neuronal pulses. The second is a sort of 'preprocessing' of the visual signals. There are three families of ganglion cells: the first discriminate between signals representing blue and yellow light; the second between red and green, and the third between black and

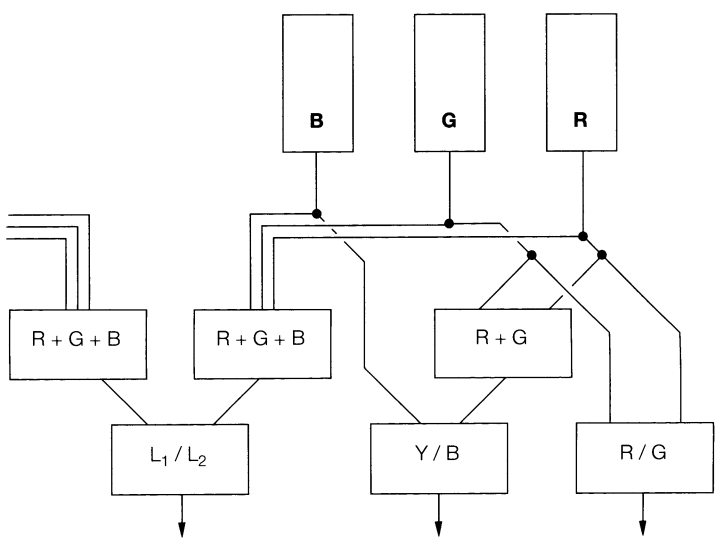

Figure 8.3.1b: *Model of the signal processing of colours in the retina. After Boogaard, 1990, fig. 7.*

white. Each has an opposing counterpart, so one might say there are six families of ganglion cells. The most important for colour vision are cells that discriminate between blue and yellow light and red and green light respectively. Often, they are called the B-Y cells and the R-G cells. The connections ('wiring') between the cones and the ganglion cells are depicted in a very schematized way in Figure 8.3.1b.

This figure represents the 'opponent' theory of colour vision. This theory is generally accepted at present. Some alternative theories are mentioned in Feynman et al. (1977, vol. I, p. 36-2).

8.3.3 The spectral sensitivity curves of separate kinds of cones

As is explai`ned in sec. 8.2.2, it is possible to represent the total spectral sensitivity of the visual system in one curve, the V_λ-curve. This curve is valid only for photopic vision or daytime vision, where only the cones are operational. The shape is essentially determined by the absorption characteristics of the visual pigments that are operational in the cones during daytime vision. Details on the chemistry of the visual pigments are given in Feynman et al. (1977, Vol. I, sec. 36.3) and Hentschel (1994, sec. 1.4). This is not a simple matter because, as is explained in sec. 8.3.2, there are at least three different 'kinds' of cones, each having its own spectral sensitivity curve. These three curves are essential for the description of the colour vision phenomena. The absorption of the pigments can be measured directly. Details are given by Hubel (1990, Chapter 8).

In Figure 8.3.2, the absorption curves of the three kinds of cones are given in a relative logarithmical scale; thus, 'zero absorption' is not represented in the figure. The absorption for each kind of cones is normalised at 100%

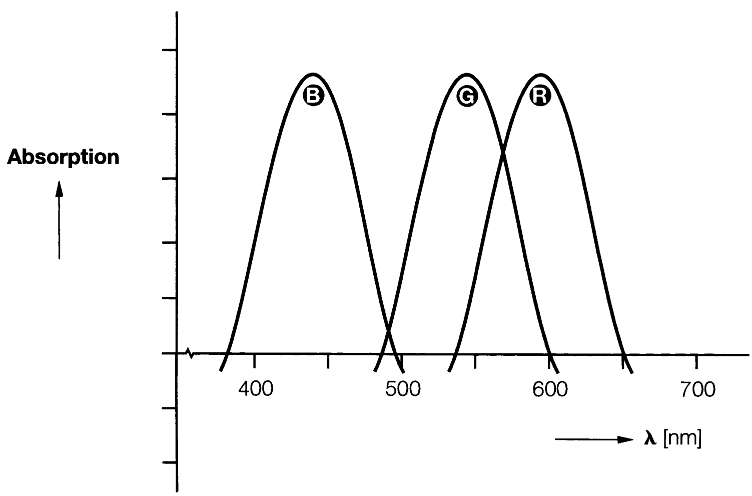

Figure 8.3.2: The absorption spectra of the three kinds of cones. After Hubel, 1990, p. 163.

Another way to find the sensitivity curves is to measure the visual response from observers with colour defective vision. Colour defective vision – often called colour blindness – is the result of a malfunction of one or more kind of cones. Such malfunctions occur in 0,3% of females and 8% of males in Caucasians (Schreuder, 1998, sec. 7.5.4; Gleitman, 1995, p. 194). It seems very likely that there is a racial component as well, apart from the obvious gender component (Walraven, 1980, p. 34). In the past, it was felt that colour deficiencies would be a risk in many tasks, e.g in road traffic (Hopkinson, 1969; Mann & Pirie, 1950). Nowadays, it has been established that such excessive risks do not occur (De Jong, 1995).

As there are three kinds of cones, and each may show different degrees of malfunction, there are many kinds of colour defective vision, each with its own name. People in which only one kind of cone function normally, are rare. The terminology is rather arbitrary. In sec. 8.3.2, it is explained that people who use only the first, the second or the third kind of cones are called the protanopes, the deuteranopes and the tritanopes respectively, irrespective of the fact that 'first','second' and 'third' are not defined. These people were used to establish the same absorption curves, but now applying psycho-physical means. The procedure was to measure the overall spectral sensitivity response from people who have only one of the three 'kinds' of cones. In Figure 8.3.3, the visual sensitivity curves for the three major types of colour defective observers are given. The curves are similar to, but not identical with those in Figure 8.3.1a, because a different procedure is used.

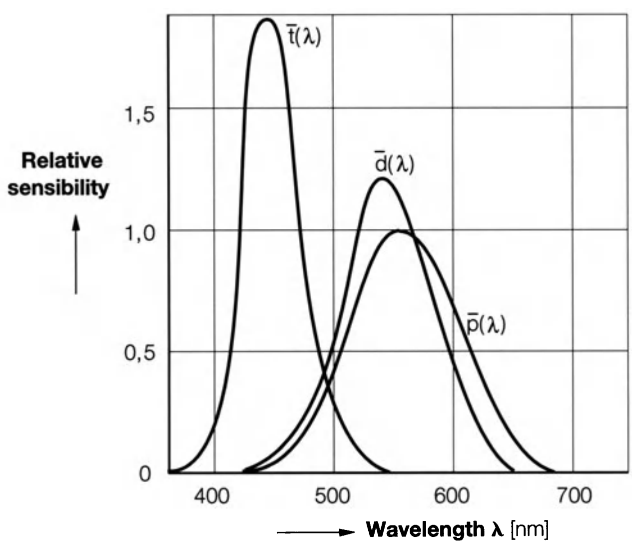

Figure 8.3.3: *The sensitivity curves for three types of colour defective vision; $\bar{p}(\lambda)$: protanopes; $d\bar{p}(\lambda)$: deuteranopes; $t\bar{p}(\lambda)$: tritanopes. After Schreuder, 1998, Figure 7.4.1. and Hentschel, 1994, fig 4.40. Based on data from König & Dieterici, 1892.*

8.3.4 The Purkinje-effect

(a) Photopic and scotopic sensitivity

In sec. 8.2.2, it is explained that it is possible to represent the total spectral sensitivity of the visual system in one curve, the V_λ-curve. The shape of the curve is determined by the absorption characteristics of the visual pigments that are operational in the cones. As is explained in sec. 8.2.3d, for scotopic vision, where the rods are operational, a corresponding spectral sensitivity curve may be defined. This curve is usually called the V'_λ-curve. The shape of the V'_λ-curve.V is essentially determined by the absorption characteristics of the visual pigments that are operational in the rods during nighttime vision. This visual pigment of the dark adapted eye is usually called the 'visual purple'. The similarity between the two is depicted in Figure 8.3.4.

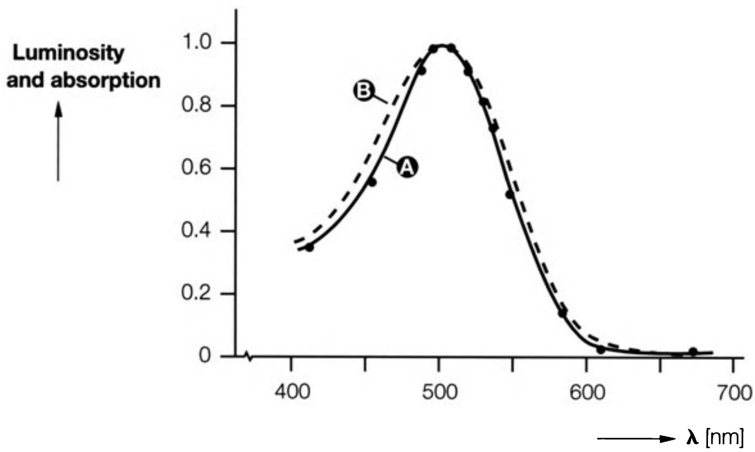

Figure 8.3.4: *The sensitivity curve of the dark-adapted eye, compared with the absorption curve of visual purple. After Feynman et al., 1977, Vol. I, fig. 35-9.*

Because the photochemical reactions in photopic vision and in scotopic vision are similar, the curves are similar in shape as well (Feynman et al., 1977, Vol. I, sec. 36.3). The curves are similar in shape to the well-known 'bell shape' curve of the normal statistical, or Gaussian, distribution, with only one maximum; the values drop off to either side. It is a matter of similarity only; neither the V_λ-curve, nor the V'_λ-curve represent stochastic variables. The difference is not in the shape itself but in the shift of the V'_λ-curve towards the shorter wavelength. The maximum of the V_λ-curve is at 555 nm and that of the V'_λ-curve at 507 nm. This is depicted in a Figure 8.3.5. It should be noted that, as has been indicated in sec. 8.2.2, the integral of the curve is a measure for the maximum efficacy of any – real or hypothetical – light source. The efficacy of light sources is explained in sec. 11.3.2; it is expressed in lumen/Watt, either in the normal, photopic units or in the less common scotopic units. As is explained in sec. 8.2.2, for photopic photometry the corresponding value is 683 lumen/Watt (Hentschel, 1994, p. 36). For the scotopic photometry, the corresponding value is 1699 (Wyszecki & Stiles, 1967).

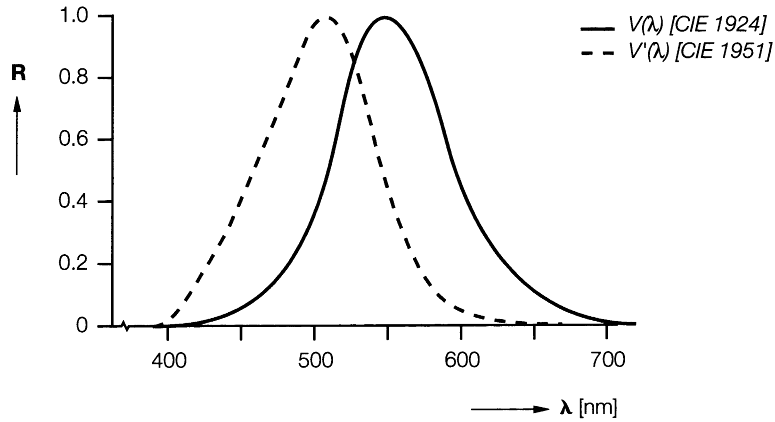

Figure 8.3.5: *The relative spectral sensitivity curves for photopic and for scotopic vision, V_λ and V'_λ respectively. After Hentschel, 1994, fig. 2.12. See also Fig. 8.2.5.*

Notes to Figure 8.3.5:
- The two sensitivity curves are independently normalised to 100% for their maximum values;
- Both curves are standardized by CIE. See for the V_λ-curve CIE, 1924; for the V'_λ-curve CIE, 1951.

(b) *The Purkinje-shift.*

As mentioned earlier, the fact that the photopic vision and the scotopic vision are different, has considerable consequences for the human visual system and for visual perception. There are four major differences:

(1) In photopic vision, the visual acuity, particularly in the foveal area, is much greater than in scotopic vision. Details are given in sec. 9.1.4;
(2) Contrary to photopic vision, colour vision in not possible in scotopic vision. Details are given in sec. 8.3.6;
(3) In photopic vision, the speed of adaptation is much higher than in scotopic vision. Details are given in sec. 9.1.3;
(4) In photopic vision, the maximum of the spectral sensitivity is found at a much longer wavelength than in scotopic vision. Details are given this section.

As is explained in sec. 8.2.3d, the shapes of the V_λ-curve and the V'_λ-curve are similar; however, the maximum of the V_λ-curve is at 555 nm and that of the V'_λ-curve is at 507 nm. The consequence is that the visual system in scotopic vision is much more sensitive to blue light, and much less sensitive to red and yellow light than in photopic vision. In other words, in scotopic vision, the visual system seems to be less effective for red and yellow light, but more effective for blue light compared to photopic vision. Thus, in scotopic vision, a blue flower looks white, and a red flower looks black. This was the original observation after which the 'Purkinje effect' was named (Moon, 1961, Appendix A). It should be noted that, because the visual observations were made in the scotopic region, no colours could be seen: flowers are either white or grey or black. The story goes that Purkinje, when looking in dim moonlight into his garden, exclaimed: "Who stole my beautiful red roses and what are those stupid white flowers doing where my beautiful blue irises ought to be?". As will be explained further on in this section, the implications are far wider than just this nice anecdote – which probably is not even true at all!

(c) Mesopic spectral sensitivity curves

As is explained in sec. 8.2.3d, there is not one single luminance value where photopic vision and scotopic vision meet. On the contrary, there is a wide zone of transition zone between them. Because it is between photopic and scotopic vision, it is usually called the zone of mesopic vision. The reason that the zone of mesopic vision does exist at all, is because the activities of neither cones nor rods is simply switched 'on' or 'off'. There are reasons to believe that the cones and the rods both operate in all luminance conditions but that their activity is not always apparent (Adrian, 1993; 1995; Schreuder, 1976; 1997). This implies that there is no sharp borderline between the zones of photopic and mesopic vision, nor between the zones of mesopic and scotopic vision. As is explained in sec. 8.2.3d, the borders of the zone of mesopic vision are somewhat arbitrary. It was suggested to use the following limits:

- For mesopic vision: upper limit 3 cd/m^2; lower limit 0,01 cd/m^2;
- For high-mesopic vision: upper limit 3 cd/m^2; lower limit 0,1 cd/m^2.

As has been indicated earlier, in the mesopic range both rods and cones are operational – or rather, where their activity is directly apparent. However, the 'mixture' of the two varies. It may be assumed that this mixture goes from 100% cones and 0% rods at the upper limit of the mesopic range (at about 3 cd/m^2) to 0% cones and 100% rods at the lower limit of the mesopic range (at about 0,01 cd/m^2). The simplest way to describe what happens between the two limits is to assume a linear relationship between these percentages and the (logarithm of the) luminance. This has been proposed by Cakir & Krochmann (1971). This simplified model is used by Schreuder (1967, 1998). In Figure 8.2.7, the graphical representation of this model is given. When needed, the model will be used, although it is too far simplified, at least according to Kokoschka (1971) and Walters & Wright (1943). The implication of this model is that, for each luminance value between the upper and the lower limit of the mesopic range, a V_λ-curve may be found. Thus, a whole 'family' of V_λ-curves does exist, and not just one mesopic V_λ-curve. A further implication is that each V_λ-curve out of the family of V_λ-curves may be constructed by a linear interpolation between the photopic V_λ-curve and the scotopic V'_λ-curve. Details are given in CIE (1986; 1989).

(d) Mesopic photometry

In sec. 8.2.2, the units of photometry are derived from the spectral sensitivity curves. Furthermore, the standard photometry is based on the photopic V_λ-curve. It would be possible to base, for each mesopic level, a whole set of photometric quantities and units, based on the V_λ-curve for that particular mesopic level. This has been proposed by Opstelten (1984). For this, a mixture-relation was used as had been proposed by Palmer (1971). The relation is:

$$L_{mes} = \frac{L'_v + nL_v^2}{1 + nL_v} \qquad [8.3.1]$$

in which:
L_{mes} = the mesopic luminance (in cd/m^2);
L_v = the photopic luminance;
L'_v = the scotopic luminance.
On the basis of experiments with 16 observers, n was about 17 (Opstelten, 1984).

As has been explained in several section of this book, all photometry is defined for photopic vision only, irrespective of the actual luminance that is present at the measurement. In this decision, all influences of the field of view are disregarded. When dealing with interior lighting, the error may be small and can, therefore, be neglected in practice. Common illuminance values in interior lighting are in the order of 300-1000 lux (De Boer & Fischer, 1981; CIE, 1975a; Anon., 2000a). The same is maybe true for certain types of outdoor lighting, such as high-class sports facilities. In sports facility lighting similar levels are no exception (CIE, 1989a; Forcolini, 1993, table 4.4). These illuminance values correspond, taking into account the reflection actors of usual materials and surfaces, with luminance well over 15 cd/m^2, so well within the photopic range.

However, in most other areas of outdoor lighting, the levels are considerably lower. In traffic route lighting, the road surface luminance is between 2 and 0,5 cd/m^2 (CEN, 2002; 2002a; CIE, 1965; 1992; 1995; 1995a; 1997; NSVV, 1990, 2002; Schreuder, 2001). They fall in the upper-most region of mesopic vision. As mentioned in sec. 8.2.3d, this region is sometimes called the 'high-mesopic region'. When one looks at other areas of outdoor lighting, such as the lighting of streets in residential areas, the luminance values are much lower. As an example, the current recommendations for the Netherlands stipulate that in footpaths in quiet, dark, residential areas with a low crime rate, the average illuminance must be at least 2 lux with a uniformity defined as $E_{h,min}/E_{h,av}$ of at least 0,3 (NSVV, 1990). $E_{h,min}$ is the minimum horizontal illuminance and Eh,av is the average horizontal illuminance. Thus, the illuminance on the footpath may be as low as 0,6 lux. With normal road surfaces this corresponds with about 0,03 cd/m^2. As has been explained in sec. 12.1.2, many crime fighting experts recommend, for reasons of public safety, to give special attention to parks and shrubs along the footpaths (Anon., 1991; 1994; Hajonides et al., 1987). As these areas are beside the actual road, the light level may easily be another factor

5 lower. So we may have to deal with luminance of about 0,01 to 0,02 cd/m^2. In sec. 12.2.2, it is explained that, when dealing with car headlighting, the luminance may be very low as well. So, in summary, it is very likely that, in quite normal outdoor lighting practice, the luminance that have to be dealt with are near the lower end of the mesopic range and not near the higher end any more at all. One should not be surprised to find large discrepancies between the measured photometric luminance and the experienced brightness.

The consequences of all this have been dealt with in considerable detail in Opstelten (1984). It should be noted that this report was never published. Some of the highlights from this report are quoted here with permission.

8.3.5 Mesopic brightness impression

The report gives a comparison of the luminous efficacy for different common light sources, expressed in photopic and scotopic lumens per Watt respectively (Opstelten, 1984). See Table 8.3.1.

Light source	**Lamp wattage**	**Efficacy** (lumens per Watt)		
		photopic	**scotopic**	**ratio**
low-pressure sodium	90	152	35	0,23
high-pressure sodium	250	109	68	0,62
high-pressure mercury	400	55	60	1,09
metal halide	400	80	115	1,44

Table 8.3.1: *Photopic and scotopic efficacy for different lamp types (Opstelten, 1984, Table 1).*

More interesting for the discussions on light pollution is what happens at different mesopic levels. Using Palmer's approximation (1971) as given in [8.3.1], some results are given in Table 8.3.2 for the lamp efficacy, expressed in apparent (mesopic) values of the lumens per Watt.

Photopic luminance (cd/m^2)		**10**	**1**	**0,5**	**10^{-1}**	**10^{-2}**	**10^{-3}**
Light source	**lamp wattage**	**apparent lamp efficacy** (lm/W)					
low-pressure sodium	90	151	145	139	108	52	37
high-pressure sodium	250	109	107	105	94	74	68
high-pressure mercury	400	55	55	56	57	59	60
metal halide	400	80	82	84	93	110	115

Table 8.3.2: *Lamp efficacy in apparent lumens per Watt (After Opstelten, 1984, table 2).*

In Table 8.3.3, the same results are given, but now for the photopic efficacy as 100%.

Photopic luminance (cd/m^2)		**10**	**1**	**0,5**	**10^{-1}**	**10^{-2}**	**10^{-3}**
Light source	**lamp wattage**	**apparent lamp efficacy** (% photopic lm/W)					
low-pressure sodium	90	100	96	95	75	34	24
high-pressure sodium	250	100	98	96	86	68	62
high-pressure mercury	400	100	100	102	104	107	109
metal halide	400	100	103	105	116	138	144

Table 8.3.3: *Lamp efficacy in % of the photopic efficacy (After Opstelten, 1984, table 2).*

As regards light pollution, there are two things to consider:

(1) The cost assessment of road lighting for different light sources has to be reconsidered. As is explained in sec. 1.2.6d, it is often claimed that low-pressure sodium lighting is by far the most economic alternative. The comparisons are complicated by the different ways in which manufacturers publish life expectancies of lamps (if they publish them at all!) and by the fact that power costs (kWh-costs), a major cost factor for road lighting, differ greatly from one country or one region to another. In road lighting, the resulting adaptation luminance must be taken into account. As is explained in sec. 11.2.7, for traffic lighting one may use the road luminance as an approximation of the adaptation luminance. As we have seen above, the light levels that are common on traffic routes are about 0,5 cd/m^2 or more. For such levels, the difference between lamp types is not very large – although the amount is about 10% for 0,5 cd/m^2. For residential street lighting, where luminance of about 0,01 to 0,02 cd/m^2 are common, the differences are quite large. In extreme cases, a metal halide lamp may be more than four times as 'efficient' as a low-pressure sodium lamp, as can be seen from Table 8.3.3. And even a more common high-pressure sodium lamp is still twice as 'efficient'. In this respect, the alleged advantages of low-pressure sodium lamps dwindle to nothing, particularly in low ambient light levels such as those that are likely to be found near astronomical observatories. The matter that the monochromatic light may be easier to filter out, of course, remains.

(2) When we consider sky glow, a completely different picture may arise. As has been explained in sec. 3.1, it is customary to use the value of $3{,}52 \cdot 10^{-4}$ cd/m^2 as the practical minimum of the natural background radiation (CIE, 1997). When the sky glow is three times brighter than the natural background luminance – amounting to about 10^{-3} cd/m^2 – the relative brightness of low-pressure sodium light is dramatically less than that of other light sources. Even when the sky glow is 30 times as bright as the natural background – about 10^{-3} cd/m^2 – the differences are still very large (See Table 8.3.4):

Photopic luminance (cd/m^2)		10^{-2}		10^{-3}	
Light source	**lamp wattage**	**abs**	**rel (%)**	**abs**	**rel (%)**
low-pressure sodium	90	34	100	24	100
high-pressure sodium	250	68	200	62	258
high-pressure mercury	400	107	316	109	454
metal halide	400	138	406	144	600

Table 8.3.4: *The relative brightness of sky glow for different light sources. Based on data from Opstelten, 1984, table 2.*

8.3.6 Colorimetry

(a) Additive and subtractive processes

As is explained in sec. 8.3.1, colours are important in daily life. As far as the colour impression goes, it is not important whether the light is coming from a 'coloured' light source directly, or that is it reflected by a 'coloured' surface. For the metrics of the colour space, and consequently for colorimetry, it is essential.

All colour considerations are based on the fact that by mixing colours, other colours emerge (Illingworth, ed., 1991, p. 74). Mixing coloured light sources is an additive process. Almost any colour can be produced or reproduced by mixing together lights of three colours, called the 'additive primary colours' (Illingworth, ed., 1991, p. 7). The most important characteristic of the additive colour mixing rules is that the three primary colours, when mixed in the right proportions, produce white light. As will be explained later-on, usually red, green and blue are chosen as the additive primary colours. They form the basis of the CIE system of colorimetry. Mixing the colours of filters or pigments, however, follow completely different rules. With this process, again almost any colour can be produced or reproduced by mixing together the light of the three primary colours, being either filters or pigments. This process is called the subtractive process (Illingworth, ed., 1991, p. 466). It is characterised by the fact that the three primary colours, when mixed in the right proportions, produce black. As will be explained later on, usually yellow, magenta (purplish) and cyan (greenish blue) are chosen as the primary colours. They form the basis of the Munsell-system of colour representation. As an example, colour television and digital photo cameras make use of an additive colour process, whereas traditional – chemical – colour photography makes use of a subtractive process. The Munsell-system is explained in sec. 8.3.7h.

The CIE system of colorimetry, that is relevant for the assessment of the colour light sources, is based on the fact that the human visual system includes three 'kinds' of cones. In sec. 8.3.3, a figure is given that depicts the spectral sensitivity response of the three 'kinds' of cones (see Figure 8.2.7). The visual sensitivity curves of three major types of colour defective observers are given. As is explained in sec. 8.3.2, the three kinds of cones are responsible for two things: they determine, in combination, the spectral sensitivity of the visual system in daytime or photopic vision, and they allow the detection of colours. This does not mean, however, that the eye follows, in observing colours, laws of additive colorimetry. As is explained in sec. 8.3.3, the actual photochemical and neuronal processes are rather different. It only means that colours may be described in this way.

(b) The CIE system of colorimetry

The CIE system of colorimetry is rather complicated. Details can be found in the standard works of Bouma (1946, 1971); Judd & Wyszecki (1967); Richter (1976); Wright (1964) and Wyszecki & Stiles (1967). A summary description is given by De Boer & Fischer (1981, sec. 4.1). We will follow this summary description. See also Baer (1990, sec. 1.2.3).

As mentioned earlier, the CIE system of colorimetry is based on the fact that they eye consists of three 'kinds' of cones. It is therefore only natural to base proposals for a colorimetry system on three primary colours. Each colour may be regarded, in the mathematical sense of the word, as a variable. It is often possible to perform a transformation of these variables in such a way that two variables represent the actual colour, whereas the third one represents the brightness. As is explained in sec. 8.3.7h, these three variables represent in the Munsell system the hue, the chroma and the value. When the value, or brightness, or lightness, is disregarded as not being a 'real' colour characteristic, only two variables are left over. This implies that colours can be graphically described in a two-dimensional diagram. Because most diagrams have roughly a triangular shape, they are often called 'colour triangles' with a primary colour at each corner. Over the years, many proposals for such triangles were made (Bouma, 1946). However, it was found that, when 'real world' colours were used, problems did arise. It turned out that some of the spectral colours, often the most saturated colours, did lay outside the triangles. "There were many colour points that could be described only by subtracting one primary colour from the addition of the other two" (De Boer & Fischer (1981, p. 92). Although there seems to be no mathematical objection to this procedure, the physical implications are unacceptable: it would mean that there should be in nature 'negative light', or something 'blacker than black' This is, of course, an obvious physical impossibility – at least in classical physics.

(c) The 1931 CIE Standard Chromaticity Diagram

The CIE solved the problem by adopting a triangle that encompasses the curve that describes the spectral colours (CIE, 1932). The implication is that the colours at the corners of the triangle do not represent not real but hypothetical colours or 'stimuli' (De

Boer & Fischer, 1981, p. 93). Conventionally, they are lettered X, Y and Z. The variables X, Y and Z are called the tristimulus values. As they are colours, real or hypothetical, they can be characterised by normalized spectral values, or spectral tristimulus values. The procedure is given in De Boer & Fischer (1981, p. 92-93). The spectral tristimulus values are tabulated in CIE (1986). The tables are also given in Baer (1990, table 1.11). A graphical representation is given in Figure 8.3.6.

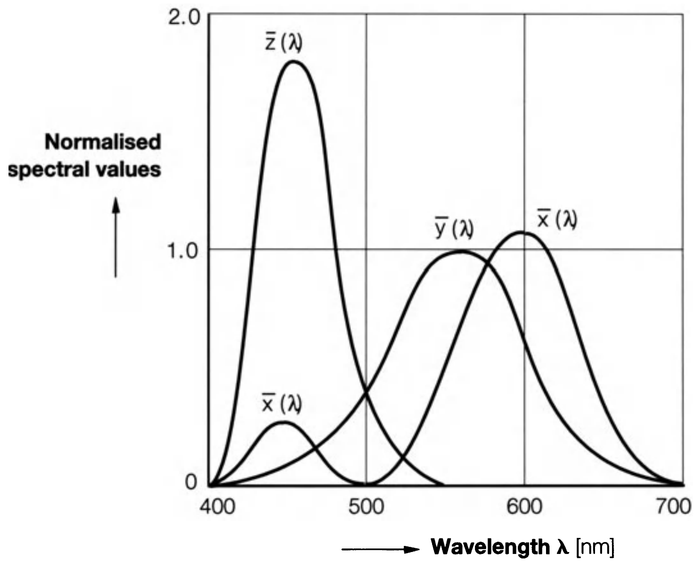

Figure 8.3.6: The standard curves for the CIE system of colorimetry, after Schreuder 1998, figure 7.4.2, based on Hentschel, 1994, fig 4.42.

The tristimulus values X, Y and Z are transformed into the chromaticity coordinates x, y and z by using the following transformation formulae:

$$x = \frac{X}{X+Y+Z}; \; y = \frac{Y}{X+Y+Z}; \; z = \frac{Z}{X+Y+Z} \qquad [8.3.2]$$

Because, as is explained earlier, z represents the luminance, it is sufficient to use x and y. As is explained earlier in this section, in this way the colours can be depicted in a colour triangle. By using the x- and y-coordinates as indicated here, the '1931 CIE Standard Chromaticity Diagram is defined (CIE, 1932; De Boer & Fischer (1981, p. 93-94). The system is usually called the CIE colour triangle. A graphical representation of the 1931 CIE colour triangle is given in Figure 8.3.7.

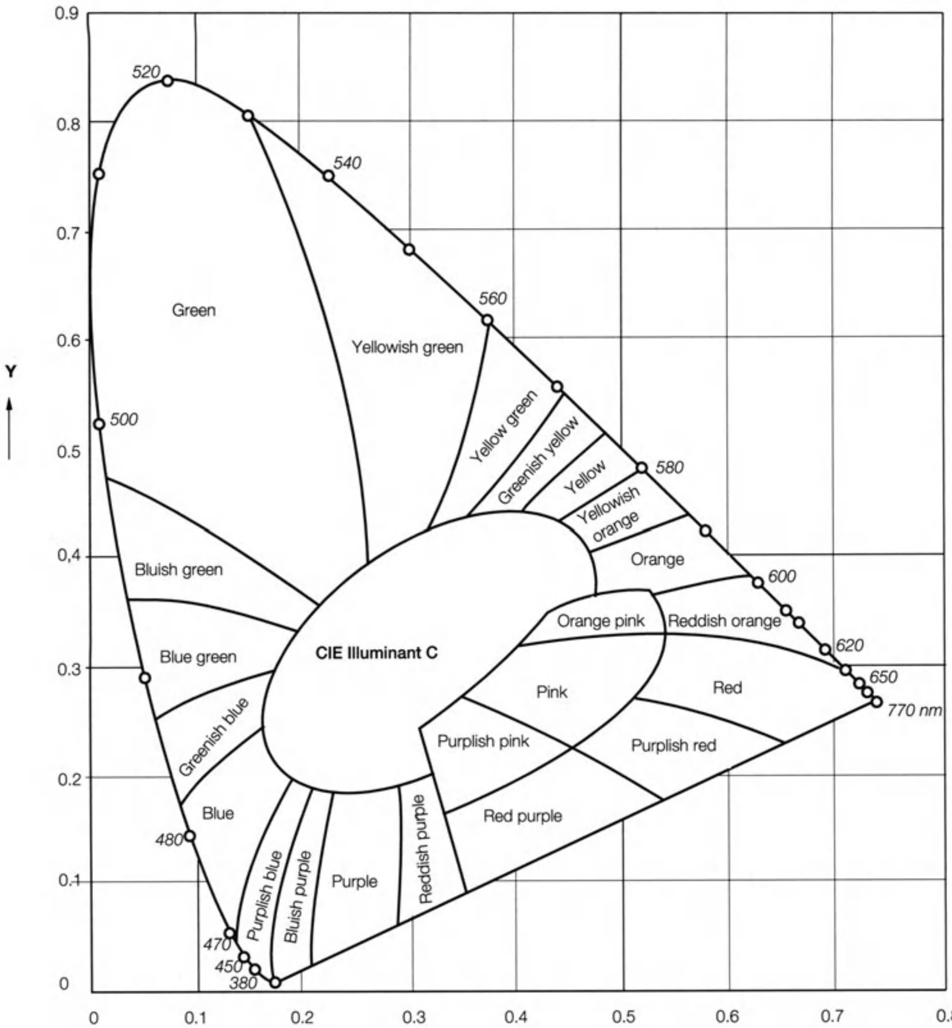

Figure 8.3.7: *The 1931 CIE Standard Chromaticity Diagram. The standardized colour names are included. After Schreuder, 1998, Figure 7.4.4. Based on De Boer & Rutten, 1974, fig. 3-21 and Baer, 1990, fig. 1.37.*

(d) *Colour names.*

Basically, each colour has its own name. Of course, there are many more shades of colour than there are suitable names. It is not completely certain how many shades of colour can be distinguished, but there are many. The ICI Company did develop an atlas with 27 850 different colours to be used in the textile industry (Walraven, 1981, p. 134). The Guiness Book of Records suggests that there are much more than 100 000 different colours. It might be pointed out here that, in computer terminology, the 'number of colours' is used in a different way. A system of colour names has been introduced by CIE with enough names – 23 different names in all – to suit most practical uses. The names and the corresponding areas they occupy in the CIE Colour plane are included in Figure 8.3.7. The names have a distinct 'business-like' slant. There is still plenty of room for poets, painters, and lovers to invent their own colour names! Still, the resolution of the visual system is limited; small changes in colour may be noticeable, but they do not always deserve a new name.

One important thing must be pointed out right away. In principle, the validity of the CIE-procedure is the same for all light, independent of where it comes from. It is obvious, however, that the CIE method is set up with light sources clearly in mind. This is immediately clear from the way the colour triangle is depicted. e.g. in Figure 8.3.6. It is based on the rules of the additive colour mixing: Red plus Green plus Blue gives White! This is clear form the colour triangle itself. Although the central are of the triangle as depicted in Figure 8.3.7 is termed 'CIE Illuminant C', what it means is that this is the area of 'whitish' colours. In sec. 8.3.7, the concept of the colour point is discussed in detail. There it is indicated that the CIE Illuminant C is defined very precisely. It is defined in the past to represent tungsten-filament incandescent lamps in the time that there were no other light sources that could be used in practice. It has therefore a precisely defined colour point. The same holds for the 'white point', which is defined as $x = y = 0{,}333$ (Hentschel, 1994, p. 107).

Thus, the CIE System is aimed clearly at the representation of light sources. These considerations indicate a further important fact about the CIE System: it is aimed at the representation of light sources for general lighting purposes. As is discussed in sec. 8.3.8, this implies that the colour rendering index has to have a high value. This in turn implies that the light sources under consideration are 'whitish' in colour; their colour points need to be close to the white point or at least close to the locus of the colour points of all blackbody radiators. This is explained in sec. 8.3.7b, where the colour temperature is discussed.

When one has to deal with other applications, like e.g. coloured signalling lights, the colour triangle will have to be used in quite another way. This is explained in sec. 8.3.8a. When one has to deal with surface colours, the CIE system is not adequate. For surface colours and for the pigments that determine them, the Munsell-system is more readily applicable. The Munsell-system is explained in sec. 8.3.7h.

Earlier in this section, the CIE Illuminant C has been mentioned. This is one of the light sources – or spectral distributions – that have been standardized by CIE for the purpose of colour assessments. In Table 8.3.5, the CIE standard illuminants are listed. The standard illuminants are characterized by their colour temperature, which is explained in sec. 8.3.7b.

Illuminant	Colour temperature (K)	Representing
A	2856	incandescent lamp
B	4874	direct sunlight
C	6774	average daylight
D65	6500	mid-day daylight
E	infinite	white; equal-energy spectrum

Table 8.3.5: *The CIE standard illuminants (Baer, 1990, p. 39, table 1.13; Hentschel, 1994, p. 107; De Boer & Fischer, 1981, p. 101).*

8.3.7 Colour points, colour temperature

(a) *Colour points*

Any colour can be produced by mixing, in the right proportion, three colours from the colour triangle. By using the x- and y-coordinates of the 1931 CIE colour plane, where z is assumed to be the luminance, this particular colour corresponds to one particular point in the colour plane. This point is called the colour point of that particular colour. One of the most striking characteristics of the CIE system is that the spectral colours all lie on a curved contour. Red is at the bottom right extreme point, blue at the bottom left point. If these two extreme points are connected by a straight line, it is found that all varieties of purple lie on this line. The resulting figure looks more or less like a triangle, be it with a blunted tip – hence the name of colour triangle. The triangular shape can easily be recognized in Figure 8.3.7.

As said earlier, each colour can be represented by one particular colour point. In Figure 8.3.8, the colour triangle is depicted again.

Notes to Figure 8.3.8:

(1) The locus of the colour points of all blackbody radiators is included as a curve more or less through the centre of the triangle. The corresponding temperatures (in K) are added to the curve;

(2) The point corresponding with 'white' is inserted in the figure as letter E. The conditions for white are: $x = y = 0{,}333$ (Hentschel, 1994, p. 107);

(3) For a number of specific light sources, the colour points are included as well:
- A: CIE Standard for daylight;
- C: CIE Standard for tungsten filament incandescent lamps;
- 2: fluorescent tube colour 'daylight';
- 3: fluorescent tube colour 'white';
- 4: fluorescent tube colour 'warm-white';
- 5: clear high-pressure mercury lamp;
- 6 and 7: two types of fluorescent high-pressure mercury lamps;
- 8 and 9: two types of high-pressure xenon lamps;
- 10: low-pressure sodium lamp;
- 11: high-pressure sodium lamp.

(After Hentschel, 1994, Figure 4.43).

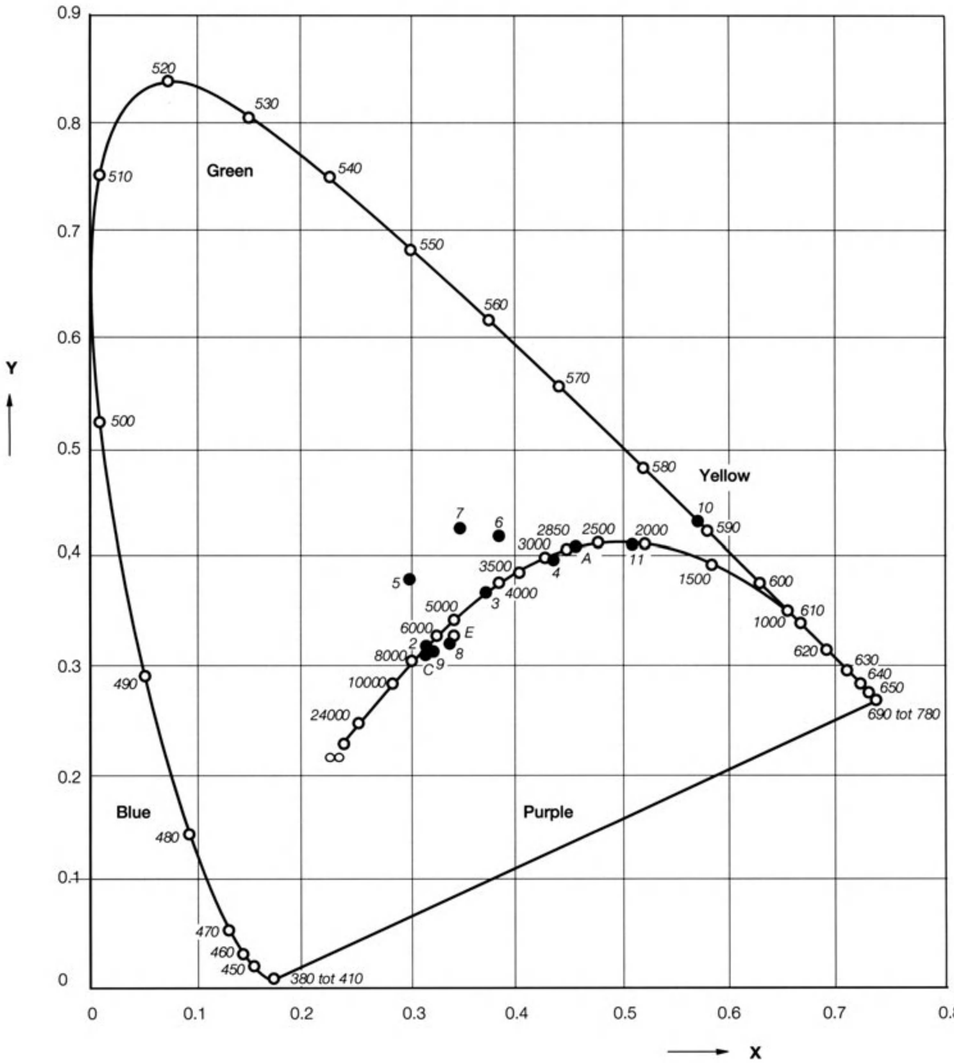

Figure 8.3.8: The 1931 CIE standard triangle. After Schreuder, 1998, Figure 7.4.3. Based on Hentschel, 1994, fig. 4.43.

The different light sources mentioned here are discussed in more detail in sec. 11.3.

(b) The definition of the colour temperature

The colour temperature is a term used to describe the colour appearance of a light source by comparing its colour to the colour of a blackbody radiator or Planckian radiator (De Boer & Fisher, 1981, p. 95). As is explained in sec. 11.1.1c, the radiation of a blackbody radiator is fully determined by its temperature, both as regards the wavelengths where the radiation is at its maximum (Wien's law) and as regards the distribution of the radiation over different wavelengths (Raleigh-Jeans' law; Breuer, 1994, p. 180). It is therefore possible to determine one specific colour point for each temperature of the blackbody radiator, independent of the nature of this radiator. When the points are connected, the result is the locus of the colour points of all blackbody radiators. This locus is included in Figure 8.3.8.

(c) Incandescent light sources

As is mentioned in sec. 11.1.1, the blackbody radiator locus is important in two ways. The first is that it is linked to incandescent lamp lighting. It is often assumed that electric incandescent lamps are the only true incandescent lamps. In an electric incandescent lamp, the actual light source is a tungsten filament that is made to glow by passing an electric current through it. We will come back to the electric incandescent lamps further-on in this section. Before the tungsten filament electric incandescent lamps were used, other incandescent lamps common. Flames of wood fire, of candles and of kerosine lamps are all incandescent light sources, where the light emitting elements are tiny carbon particles made to glow by the heat of the flames (Schreuder, 2001a). Electric arc lamps work in exactly the same way: the tiny carbon particles made to glow by passing a current through the plasma. Gas lamps have an incandescent mantle that is made to glow by the heat of the gas flame (Hütte, 1919, Volume II, p. 814; 816-818).

Before the tungsten filament electric incandescent lamps were applied on a large scale, the other lamp types prevailed. Before the 1880s, the most-used light sources were candles and wooden chips and torches – much the same as at present in many developing countries. Some photometric characteristics of those light sources are given in Table 8.3.6. For comparison, some more modern lamp types are included in the table. See also Table 8.3.7.

Lamp family	Type	Watt	cd	Lumen	lumen/Watt
candle	wax	55	0,1	1	0,02
candle	stearin	80	1	10	0,125
kerosine	0,02 l/h	200		10	0,05
kerosine	0,05 l/h	488		100	0,21
incandescent	signal	3		30	10
incandescent	GLS	60		730	12
fluorescent	PLE*	11		600	
LED white		50°		0,07	1,5
LED yellow		30°		0,04	6,3

Table 8.3.6: *Light source characteristics. After Schreuder, 2001a. *) ballast included. Wax candle data and kerosine lamp data from Mills (1999). Stearin candle data from Vermeulen (2000). Incandescent and fluorescent lamp data from Philips Eindhoven (Anon., 1997). Yellow LED data from Hewlett Packard Company (NY), white LED data from Nichia Company (NY).*

From the 1880s to the 1920s, the main light sources in operation were gas lights with incandescent mantles, both for indoor as for outdoor lighting (Hütte, 1919, Volume II, p. 814; 816-818). Also, for large outdoor installations, carbon arc lamps were used (Hütte, 1919, Volume II, p. 821-828). Some photometric characteristics of those light sources are given in Table 8.3.7.

Lamp family	Type	Watt/lumen	eff. lumen/W
gaslamp	low pressure	0,25-0,45	6,8-12,6
gaslamp	high pressure	0,15-0,25	12,6-20,9
tungsten lamp	clear glass	0,25-0,4	7,8-12,6
open arc lamp	direct current	0,05-0,12	see text
open arc lamp	alternating current	0,07-0,15	see text

Table 8.3.7: *Light source characteristics. After Hütte, 1919, Volume II, p. 831, table 3.*

In Table 8.3.7, the efficacy of the lamps is expressed in the number of Watts required for 1 lux on an area of 1 m^2. If the area is assumed to be 1 m^2 from a distance of 1 m, the efficacy can be expressed approximatively in the more common measure of lumen/Watt by using the reciprocal values given in the table, multiplied by 2π. These values are included in Table 8.3.6. As carbon arc lamps were used to illuminate large areas, the assumptions used here do not apply. The corresponding lumen/Watt-values are therefore omitted from the table. The efficacy of carbon arc lamps is about 16 to 18 lm/W, depending on the construction and the use of the lamp (Barrows, 1938, p. 80-82).

From the 1910s to the 1940s, the main lamp for almost all lighting applications was the tungsten filament electric incandescent lamp. The historical evolution of the different filament electric incandescent lamps is described in detail in Barrows (1938, p. 63-80). Although since 1930, gas discharge lamps and more recently also quantum lamps like lasers and LEDs are used on a large scale, still the tungsten filament electric incandescent lamp is by far the most common lamp type, in spite of its lower efficacy. In sec. 11.3.3, some reasons for this preference are mentioned. In a further part of this section, a more detailed comparison between the characteristics of these diverse lamp types is made.

A completely different class of blackbody radiators is formed by the most common light source of all: the Sun. The Sun is, of course, not exactly a blackbody radiator but as is depicted in Figure 8.3.9, the deviations are not large (Budding, 1993. p. 36).

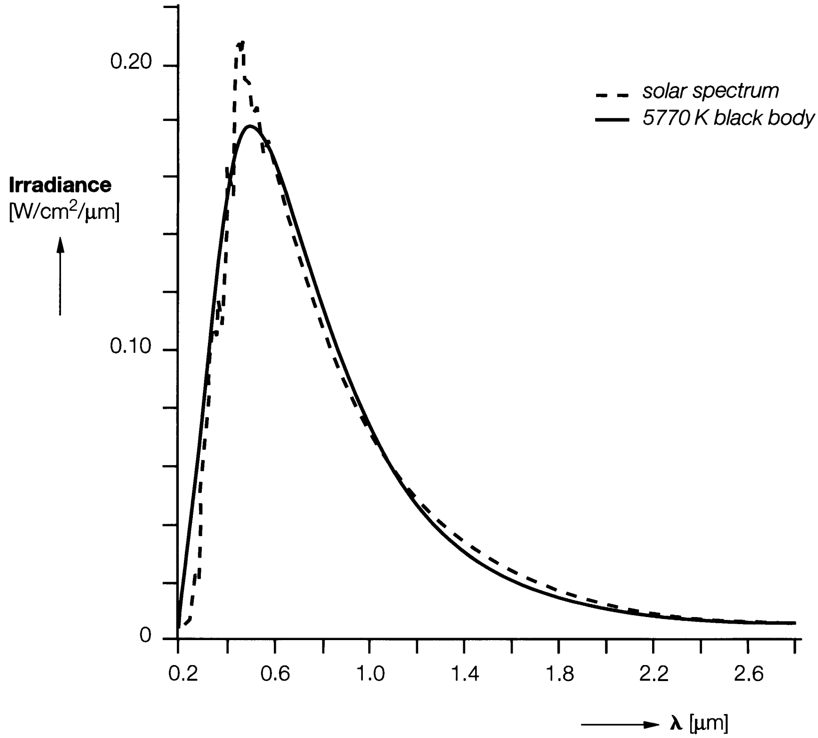

Figure 8.3.9: *The solar spectrum (dashed) and the spectrum of a 5770 K blackbody (full). After Budding, 1993, fig. 3.3.*

It is generally accepted that the Sun is a quite 'ordinary' star. The main reason is that it is lying in the main sequence of the Hertzsprung-Russell-diagram (Herrmann, 1993, p. 152). It is found that by far the most stars are on this main sequence (Lafferty & Rowe, eds., 1997, p. 288; Weigert & Wendker, 1989, p. 97). Because almost all celestial bodies show a continuous, star-like spectrum, they all may be regarded as blackbody radiators.

(d) The locus of the blackbody radiators

The locus of the blackbody radiators is included in Figure 8.3.8 as a curve that runs more or less through the centre of the triangle. The corresponding temperatures (in K) are added to the curve. The temperatures in the graph run from 1000 K to well over 24 000 K. It should be noted that the sign for 'infinity' is added. This is of course not a physical temperature. According to the kinetic theory of gasses, the mean kinetic energy of molecules in an ideal gas is:

$$E = \frac{3}{2} K \cdot T \qquad [8.3.3]$$

See Feynman et al. (1977, Volume I, p. 39-10). A physical temperature of infinite height would mean an infinite kinetic energy – clearly an impossibility. The sign for 'infinity' is just a symbol. It is supposed to indicate the colour point of the ideally blue sky. This follows from the way the light is scattered by small particles. According to Rayleigh's Law, for particles smaller than 0,1 of the wavelength, the scatter of the light can be determined from:

$$s = K \cdot \frac{(n-1)^2}{N \cdot \lambda^4} \qquad [8.3.4]$$

in which:
s: the scattering per unit of volume;
K: a constant;
n: the refraction index of the particles;
N: the number of particles per cm^3;
λ: the wavelength of the light.

This way to denote Rayleigh's Law is from Minnaert (1942, Vol. I, p. 240). See also Schreuder (1998, sec. 4.4., p. 30-31); Van de Hulst (1981); Douglas & Booker (1977).

(e) The characteristics of filament materials

As we indicated earlier, the graphical representation in Figure 8.3.8 includes the locus of the blackbody radiators for temperatures from 1000 K to well over 24 000 K. The temperature range over which incandescent light sources can be used in practice is, however, considerably narrower. When the temperature is below some 2000 K, the light output is so low as to be of little practical use. The metal with the highest melting point is tungsten. Tungsten melts at 3653 K (Schreuder, 1998, p. 27). The working temperature of filaments depend very much on a variety of conditions (De Boer & Fischer, 1981, p. 144-149; Stevens, 1969, p. 59-64). Lamps are seldom run at higher filament temperatures than about 3000 K. It therefore sufficient to restrict the locus of the blackbody radiators to those temperatures. This is depicted in Figure 8.3.10. This figure shows a part of the CIE Chromaticity Diagram with the blackbody locus between 2500 K and 8000 K. It also depicts the lines that represent those colour points that are similar to the corresponding blackbody colour points. These lines are called lines of constant correlated colours (De Boer & Fischer, 1981, p. 96). We will come back to the lines of constant correlated colours in another part of this section, when the characteristics and the application of near-white light sources is discussed.

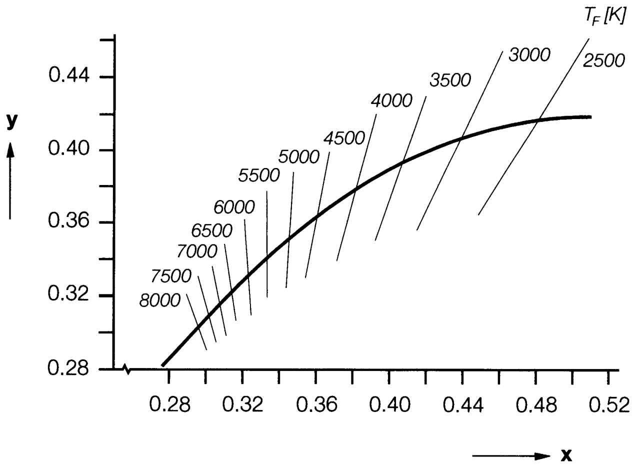

Figure 8.3.10: *Lines of constant correlated colours. After Baer, 1990, fig. 1.38.*

It must be noted that metals are not black-bodies. This is due to the quantum effects that take place when a metal is heated. Metals are selective radiators (Moon, 1961, p. 124). In Table 8.3.8, the deviation from the blackbody radiation is given for several metals, some of which have been used in the past for incandescent filaments.

Metal	**T** (K)	**Deficit ratio wavelength** (nm) 665	463
tantalium	2400	0,404	0,450
platinum	1800	0,310	0,386
nickel	1400	0,375	0,450
gold	1275	0,140	0,632
molybdenium	2400	0,341	0,371

Table 8.3.8: *The deviation from the blackbody radiation. After Moon, 1961, table XVII, based on data from Worthing, 1926.*

Tungsten is also a selective radiator. In Figure 8.3.11, the discrepancy between the radiation of Tungsten and the blackbody radiation is depicted.

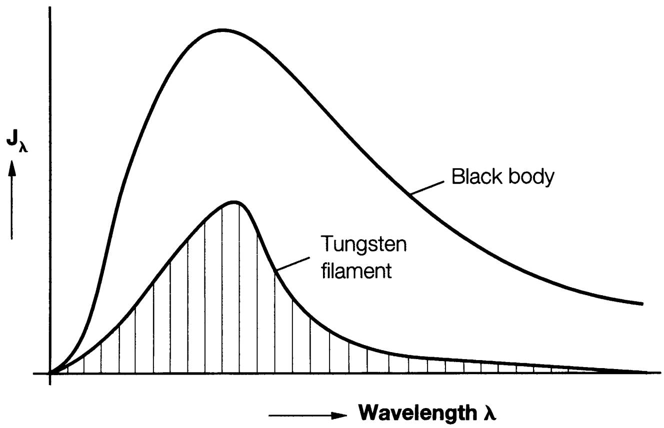

Figure 8.3.11: *The difference between the radiation of Tungsten and of the blackbody. After Schreuder, 1998, Figure 4.2.4. Based on Moon, 1961, fig. 5.10.*

Because Tungsten is a selective radiator, the colour temperature changes with the metal temperature. In Table 8.3.9, the metal temperature and the corresponding colour temperature are given.

Metal temperature (K)	Colour temperature (K)
2000	2031,5
2200	2241,3
2400	2452,7
2600	2665,8
2800	2830,6
3000	3097,0
3200	3315,0
3400	3534,7

Table 8.3.9: *The metal temperature and the corresponding colour temperature for Tungsten. After Baer, 1990, table 1.12.*

(f) *Near-white light sources*

The blackbody radiator locus is important in two ways. The first was that it is linked to incandescent lamp lighting, which were for a long time the only useful light sources. The second is that it is linked to general illuminating engineering. Moon has expressed the goal of illuminating engineering in an almost poetical way: "In the remote past when human beings spend most of their waking moments out of doors, their lighting was provided on a satisfactory and lavish scale by nature. Civilized man, however, spends most of his time in buildings lighted either through windows or by artificial illumination." (Moon, 1961, p. 2-3). Implicitly but not explicitly, ideal lighting conditions are assumed to be identical to natural daylight. See also sec. 4.5.3. When introducing the concept of the colour rendering of light sources, De Boer and Fischer remark: "We compare the source with a familiar reference source. The best known and most widely used reference source is mid-day daylight." (De Boer & Fischer, 1981, p. 101). This makes it clear that providing 'natural' lighting conditions is considered the first priority; in this respect, natural lighting is almost identical with natural colour. Hence the drive to ever better lamps with ever better colour rendering characteristics.

As mentioned earlier, the mid-day daylight is considered as the most 'natural' light (De Boer & Fischer, 1981, p. 101). In the CIE-system of standard light sources, illuminant D65 is introduced to represent the mid-day daylight with an equivalent colour temperature of 6500 K (Hentschel, 1994, p. 103). In Figure 8.3.7, the whole central area of the colour triangle is termed 'CIE Illuminant C'. As is explained in sec. 8.3.6d, this only means the area of 'whitish' colours.

The appearance of light seems to depend on several things:

(1) The adaptation level. In sec. 8.2.3, the influence of the light level (adaptation luminance level) on a large number of characteristics of the visual perception is discussed;
(2) The colour of the light, expressed by the colour point. This is the major influence on the impression; this is the ground for the preference of 'whitish' light in almost all fields of lighting application;
(3) The colour temperature. The overall impression of the visual surroundings in a room or a street is determined to a large degree by the colour temperature; hence the terminology of 'cool' and 'warm' light, as well as a 'cool' and a 'warm' room. However, the way the colours of objects are experienced does not depend much on the colour temperature, probably because variations in the spectral composition of the light are largely compensated by the chromatic adaptation of the visual system;
(4) The colour rendering. This is discussed in detail in sec. 8.3.8.

In summary, users of rooms prefer light that looks like mid-day daylight. A difference in light level is readily accepted as long as the levels stay within the area of photopic vision and as long as Weber's Law still holds (Sec. 9.1.1). Also, deviations in the colour temperature are readily accepted; these are quite common in nature as well. Deviations in the colour of the light and deviations in the colour rendering of the light sources are, however, not easily tolerated. As has been explained earlier, this is the reason for the preference of the whitish light.

Now we come back to the lines of constant correlated colours that are depicted in Figure 8.3.9. Each line in this figure indicates the colour pints of light sources that are equally 'whitish'. As the line intersect the blackbody locus, it is possible to give a value of the colour temperature to each line. This value of the colour temperature belongs to the colour point of the intersection between the line of constant correlated colours and the blackbody locus. This colour temperature can be allotted to each point of the line of constant correlated colours. In this way the equivalent colour temperature can be defined for each light source, independent of the spectral composition of its light, as long as its colour point is close to he blackbody locus – as long as it is 'whitish'. In the characteristics of different light sources that are described in sec. 11.3, the equivalent colour temperature is included.

(g) Colour differences

In sec. 8.3.6d, it is explained that it is possible to discern a very large number of different shades of colours. Although small changes in colour may be noticeable, they do not always deserve a new name. The name-giving procedures may be 'grainy'. Studies by MacAdam indicated how large the areas in the chromaticity diagram are that contain colours that are 'almost' the same. As these areas usually have a more or less elliptic shape, they are called 'MacAdam ellipses' (Schreuder, 1998, p. 118). The orientation and the size of the ellipses are determined by Stiles (1946). The MacAdam representation has a disadvantage that the areas are not equally large. By means of an appropriate transformation of the coordinates, the ellipses can be made into circles with almost the same size. In 1960, CIE introduced the 'Uniform Chromaticity Scale Diagram' (the UCS-diagram). This diagram is depicted in Figure 8.3.12.

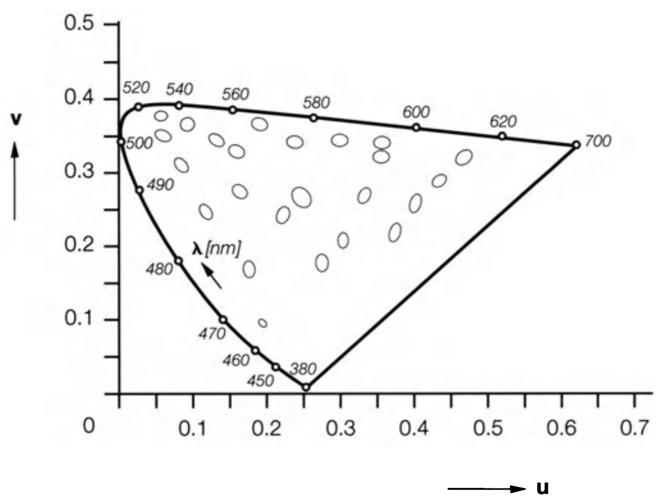

Figure 8.3.12: *The CIE Uniform Chromaticity Scale Diagram. After De Boer & Fischer, 1981, Figure 4.4.*

(h) The Munsell system

The Munsell system is used in illuminating engineering to specify object colours under daylight conditions. Because the Munsell system is related to surface colours and thus to pigments, it is based on a subtractive colour mixing processes. The three dimensions are called hue, value and chroma. The hue scale contains five Principal Hues: Red (R), Yellow

(Y), Green (G), Blue (B) and Purple (P) as well as five Intermediate Hues: YR, GY, BG, PB, and RP. Finally, each of the ten hues is subdivided in ten gradations, numbered from 1 to 10. Value, which is the lightness of the hue, is indicated on a grey scale ranging from 0 (black) to 10 (white). Finally, chroma, the saturation of the hue, or, in other words, its freedom of dilution with white, is indicated by a number of steps from the totally unsaturated condition. This description of the Munsell system is based on De Boer & Fischer (1981, p. 90-91)

The colours are not measured. In order to find out the Munsell value of a particular surface colour, it is compared to the collection of coloured chips that constitute the 'Munsell Book of Colour'. The Munsell colour system is arranged in such a way that neighboring colour samples have the same distance as regards their perception (Boogaard, 1990, p. 6). Having three dimensions, it is not possible to make a two-dimensional representation of the Munsell system that might be printed on a page. The most common representation is by a three dimensional shape. The shape is called the Munsell colour space. Due to the different characteristics of the different hues, the shape is not symmetric. The central axis is the axis of totally unsaturated colours – the lightness scale – ranging from black (0, at the bottom) to white (10, at the top). This axis looks like the stem of a tree. The branches are the hues, one hundred in number for each step of lightness. Along the length of the branches, the chroma increases from zero at the stem to its maximum at the end of the branch. The asymmetry is due to the fact that not all hues have the same maximum value of chroma. Colours 'outside' the shape do not exist. In Figure 8.3.13, the Munsell colour space is depicted in a perspective sketch.

8.3.8 The colour characteristics of light sources

(a) *The colour impression*

Coloured surfaces reflect incident light, but not to the same extent for different wavelengths of the light. Although the colour impression of a surface which does not emit light itself, is created by the colour impression of the light that is reflected by the surface, is it customary to speak of the colour impression of the surface. This impression depends on:

(1) The spectral distribution of the incident light;
(2) The spectral distribution of the reflection;
(3) The chromatic adaptation of the visual system.

It is generally accepted that the colour impression of a surface can be considered is being 'normal' when the surface is illuminated by mid-day daylight.

If a light source is to fulfill the primary requirement of illuminating engineering, which means that all objects look like they do in mid-day daylight, the spectral distribution of the light emitted by the light source must be identical, or at least very similar, to that of the mid-day daylight. It should be kept in mind that the colour appearance of the light source – its colour point in the Standard Chromaticity Diagram – is not sufficient to

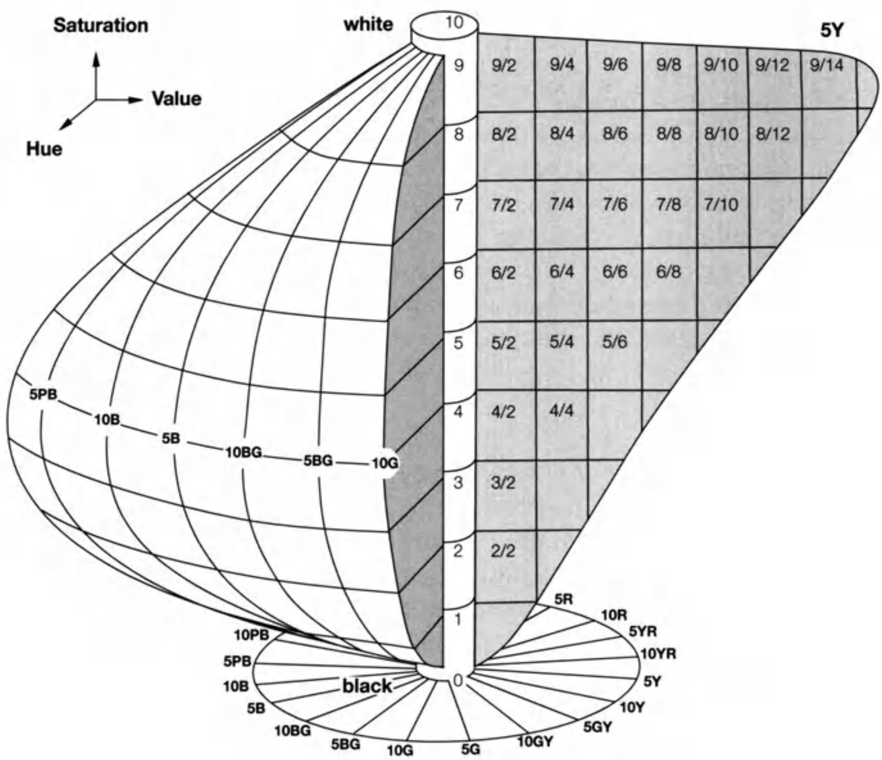

Figure 8.3.13. The Munsell colour space. After Boogaard, 1990, Figure 4 based on data from Nickerson, 1961).

guarantee this. It is well-established from practice that light sources of similar colour appearance can cause a completely different colour impression on one and the same surface (De Boer & Fischer, 1981, p. 101). A well-known example of this is the confusion that easily may arise when, in road lighting, low-pressure sodium lamps are seen at the same time as the yellow lamps of road traffic signalling systems. In fact, this is a point of major concern in the standardization of road traffic signals. "The low-pressure sodium lamps that are used for road lighting could be mistaken for yellow traffic lights. It is therefore suggested that, where-ever this problem could occur, traffic lights should be placed, if possible, in positions where the risk of confusion would be minimised, and the traffic lights should at least be duplicated" (CIE, 1988). See also CEN (2001); CIE (2000).

(b) Chromatic adaptation

Chromatic adaptation is a complicated, well-studied subject. Chromatic adaptation can be described as follows: "It is the adjustment of the eye to the colour of the light in the surroundings. As an example, when the light contains much red, the nervous tracts that are activated by red light – to begin with the red sensitive cones – become less sensitive, The signal is reduced in strength. In this way, objects more or less keep their colour as it is perceived in white light, in spite of the changes in the spectral composition of the light" (Walraven, 1981, p. 242). This effect is often called the colour constancy. The reduction in strength of the signal is called inhibition. The adjustment is not instantaneous; usually, it takes a few seconds (Schreuder, 1964, p. 84-86). This persistance leads to after-images. When the spectral composition of the light is changed suddenly, it takes some time for the inhibition to be effective or, conversely, to diminish. The result is a negative after-image. Both in brightness and in colour, the negative – or the opposite – of the object that was observed, seems to persist. A bright object seems to become dark (Schreuder, 1964, p. 8; Gregory, 1965, p. 49); a green object seems to become red (Walraven, 1981, p. 43; p. 142). This is the reason that the phenomenon is also called the successive contrast (Walraven, 1981, p. 40).

(c) The colour rendering

We have mentioned already several times that the primary goal of illuminating engineering is to make the visual surroundings look 'natural'. Light sources have to fulfill certain requirements as regards the way the colours of objects look when illuminated by them. The requirement to the spectral distribution of the emitted light are called the colour rendering characteristics of the light source. It is quantified as the colour rendition of the source. It should be mentioned that usually the term 'colour rendering' is used as a synonym for the more correct term 'colour rendition'.

In principle, the procedure to assess the colour rendering a light source is simple. Take a number of standard surface colours. These samples are alteratively illuminated by the standard light source and by the light source that must be tested. In both cases, the spectral composition of the light, that is reflected by the sample, is measured. The smaller the difference between the two, the better the colour rendering of the lamp. The actual procedure is more complex. It is described in detail in De Boer & Fischer (1981, sec. 4.3, p. 100-110).

The complexities relate to three aspects
(1) The selection of the standard colours;
(2) The selection of the standard light source;
(3) The way to take the chromatic adaptation into account.

(d) The standard colours

The standard colours were selected from a large number of test colours (Ouweltjes, 1960). Out of 19 test colours, 8 standard colours were selected (CIE, 1965a; 1974; it should be noted that the references given by Ouweltjes are not exactly right; it is likely that they refer to drafts of later publications like e.g. CIE, 1965b; 1979; 1979a, or CIE, 1986, as referred to by Hentschel, 1994). Later, 6 more colours were added to these 8 to represent several strong colours, the complexion of the human face and of foliage (De Boer & Fisher, 1981, p. 104). It may be noted that only the Caucasian skin is included (De Boer & Fisher, 1981, p. 104). The 14 standard colours are given in Table 8.3.10.

In order to adapt the CIE system of standard colours to other parts of the world, notably to Asia, a Number 15 is added, that represents the Japanese female face complexion. On the basis of a survey by Kawakami (1955), regarding the skin colour of Japanese females for the use of colour films, the spectral distributions of the reflection factor of the skin colours has been is measured by Seki et al. (1956). Standard colours are based in these measurements. In 1967, the first version of the Japanese Industrial Standard, JIS Z 8726 "Method of measuring and specifying color rendering of light sources" was established (JIS, 1967, 1990), based on the CIE Publication No. 13, (CIE, 1965c). In the Standard, a test colour R15 for skin colour of Japanese females was specified, on the basis of the measurements by Seki et al. (1956). It was added to the 14 international test colours specified that were mentioned earlier (CIE, 1965). The Munsell notation of the skin colour is added to Table 8.3.10. The Standard JIS Z 8726 has been revised in 1975 and 1990. In 1990 version, taking into consideration of the statistical survey carried out by Kaneko et al., the spectral distribution of reflection factor of R15 has been slightly modified (Kaneko et al., 1979).

The resulting standard colours are described in Table 8.3.10. For reference, the Munsell-notation of the colours is added. The notation is discussed in detail in De Boer & Fisher (1981, p. 90-91).

Number	Approx. Munsell-notation	Colour appearance under daylight
1	7,5R6/4	light greyish red
2	5Y6/4	dark greyish yellow
3	5GY6/8	strong yellow green
4	2,5G6/6	moderate yellowish green
5	10BG6/4	light bluish green
6	5PB6/8	light blue
7	2,5P6/8	light violet
8	10P6/8	light reddish purple
9	4,5R4/13	strong red
10	5Y8/10	strong yellow
11	4,5G5/8	strong green
12	2PB3/11	strong blue
13	5YR8/4	light yellowish pink; human complexion
14	5GY4/4	moderate olive green; leaf green
15	1YR6/4	(No colour name is given)

Table 8.3.10: *The characteristics of the 14 standard colours. After De Boer & Fischer, 1981, Table 4.4. The Number 15 is added, according to the remarks made in this section.*

(e) The selection of the standard light source

Colours are by agreement understood to look 'natural' when viewed under daylight conditions. One might even call this a definition of normality! However, both the colour temperature and the spectral composition of daylight are far from constant (De Boer & Fischer, 1981, p. 101). The spectral energy distributions of 622 samples of daylight were studied by Judd et al. (1964). Based on these measurements, CIE selected a number of reference light sources with a colour temperature above 5000 K. Additionally, a further number of reference light sources with a lower colour temperature were selected by CIE, using the blackbody radiator as their basis (De Boer & Fischer, 1981, p. 101). It seems that such a large number of reference light sources were defined because that was, at the time, the only way to take the chromatic adaptation into account.

The relative spectral energy distributions of a number of reference light sources selected by CIE on this bases are depicted in Figure. 8.3.14.

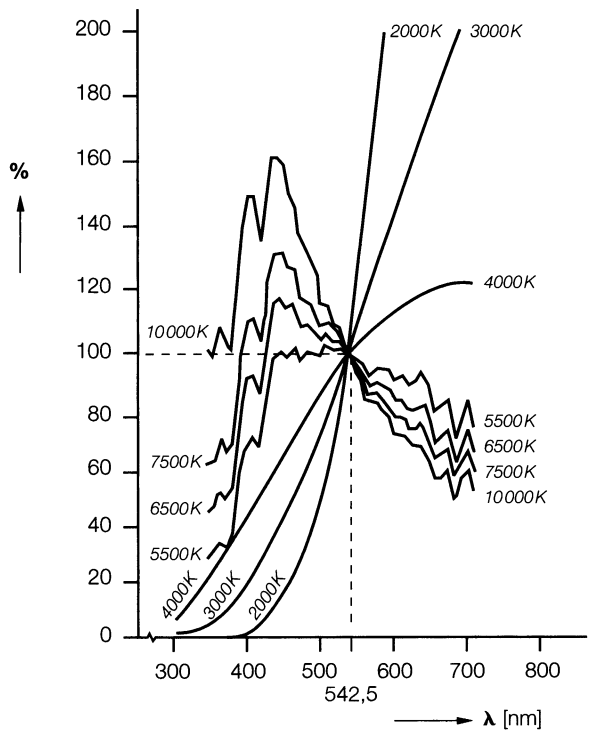

Figure. 8.3.14: *The relative spectral energy distributions of a number of reference light sources selected by CIE. After De Boer & Fischer, 1981, fig. 4.9.*

It might seem peculiar to base standard light sources with a colour temperature above 5000 K on daylight measurements and those with a lower colour temperature on the blackbody radiator. This procedure is supposed to be justified by the fact that, in the past – quite long ago, by the way! – offices were lit either by daylight (high colour temperature) or by incandescent lamps (lower colour temperature). Under these conditions, it was sufficient to define just two standard light sources. The first is Illuminant A with a colour temperature of 2856 K, representing incandescent lamps and the second is Illuminant D65 with a colour temperature of 6500 K, representing average daylight conditions (Hentschel, 1994, p. 103). Although it never has been clearly stated, this implies that the applicability of the original CIE-system to assess the colour rendering of lamps for other than office use was questionable. More recently, the situation did improve when only two different standard light sources were used. These illuminants are described in sec. 8.3.6d.

(f) The colour-shift method

The colour-shift method was accepted by CIE as the standard method for the determination of the colour rendering characteristics of light sources (De Boer & Fisher, 1981, p. 104, again without further references). The first step is to determine the chromaticity of the light source to be tested, that is its colour point in the UCS-diagram that is discussed in sec. 8.3.7g. This allows to determine the colour temperature of that lamp, assuming – as we always do in the considerations about colour rendering – that the light of the lamp is 'whitish'. After that, a reference light source is chosen with a colour temperature similar to, or even the same as that of the lamp to be tested. The chromaticity of the eight (or fourteen, or fifteen) standard colours is assessed for the two energy distributions, that of the lamp to be tested and that of the reference light source. For each of the standard colours, a difference in chromaticity can be determined. This difference in chromaticity represents a colour shift. Because in the Uniform Chromaticity Scale Diagram or UCS-diagram, the areas that contain colours that are 'almost' the same, have been transformed into circles with almost the same size it is mathematically sound to use the average colour shift. The average colour shift, corrected for the chromatic adaptation, is a measure of the colour rendering characteristic of the lamp to be tested. The smaller the shift, the better the colour rendering.

(g) Taking the chromatic adaptation into account

The third factor to take into account is the chromatic adaptation. In the CIE-system, this is done by: "subtracting vectorially the difference in colour points of the reference source and the source to be tested from the average colour shift" (De Boer & Fisher, 1981, p. 104-105). On the basis of these considerations, the colour rendering of light sources can be assessed.

8.3.9 The colour rendering of light sources

The colour shift for an individual standard colour is described as:

$$R_i = 100 - 4{,}6\delta E_{a,i} \qquad [8.3.5]$$

in which:
$\delta E_{a,i}$: the colour difference expressed values that correspond to the UCS-diagram as discussed in sec. 8.3.7g;
R_i: the Special Colour Rendering Index (SCRI) for an individual colour.(After De Boer & Fischer, 1981, p. 105).

The colour rendering of a light source is expressed numerically in the 'General Colour Rendering Index' (GCRI) for the standard reference colours. The GCRI for the eight standard reference colours $R_{a,8}$ is defined, after Baer, 1990, p. 39., as the average of the 8 different SCRI's, as follows:

$$R_{a,8} = \frac{1}{8}\sum_{i=1}^{8} SCRI_i \qquad [8.3.6]$$

The index $R_{a,14}$ for the fourteen standard reference colours is defined in a similar way. Details are given in De Boer & Fischer (1981, sec. 4.3, p. 100-108; see also Schreuder, 1998, sec. 7.4.4 and Baer, 1990, p. 39).

In Table 8.3.11, a lamp classification system based on $R_{a,8}$ is given.

Colour rendering class	CRI	Requirements
1A	$100>R_{a,8}>90$	very high
1B	$90>R_{a,8}>80$	very high
2A	$80>R_{a,8}>70$	high
2B	$70>R_{a,8}>60$	high
3	$60>R_{a,8}>40$	moderate
4	$40>R_{a,8}>20$	low

Table 8.3.11: *Lamp classification based on $R_{a,8}$. After Hentschel, 1994, Table 4.5.*

In Table 8.3.12, the General Colour Rendering Index for the eight standard reference colours ($R_{a,8}$) is given for a number of light sources that are commonly in use in outdoor lighting. For convenience, the lamp coding system from Philips is used. Also, the luminous efficacy (Lumen per Watt) and the colour temperature are added. These lamp characteristics are discussed in secs. 11.6.4 and 8.3.7 respectively.

Lamp type	Luminous efficacy (lm/W)	Colour temperature (K)	CRI $R_{a,8}$
incandescent lamp 100 W	14	2800	100
halogen lamp 500 W	19	3000	100
fluorescent tube 36/40 W			
– colour 29	83	2900	51
– colour 33	83	4100	63
– colour 57	45	7300	94
– colour 93	64	3000	95
– colour 94	65	3800	96
– colour 95	65	5000	98
SL 18 W	50	2700	85
sodium lamps			
– SOX-E 131 W	200	1700	–
– SON-T 400 W	118	2000	23
high-pressure mercury lamps			
– HP 250 W	47	6000	15
– HPL C 250 W	56	3300	52
– CSI 250 W	60	4200	80

Table 8.3.12: *Lamp characteristics of light sources commonly in use in outdoor lighting. After Schreuder, 1998, Table 7.4.2.*

Notes to Table 8.3.12:
– Incandescent lamp: normal General Lighting Service (GLS) lamp, mostly for indoor use;
– Halogen lamp 500 W: lamp specially used in floodlighting etc.;
– Fluorescent tube 36/40 W: the traditional TL-lamp with 26 mm diameter;
– SL 18 W: compact fluorescent lamp with integrated ballast;
– SOX-E 131 W: low-pressure sodium lamp;
– SON-T 400 W: high-pressure sodium lamp;
– HP 250 W: high-pressure mercury lamp without colour collection;
– HPL C 250 W: high-pressure mercury lamp with improved colour collection ('comfort');
– CSI 250 W: metal-halogenoid lamp for outdoor use.
Except when otherwise stated, ballasts not included.

8.4 Gender specific aspects of vision

It is usually taken for granted, that the sensory systems of women and men are identical. Research in gender differences, just as research in racial differences, has been considered as 'politically incorrect', and thus was obstructed for several decades. Before that, before the feminist and racial revolutions of the 1960s and 1970s, there was no need to look into this matter, because all (white, male) researchers were convinced that male Caucasians were superior in all ways.

A careful analysis of all available date is given in Pease & Pease (2002). This book is written, in a very popular way, for the general public. Although it seems that the data on which it is based are reliable, it is not very well possible to check the assertions made, because references are almost totally absent. In spite of that, we have quoted a number of these statements, because it is one of the very few books, that cover this – neglected – area of research. In view of these shortcomings in the bibliography, we will just give a number of quotes without any further comments.

(1) "Men and women have developed in different ways, because they needed to. Men went hunting, women collected. Men protected, women cared. As a result, their bodies and their brains developed in totally different ways" (Pease & Pease, 2002, p. 20).

(2) "The retina consists of 130 million rods, that process black-and-white images, and 7 million cones, that take care of the colours. The X-chromosome provides these colour-cells. Women have two X-chromosomes, which makes that they have more variation in cone-cells than men. This difference results in the ability of women to describe colours more in detail" (Pease & Pease, 2002, p. 36-37).

(3) "The brain of men, that is built for hunting, has a much smaller field of view. The brain of women is able to decode information in a much wider peripherical range, because of their history of defenders of the nest" (Pease & Pease, 2002, p. 39).

(4) The famous ambiguous figure, introduced by Edward Boring, is depicted in Figure 8.4.1.

Figure 8.4.1: *The Boring ambiguous figure. After Pease & Pease, 2002, p. 42.*

This figure is seen and interpreted in different ways by men and women. "Women see the old woman with her chin hidden in the collar of her fur coat, and men see the turned-away profile of a young woman" (Pease & Pease, 2002, p. 41-42).

(5) "Although a woman can see better in the dark than a man, particularly in the red part of the spectrum, the eyes of a man can see better over a long range, and over a narrower area, which provides him with a much better – and thus safer – night vision over long distances than a woman" (Pease & Pease, 2002, p. 43).

(6) "We know that the right side of brain, the creative side, governs the left side of the body, whereas the left side of the brain, the side of logic, ratio, speech, governs the right side of the body. The left side of the brain contains – more in particular in men – language and vocabulary. In the right side, visual information is processed and stored. Left-handed people incline to the right, the creative side of the brain. That is why a disproportional number of geniuses are left-handed. There are more left-handed women than men, and about 90% of all people are right-handed." (Pease & Pease, 2002, p. 64).

(7) "The neurologist Roger Gorski confirmed, that the female brain has a heavier corpus callosum than that of a man. Women have about 30% more connections between the brain halves. The female brain is built to perform several tasks simultaneously. A woman can do different, unrelated things simultaneously, and her brain is always active." (Pease & Pease, 2002, p. 70-71).

(8) One might call a brain either 'male-wired' or 'female-wired'. There is no strict correlation between male bodies and male brains, nor between female bodies and female brains. "It is estimated that about 80% to 85% of men have male-wired brains, the rest have brains that look more like female-wired. Some of those may become homosexuals." (Pease & Pease, 2002, p. 74-75).

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9 Visual performance, task performance

When considering the threshold values for any visual function, one must take into account that the visual system acts logarithmical and not linear. That means that for the same increase in experience, the ratio between the stimuli, and not the difference between the stimuli, is constant. This constant is often called the Weber fraction. The first aspect of visual performance to consider is that of the primary visual functions.

The primary visual functions are:

- *the luminance discrimination with special attention to the subjective brightness;*
- *the contrast sensitivity with special attention to the transition from photopic to scotopic vision;*
- *the visual acuity;*
- *the speed of observation and the detection of movement;*
- *the detection of point sources.*

In all cases, that the visual performance decreases, and often decreases dramatically, when the general light level decreases. This is of special interest for the reduction of light pollution: indiscriminate switching off of lamps may have negative effects on safety, visual efficiency, and comfort.

Other aspects are the conspicuity of distant luminaires. Distant, normal, well-adjusted outdoor luminaires near the horizon have no negative influence on astronomical observations. The same applies to much of the considerations about the sky glow of distant cities. Eliminating these factors is a matter of aesthetics, not of visual performance.

The other main subjects that are treated in this chapter are dazzle and glare. Glare may hamper or even obstruct visual observations. There are three types of glare: blinding glare; disability glare; discomfort glare. When considering light pollution, the main emphasis is on disability glare. A recent proposal is the three-step CIE Standard Glare Observer, where the influence of the position of the glare sources, the age of the observer, and the pigmentation of the eyes are taken into account when considering the glare level that is provoked by a lighting installation. The obvious way to reduce glare is to adapt the lighting equipment. This relates to the Upward Light Ratio of the *luminaires. It is clear that in reducing the light emission of luminaires at angles close to, but under the horizon, the requirements to reduce light pollution and the requirements to reduce glare are very similar. As regards discomfort glare, it may be helpful for comparing different, but similar lighting installations. However, discomfort glare does not seem to be suitable for a general quality characteristic for the design of lighting installations on which fixed, numerical criteria can be based.*

9.1 Visual performance

9.1.1 Law of Weber; primary visual functions

(a) *Threshold values*

It is customary to place the birth of experimental psychology at the laboratory of Wundt founded in Leipzig in 1879 (ENSIE, 1950, vol. X, p. 1256). Many experiments preceded that date, notably those of Weber, who postulated around 1830 his famous 'law', usually called the Weber law:

$$\frac{\delta I}{I} = k \qquad [9.1.1]$$

in which:
I: the intensity of the stimulus;
δI: the differential threshold of the stimulus;
k: a constant.

The 'law' is presented here in the form as given by Krech et al.(1969, p. 113). Later, in 1850, Fechner integrated the equation and since them the law is also known as the Weber-Fechner law (ENSIE, 1950, vol.I, p. 448). It might be noted that the stimulus may be of many sorts. In view of the objections that were made against the integration process that was proposed by Fechner, it seems that the term 'law' may be used a little loosely – a matter only too common in psychological texts!

We will include a few remarks about the threshold stimulus and its assessment. Usually, the threshold of detection of a stimulus is usually defined as the value of the stimulus that provokes 50% positive detections of the stimulus. In other words, the threshold means that it is equally probable that the object can be seen or that it can not be seen. Most measurements are arranged in the following way. Say, we want to know at which value of the luminance of the surrounding (L_2) an object can just be seen. If the threshold value is still completely unknown, a trial experiment will have to be made to find out the right order of magnitude. Now, the stimulus is presented a large number of times in random order to the observer at stimulus values that range from well below to well above the expected threshold value. For each stimulus value, the number of correct detections, or hits, is recorded. The results can be plotted as a cumulative distribution. Well-established statistical procedures can be used to find the best approximation to the 50% value (Buijs, 1995; Dixon & Massey, 1957; Moroney, 1990; Schreuder, 1998). Often, a regression curve may be established. An example, taken from research into the entrance lighting of long traffic tunnels is given in Figure 9.1.1.

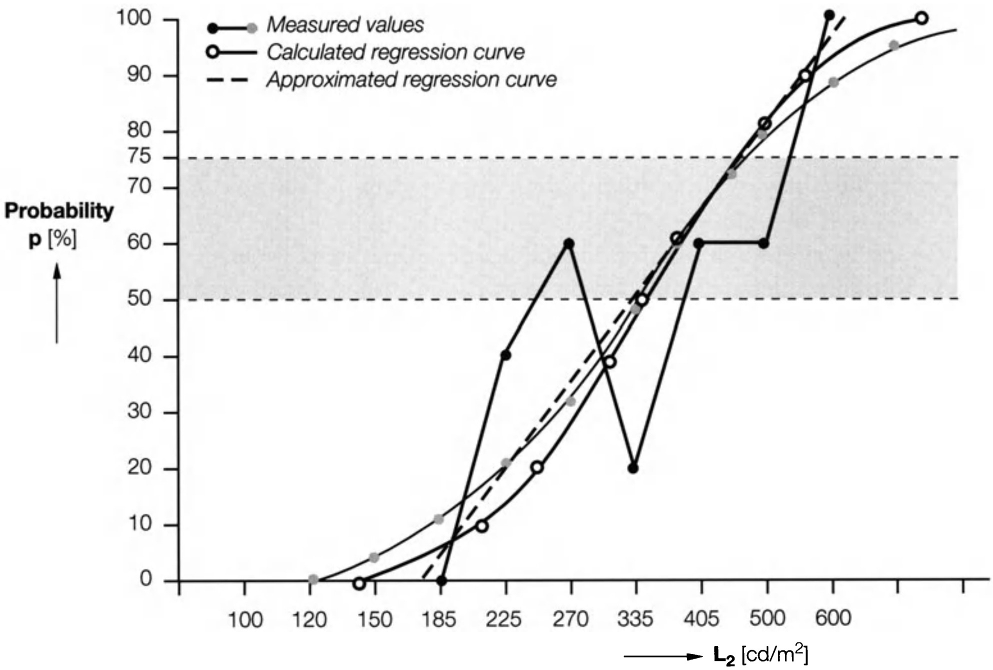


Figure 9.1.1: *An example of the assessment of the threshold value: comparison between approximated and calculated regression curves. After Schreuder, 1964, figure 36b.*

One may use the same procedure to establish other values of the probability of detection. The theory of this method of investigation in described in detail in the classical study of Guilford (1936). See also Middleton (1952, p. 84) and Blackwell (1952). Blackwell, in his classical studies in contrast sensitivity, mostly used the 95%-percentile, looking for 95% probability of detection (Blackwell, 1946; CIE, 1981). In this case, the required number of tests is even larger. We will come back to these studies in sec. 9.1.3c.

Obviously, this way to assess the threshold value is a complicated and time-consuming matter. Practice has shown, however, that making 'short cuts' often leads to disaster. Then, there are other problems that have to do with the interpretation of the data and the further data processing. More in particular, if the threshold is determined for one observer at the time, it is customary to calculate 'the' threshold by taking the arithmetical mean of the individual threshold data (Blackwell, 1946). One also could take all individual tests together and determine the threshold by calculating the regression from the accumulated data. The problem is that one can never be certain that the regression of the averages is the same as the average of the regression. The ground for this uncertainty is that we refer to stochastic data; there is no mathematical function 'per se' in nature. All we do is to 'allot' mathematical entities to the data points. Similarly, when the cumulative distribution is established, it usually is drawn as a curve giving the relationship between the dependent variable (e.g. the contrast sensitivity) on the ordinate (the y-axis) and the independent variable (e.g. the adaptation luminance) on the abscissa (the x-axis). An example is given in sec. 9.1.3c, where the CIE RCS-curve is discussed.

The problem is that the graph may easily be mistaken as a representation of a mathematical function of the type $y = f(x)$. In mathematics, when we have a 'real' function, one may write $x = f'(y)$ as well. In mathematically defined functions, usually f and f' are closely related. Not always; when the function is not continous, or when it contains singularities, there may be a problem in defining the relation between f and f'. There are other constraints as well. However, they do not need to bother us here, primarily because psycho-physical data themselves are not a mathematical function in the first place! The concept of mathematical functions is described in Bronstein et al. (1997) and Daintith & Nelson (1989, p. 138-139). However, this reversal of dependent and independent variable is not justified when we deal with the representation of experimental, psycho-physical data. If one tries to do so, one might end up with ridiculous results.

As an example, we quote some unpublished considerations by Schreuder (1964a). The subject was the proposal by Blackwell to establish illuminating engineering on 'performance data' (Blackwell, 1959). Blackwell applied a field factor to incorporate non-ideal, day-to-day conditions. The field factor is arbitrarily chosen as 15. We follow here the example of Blackwell, where the consecutive carbon copies of a type-written letter are considered. Those of us who are old enough to know what carbon copies are, will know that the contrast deteriorates with each consecutive copy. Using the RSC-curve that is discussed in sec. 9.1.3c, Blackwell calculated the required illuminance to be able to read the original. His result was 75 lux. The first copy required 1800 lux, the second 15 000 lux and the third to the seventh copy would require more than 100 000 lux, implying they could not be read even in full sunlight. Obviously, these results are absurd. What would have been the right reasoning was that the original was difficult to read. It was suggested in the paper that the typing was done with a very small letter type. Or maybe the field factor was too high to be realistic. Whatever the case, with adequate lighting the original could be read. The copies, with poorer contrasts, did require more light, but the visibility remained poor even at the highest light levels. The answer is, of course, in the RCS-curve itself: at high levels, the curve flattens and it approaches an asymptote that is parallel to the x-axis. This means that the visibility is independent on the light level – which is, of course, the case.

(b) The Weber fraction

The fundamental significance of the Weber-Fechner Law is the fact that δI is not infinitesimally small. In other words, the stimulus must increase by a considerable amount before the experience corresponds to the impression of an increase in sensation. Of course, all measurements are fraught with inaccuracies, partly due to the fundamental uncertainty as introduced by Heisenberg (Illingworth, 1991, p. 503) and partly by more mundane measuring errors due to the characteristics of the measuring apparatus. In psycho-physical research, however, these uncertainties are inherently much larger than in 'traditional' physical measurements, because the measuring apparatus is the living organism itself. See for further details Krech et al. (1969, Unit 6) and Schreuder (1998, sec. 7.1). We will discuss some of the implications of the step-wise character of sensory information in sec. 9.1.2

In equation [9.1.1] we have introduced the mathematical expression of Weber's Law. The constant k is often called the Weber fraction. Experiments did show, however, that k is in reality not constant at all. This is the ground for the objections against the Fechner integration of the Weber Law. One might wonder why the Weber fraction is not a constant. When considering the contrast sensitivity, it is true that the measurements stretch over a wide range of adaptation luminances that include both photopic and scotopic vision. As is explained in sec. 9.1.3c, rods tend to cluster together in scotopic vision, changing the receptory process. But in photopic vision this is not the case. Strangely enough, this question is never posed seriously in the literature. We do not have an answer, but probably the bleaching of the visual purple plays a role. As is found experimentally, the bleaching depends on the light level (Rushton, 1963; Rushton & Gubisch, 1966; Rushton & Westheimer, 1962). The tests of Rushton and his collaborators are mentioned in sec. 8.2.3b. The fact remains that the contrast sensitivity is not a constant over a wide range of adaptation luminances, all within the photopic zone. This holds not only for the contrast sensitivity, but for most other visual functions as well, such as the visual acuity, the speed of detection etc. These functions are described in other parts of this chapter.

(c) The primary visual functions

Because visual functions are interdependent, one has some freedom as to where to begin the discussion of them. The eye is an light-detecting organ, so it is natural to begin there. The physiology of the detection of light is discussed in sec. 8.1. The fundamental aspect of detection is the ability to judge whether the light is there or not; this is, in it simplest form, an important visual function with many practical implications like the detection of signalling lights, of stars etc. The visibility of point sources is discussed in sec. 9.1.7. We will begin the discussion in this chapter with the detection of differences of light, or, in other words, the discrimination of luminances. In practice, this means the ability to detect an object against its background. Contrast observation is discussed in sec. 5.1.1; see also sec. 3.3.1. For obvious reasons, the corresponding visual function is called the contrast sensitivity. In order to recognise the object, its shape or form must be discerned; this function is called the visual acuity. In secs. 14.5.2d and 10.2.1, the related phenomena of pattern recognition and Gestalt observation are discussed. As is discussed in sec. 8.2.3b, many phenomena depend on the state of adaptation. The time-dependent adaptation processes, as well as the speed of observation and the related flicker-effect will be discussed in this chapter, and so will be the detection of movement. The next aspect that will be discussed is, as indicated already, the detection of point sources. The chapter will end with the discussion of dazzle and glare.

9.1.2 Luminance discrimination

(a) *Laws of Ricco; Bloch; Blondel and Rey; Talbot*

Luminance discrimination relates to the ability to discern two adjacent sections of the field of view if they differ in luminance. As has been indicated earlier, the related visual function is called the contrast sensitivity. Contrast observation is discussed in sec. 5.1.1; see also sec. 3.3.1. Matching two sections that differ in specific characteristics (e.g. in colour) is the basis of photometry; the fact that the discrimination – or the equality – is judged by a living organism, is the reason for the prominence of Weber's Law.

There is a direct relationship between the luminance to be found in the world outside the eye and the retinal luminance to be found within the eye. The relation depends on the pupil diameter and thus on the state of adaptation, in two distinct ways. Firstly, the pupil acts as a stop that limits the amount of light entering the eye; secondly, the transmission of the outside areas of the pupil is lower than that of the pupil centre, making light rays that pass through the outside areas of the pupil less 'efficient' – the so-called Stiles-Crawford effect, that is discussed in sec. 8.1.2 (Stiles & Crawford, 1933). However, as long as changes in the pupil diameter may be disregarded, the 'outside' luminance is directly proportional to the retinal luminance 'within'. This allows us to discuss the visual functions in terms of luminances 'outside', that may be measured in a straightforward way by standard photometric equipment. It might be added that, from a philosophical point of view, this fact that seems so simple and straightforward is not simple at all. A detailed analysis of the consequences is given by Moon (1961) and Moon & Spencer (1981), using the light field concept introduced by Gershun (1938). For practical lighting engineering purposes, these philosophical details may be disregarded.

The implication of the foregoing discussion is that two adjoining sections of the field of view that have the same luminance will also look equally bright. This is not always the case, however. Three important exceptions will be briefly discussed here.

The first is that two sections of the field of view of different size look equally bright as long as the product of the diameter and the luminance is constant. This is called Ricco's Law, and it applies to areas up to 6 degrees in diameter. (Moon, 1961, p. 404). Ricco's Law (also called the law of Ricco-Piper; Hentschel, 1994, p. 49) can be written as follows:

$$L = \frac{r^2}{k_1} \qquad [9.1.2]$$

in which:
L: The luminance of the test object;
r: Its radius;
k_1: A constant.

We will come back to this effect later in this section.

The second exception that we will discuss, relates to the visibility of weak flashes of a duration shorter that 0,2 seconds (Moon, 1961, p. 404). It was found by Bloch in 1885; therefore the relation is called Bloch's Law:

$$E_{ret} \cdot \delta t = k_2 \qquad [9.1.3]$$

in which:
E_{ret}: The retinal illuminance caused by the flash;
δt: The duration of the flash;
k_2: A constant.

The third exception is related to sections of the field of view where the luminance varies periodically in time. In practice, this usually means flashing lights. The threshold of visibility of a square-wave flashing light is given by the equation of Blondel and Rey:

$$E = \frac{E_t \cdot (a + t)}{t} \qquad [9.1.4]$$

in which:
E: The illuminance threshold for the flashing light at the observer's location;
E_t: The illuminance threshold for a steady light;
t: the flash duration;
a: A constant. This constant is about 0,2 for lights seen at threshold at night (Douglas & Booker, 1977, sec. 4.4.4).

The effective intensity of a flashing light is defined as:

$$I_e = \frac{I \cdot t}{(a + t)} \qquad [9.1.5]$$

When the frequency is over 10 Hz, the light appears to be steady due to the persistence of vision. In Talbot's Law, an approximation is given for the subjective brightness (or effective intensity). This is the time-average of the instantaneous intensity (Stevens, 1969, p. 9). The apparent intensity of a flashing light is, in the way as given by Illingworth, ed. (1991, p. 474):

$$I = I_0 \cdot \left(\frac{t}{t_0}\right) \qquad [9.1.6]$$

in which:
I: The apparent intensity of the flashing light;
I_0: The actual intensity;
t: The duration of the flash;
t_0: The total time.

This law is assumed to apply for threshold as well as for above-threshold conditions.

(b) Stimulus and response

Electromagnetic energy only provokes a sensation of 'light' when it activates in one way or another the visual system – when it hits the eye. The philosophical implications are rather complicated: it comes down to: "The Rays are not Colored". Wright used this quote from Newton's Opticks for the title of the delightful little book where he discusses some of these implications (Wright, 1967). See also Zajonc (1993).

In the earlier years of photometry, little distinction was made between the physical stimulus (the electromagnetic energy) and the response (the sensation of light provoked by that stimulus). For both, the concept 'brightness' was used. Only when it was found that the stimulus and the response were not always directly related in a linear fashion, the need arose to make a clear distinction between the two. The concepts of stimulus and response as they are used in psychology and in psycho-physics are discussed in sec. 10.4.2a. See also Blackwell (1952); Hebb (1958); Michon et al., eds., 1979; Sanders (1972); Schreuder (1973, 1998); Skinner (1965, 1972).

As is explained in a further part of this section, at the stimulus-side the concept luminance is introduced to signify the measurable, objective quantity. At response-side, the concept luminosity is introduced to signify the subjective appraisal. The term 'luminosity' never took hold on a large scale; it is usually still called 'brightness'. An exception is Stevens (1969, p. 15) who uses the term luminosity once in a while. At the other hand, the term 'brightness' was still used in recent times to signify the luminance (Moon, 1961, p. 556).

It would seem logical that the stimulus and the response vary in the same way when the illumination changes. In an earlier part of this section, we have mentioned a few instances where the same visual impression – the same response – could result from different stimuli. But still, as long as the Weber fraction may be regarded as a constant, the luminance and the brightness of an object do change in the same way when the illumination changes – the two are directly proportional. In this, the Weber fraction is to understood as the constant 'k' in [9.1.1]. However, as is explained in sec. 9.1.1b, the Weber fraction is not a constant at all.

(c) Subjective brightness

It is well-known from experimental psychology that it is quite possible to scale impressions and sensations in an equivocal way (Steyer, 1997). However, not everyone seems to agree. "Sensations cannot be measured. There is no way of setting up a unit or of evaluating in terms of a unit. Any equation like the Weber-Fechner one is pure nonsense" (Moon, 1961, p. 421-422). In spite of such criticism, several proposals have been made in illuminating engineering to scale the visual impression, usually designated as 'subjective brightness' (Bodmann & Voit, 1962; De Boer & Fischer, 1981; Hopkinson, 1957; Marsden, 1968).

During the Second World War, visibility of dim stimuli was important with respect to the wide-spread 'black-out'. Furtheron in this section we will have to say a little more about this. In 1941, a major study on the relation between the luminance stimulus and brightness response was published (Hopkinson et al., 1941; further details are given in Padgham & Saunders, 1966). A detailed discussion of these studies is given by Stevens (1969, p. 16-18). We will give here a summary of this discussion. The results of this study are depicted in Figure 9.1.2.

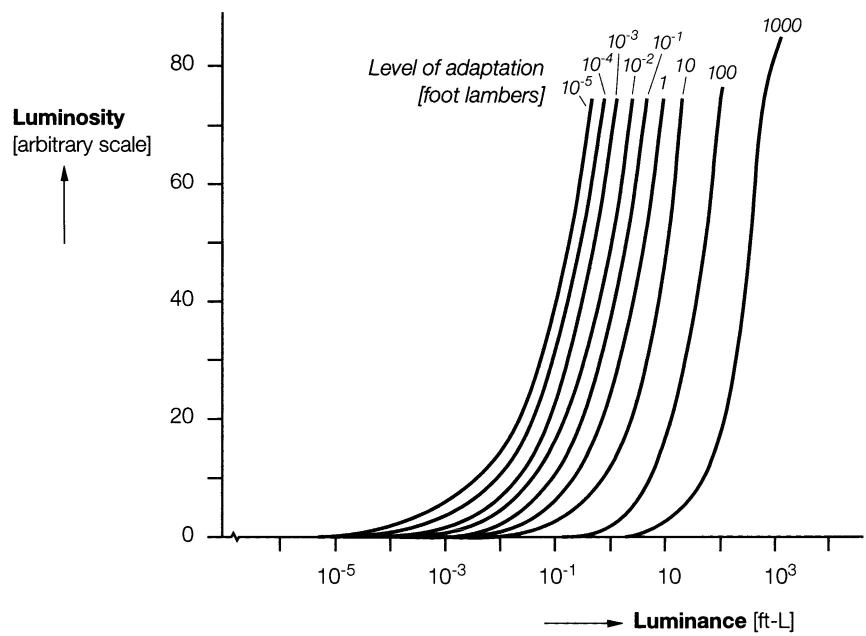


Figure 9.1.2: *The relation between luminosity and luminance for different levels of adaptation. After Stevens, 1969, fig. 1.7, based on data from Hopkinson et al., 1941.*

Note: the original figure is reproduced. To convert the luminances into metric values, multiply the foot-Lambert-values by 3,43 to get cd/m^2-values. The conversions are given in sec. 14.3.2a.

In this figure, three aspects are striking:

(1) The curves for equal luminance bend off near the line of zero luminosity, causing the 'crowding' of the luminosities that we will discuss later;

(2) The curves for equal luminance are not equidistant. It is likely that this 'crowding' for low luminances is related to the fact that the contrast sensitivity, that is discussed in sec. 9.1.3, decreases with decreasing luminance. This effect is represented in Table 9.1.1.

Adaptation luminance (fL)	**Luminance** (fL)
1000	400
100	60
10	12
1	5
0,1	2
0,01	1
0,001	0,5
0,000 1	0,3
0,000 01	0,2

Table 9.1.1: *The relation between the adaptation luminance and the luminance of the test object for a luminosity of 50. Based on data from Figure 9.1.2.*

Note: as in Figure 9.1.2, the luminance in this table is given in the non-ISO quantity of foot-Lamberts (fL).

(3) There does not seem a clear breach in the visibility process at the transitions from photopic to mesopic, and from mesopic to scotopic vision. The curves for equal luminance are smoothly grouped, as can be seen from Table 9.1.1. This is to be expected because there indeed is no sudden transition from photopic to scotopic vision, in spite of the fact that in many publications such a sudden transition is suggested by drawing a sudden bend, or 'knee', in the curves. As is explained in sec. 8.3.4c, the mesopic area is the transition from photopic to scotopic vision. In mathematical terms, one might expect a maximum but not a singularity in the second derivative of the function.

We will quote here some parts of the as given by Stevens. "As an example, in a surrounding with a luminance of 1 fL, an object with the same luminance will, of course, be visible. It has been given the arbitrary luminosity value of 22. The 1 fL-curve above this point is practically straight so that over this region the Fechner law holds. At lower values of luminance, however, the curve bends round so that the rate of change of luminosity is smaller than is found at higher levels of luminance. When we approach the lower limit of luminosity the eye is less sensitive and quite large changes in luminance are hardly discernible" (Stevens, 1969, p. 16-17).

The effect is more pronounced at lower levels of adaptation. In moonlight, the adaptation level may be about 10^{-2} cd/m^2 (Middleton, 1952, p. 91) or maybe 10^{-3} fL (Stevens, 1969, p.17). The luminosity of a grey object at this luminance is very low; it is about 1 compared to zero for a black object. When looking at the graphs, it may be seen that the luminosities of all greyish objects are close ("crowded together"; Stevens, 1969, p. 17). For light coloured objects, like e.g. white painted road markings, however, the situation is different. Although the increase in luminosity is less than one might expect from the increase in luminance, they are highly conspicuous because they 'stick out'. This effect is clearly noticeable in dim surroundings, and it is a major contribution of white painted road markings to the safety and ease of pedestrians.

In Table 9.1.2, an example is given. We assume a street scene with an average scene reflection of 20% (Schreuder, 1964). In the scene we assume several objects:
(1) a black-painted utility pole with a reflection of 5%;
(2) a piece of asphalt road surface with a reflection of 10%;
(3) a piece of cement concrete pavement surface with a reflection of 20%;
(4) a white-painted road marking with a reflection of 70%.

Object	**Object reflection** (%)	**Values of luminosity for adaptation luminance** 10 fL	0,001 fL
(1)	5	26	0
(2)	10	42	1
(3)	20	63	3
(4)	70	95	7

Table 9.1.2: *The luminosity of different objects at different adaptation luminances. Based on data from Figure 9.1.2.*

Note: as in Figure 9.1.2, the luminance in this table is given in the non-ISO quantity of foot-Lamberts (fL).

More recently, the available data were analyzed again by Haubner et al. (1980). A brief description of the procedure and of the main results is given by Hentschel (1994, p. 52-54). The following discussion is based on this description.

The 'Haubner scale' that was introduced here, has a 'zero' point, contrary to the logarithmic scales that are used for the luminance (Haubner et al., 1980). The zero point corresponds with the impression 'black'. Its luminance depends on the adaptation luminance. However, it is more convenient to express the brightness as well in a logarithmic scale. The results established by Haubner et al. (1980) are depicted in Figure 9.1.3.

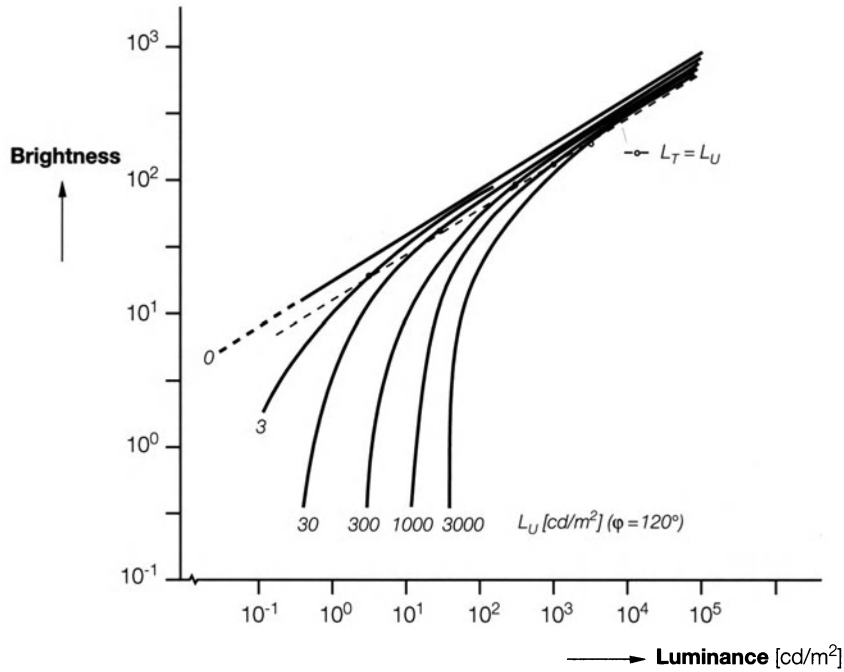


Figure 9.1.3: *The brightness H of a test object of two degrees with luminance L_T for different surrounding luminances L_u. After Hentschel, 1994, Figure 3.8. Based on data from Haubner et al., 1980.*

For the discussion about the restriction of light pollution, particular interest goes to the condition 'black' or 'just no brightness'. The corresponding luminance L_{s0} follows from:

$$L_{s0} = \left(S_0 + S_1 \cdot L_u^n\right)^{1/n} \qquad [9.1.7]$$

in which:
L_{s0}: Luminance for the condition 'black';
S_0 and S_1: Factors dependent on the size of the test object, according to Table 9.1.3;
L_u: Luminance of the surrounding field around the test object (180 degrees);
n: Exponent with the value of 0,31 ± 0,03.
(After Hentschel, 1994, p. 53).

Size of test object (minutes of arc)	S_0	S_1
10	0,273	0,40
20	0,201	0,36
30	0,180	0,32
60	0,131	0,27
90	0,109	0,25
100	0,075	0,25
120	0,072	0,24

Table 9.1.3: *Values of the factors in [9.1.7]. After Hentschel, 1994, Table 3.1. Based on Haubner et al., 1980 (rounded-off values).*

As an example, take a very dark night with $L_u = 10^{-3}$ cd/m^2 and a rather large object of two degrees diameter (120'). According to Table 9.1.3, $S_0 = 0{,}072$ and $S_1 = 0{,}24$. The exponent n is close to 0,3; as an approximation, we will take $1/n = 3$. According to [9.1.7], we will find for L_{s0}, the luminance that corresponds with the condition 'black':

$$L_{s0} = \left(S_0 + S_1 \cdot L_u^n\right)^{1/n} \qquad [9.1.7]$$

$L_{s0} = (0{,}072 + 0{,}24 \cdot 0{,}001^{0,3})^3$;
$L_{s0} = (0{,}072 + 0{,}0621^{0,3})^3$;
$L_{s0} = (0{,}134)^3$;
$L_{s0} = 0{,}002\,406$ cd/m^2;
rounded off:
$L_{s0} = 2{,}4 \cdot 10^{-3}$ cd/m^2

According to this calculation, a luminance about 1,5 times higher than the adaptation luminance would appear 'totally black'. As there are several parameters in this calculation that are arbitrarily chosen, and as there are several approximations involved, we must be cautious to draw far-reaching conclusions from the result. Still, it would seem that, at least for visual astronomy the IAU-suggestion of restricting artificial air glow stray light to not more than 10% of the natural background, is more stringent than necessary. The IAU-suggestions are discussed in sec. 3.1. See also Anon., 1978; CIE, 1997.

It may be interesting to note that many of the earlier investigations, particularly those of Hopkinson et al. (1941) were made during the Second World War when strict rules about 'black out' did exist in most European countries. It was at that time considered an important matter to establish how much – or how little – one might see in very dim surroundings. In the modern world, people are usually not interested in dim surroundings. Of course there are important exceptions to this statement: most criminals and some lovers prefer dim surroundings. And, of course, astronomers, both amateurs and professionals. What we try to achieve with the battle against light pollution is that the surroundings around astronomical observatories are indeed 'dim'!

(d) Constancy

There is another phenomenon related to subjective brightness that is worth to be mentioned: the phenomenon of constancy. This concept signifies that a certain impression remains unchanged even if the external conditions, and thus the physical stimulus, change. As an example, we will consider a white piece of paper with black letters printed on it. Whatever the light level, we always will experience the letters as black and the paper as white, even if the luminances are quite different. We will assume that the reflection factor of the paper equals 90% and that of the ink of the letters 3%. In Table 9.1.4, the comparison is worked out for an office room with an illuminance of 1000 lux and a street with an illuminance of 10 lux. The luminances are calculated straightforwardly; the luminosities are assessed from the data of Figure 9.1.2.

Material	**Reflection**	**Office (1000 lux)**		**Street (10 lux)**	
		luminance	**luminosity**	**luminance**	**luminosity**
paper	0,9	286	60	2,86	22
ink	0,03	9,6	8	0,096	5

Table 9.1.4: *The luminance and the luminosity of paper and ink in different surroundings*

From Table 9.1.4, it follows that the luminance of the letters indoors is much greater than the luminance of the paper in the street. Still, we will never be in doubt that the letters are printed in black. Part of this may be explained by the fact that the luminosity of the letters indoors indeed is lower than the luminosity of the paper outdoors.

However, this explanation does not seem to be sufficient. In our example, we assumed that we knew beforehand that the paper was white and the letters were black. Another example is the brightness of the ceiling in a room with daylight entering at one side only, like e.g. an ordinary classroom. The luminance of the ceiling might easily differ from one point to another by a factor of 2 or even more. Observers will have no trouble at all to see this; still, they will assume that the colour and the reflection factor over the whole ceiling are the same, because that is normally the case in class-rooms and that is what the observers may expect.

This touches to one of the basic concepts of visual perception: observers usually will 'see' what they expect. The expectancy plays a crucial role here. The importance of the expectancy and its implications are discussed in sec. 10.3.2. In psychology, this aspect is covered in the 'cognitive psychology'. "These considerations did not receive much attention during the decades of the dominance of the behaviourism in psychology. In the 1960s, however, this changed gradually in what is sometimes called the 'cognitive revolution'." (Straub, 1997, p. 258; see also Norman, ed., 1976).

Another example is the Moon. We all know that the Moon shines with a 'silvery light'. It looks like silver because it is so much brighter than the night sky. As is explained in sec. 3.1, the luminance of the night sky is about 10^{-4} cd/m^2, whereas with a reflectance of 3% and an illuminance of 120 000 lux, the luminance of the Moon would be well above 10^4 cd/m^2 – many millions brighter than the night sky. No wonder it looks like silver. So, even in murky and misty conditions, or in twilight, we will see the Moon as a silver disk. This impression is not altered by the fact that, since the Apollo project, we know that the reflection factor of the Moon is about 3 to 5% – about the same as that of a cinder path! Even more so, a clever experiment, first reported by Sir John Herschel, allows us to see the fact that the Moon actually is fairly dark. All one needs to do is to look at the rising full Moon at the same time as looking at a wall that is illuminated by the setting Sun (Minnaert 1942, volume I, p. 86-87). A direct comparison between the Moon and the wall will show that the Moon is dark grey, not silver at all! And still we all persevere in this illusion. Several other optical – or 'visual' – illusions are discussed briefly in sec. 10.2.2. This illusion is mentioned here to stress the importance of expectancy in visual observation. The role of expectancies in road traffic is explained in sec. 10.3.2 (Schreuder, 1998, p. 138)

9.1.3 The contrast sensitivity

(a) The contrast

The ability to see small differences in the luminance seems to be the most fundamental visual capability, in the way that most other visual functions are either a corollary of this ability or can be derived from it. Now, the absolute difference between the sections of the field of view is not always relevant; this is much more the case for the relative difference or the contrast (Schreuder, 1998, sec. 7.2.2). As is mentioned in sec. 5.1.1, in illuminating engineering, it is customary to define the contrast as:

$$C = \frac{L_0 - L_b}{L_b} \qquad [9.1.8]$$

in which:
C: The contrast;
L_0: The luminance of the object;
L_b: The luminance of the background.

According to this definition, the contrast can have positive and negative values, running from -1 for $L_0 = 0$ to $+\infty$ for $L_b = 0$. The equation is asymmetric because both L_0 and L_b appear in the nominator and only L_b in the denominator. Other definitions of the contrast avoid this, but they are not commonly used in illuminating engineering, although they are common in establishing a diagnosis in case of ophthalmological disorders. An example is given in Schreuder (1990; 1991; 1993).

A contrast of zero corresponds with a situation where $L_0 = L_b$. The object is invisible. It was found that perception, at least for small contrasts, does not depend on the sign of the contrast according to [9.1.8]. An object can be seen equally well when it is light against a dark background (positive contrast) as when it is dark against a light background (negative contrast; Adrian, 1961; Blackwell, 1946; Schreuder, 1964). Blackwell, in his incomparable style, expressed this as follows: "It is apparent that in most instances there is evidence that negative stimuli are equivalent to positive stimuli of equivalent area and contrast" (Blackwell, 1946, p. 639). It should be noted that what Blackwell calls 'negative stimuli', corresponds to 'positive contrast' according to the standard definition of contrast as given in equation [9.1.8].

For larger contrasts, this invariance does not apply because of the asymmetry of the equation [9.1.8] with which the contrast is defined. However, also physiological effects seem to play a role (Adrian, 1995; Aulhorn, 1964).

(b) The sensitivity to changes in the contrast

The sensitivity to contrast is the measure for the smallest luminance difference which can still be perceived. It is therefore a threshold value (sec. 9.1.1a). The most common way to designate this threshold is, as has been indicated earlier, the contrast sensitivity. Also its reciprocal value is often used; this is termed the 'sensitivity to luminance differences'. The contrast sensitivity depends on a number of surrounding factors but the main factor is the adaptation luminance (or the adaptation level). In general, the adaptation luminance can be considered as being equal to the background luminance, designated earlier as L_b. In its most general form, contrast sensitivity can be written as:

$$CS = \frac{\delta L}{L} \qquad [9.1.9]$$

and its reciprocal value, the sensitivity to luminance differences as:

$$LD = \frac{L}{\delta L} \qquad [9.1.10]$$

Both CS and LD do not only depend on the adaptation level but also on the size of the test object, the time of exposure, the colours of objects and backgrounds and several other factors. Further details are given in Hentschel (1994, sec. 3.2).

(c) The RSC-curve

During the Second World War, a large number of tests were made in the USA. As they were carried out with the support of the Tiffany Foundation, they are commonly referred to as the 'Tiffany Studies'. Details about this huge undertaking are given in Middleton (1952, p. 87-90). They were reported by Blackwell, the project leader, in his classical publication in 1946 (Blackwell, 1946). In later years, these studies formed, in combination with other studies, the basis for the CIE Relative Contrast Sensitivity Reference Curve or RSC-curve (CIE, 1981; see also De Boer & Fischer, 1981, p. 18). Blackwell also introduced the concept of visibility level (or VL). It was expected that this concept would replace the luminance concept as a metric for visibility in different conditions. In practice, however, its use was limited and it is applied only in some aspects of road lighting, more in particular in the 'Small Target Visibility' (or SVT) concept. This concept is discussed in sec. 10.2.1b. See e.g. Adrian (1993, 1995); CIE (1995); Enzmann (1993); Eslinger (1993); Gallagher et al. (1975); Janoff (1993, 1993a); Schreuder (1998) and Van Bommel & De Boer (1980). It must be noted that there are doubts whether the Visibility Level is the most appropriate measure of visibility on road lighting (Narisada, 1999; Narisada & Karasawa, 2001; Narisada et al., 1997, 2003). The Standard RSC-curve is depicted in Figure 9.1.4.

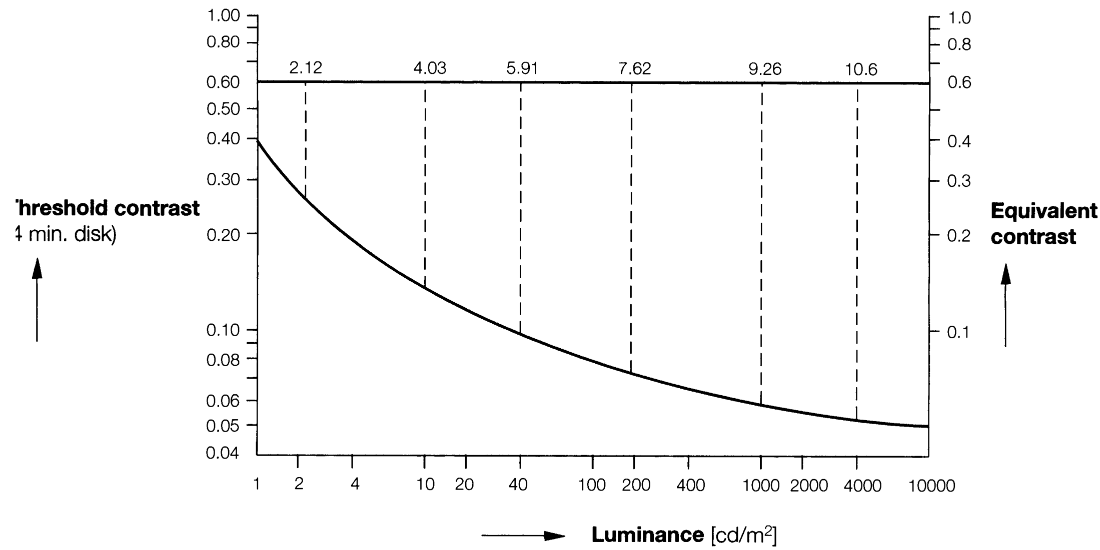


Figure 9.1.4: *The relation between contrast sensitivity and adaptation: The CIE RSC-curve. After Schreuder, 1998, fig 7.2.3.*

This curve is generally accepted as the standard for the contrast sensitivity. It is clear from the diagram that the contrast threshold is quite high for very low luminance levels. It decreases considerably with increasing luminances; the decrease seems to go on until the end of the range that is depicted in Figure 9.1.4. The threshold seems to level off for adaptation levels that correspond with average daylight conditions. When stating this, it should be realised that the curve is extrapolated towards its end. Blackwell did not do measurements at luminance values over about 300 cd/m^2 (Blackwell, 1959, after Schreuder, 1964). The rest is extrapolated. The same conclusion can be drawn from the data as presented by Hentschel (1994) and Middleton (1952). In the representation of Adrian (1969), the highest measuring point as quoted from Blackwell (1946) is at 200 cd/m^2. The Adrian-data are included in Hentschel (1994, figure 3.7) and reproduced here in Figure 9.1.7. In the representation of Middleton (1952, Fig. 5.2 and 5.3), the highest measuring points as quoted from Blackwell (1946) are at about 200-400 cd/m^2. A hint of further extrapolation is given. Part of these data are reproduced here in Figure 9.1.8.

Measurements at the highest values of the luminance range are rare. They, however, present a different picture. It has been found that for levels between 200 and 2000 cd/m^2, the contrast sensitivity is almost constant (in agreement with Weber's Law!) and that the contrast sensitivity increases again when the adaptation level is over about 2000 cd/m^2. This increase was already found in the 1880s in the famous experiments of König & Brodhun (1889). It was later reconfirmed by Schreuder (1964; 1998). Not everyone seems to agree: "The more recent results of Blanchard, Holladay and others check the König values fairly well, though they do not show the decrease in the contrast sensitivity at higher values of the adaptation luminance" (Moon, 1961, p. 419). It should be noted, however, that the measurements of Blanchard, Holladay, and Stiles & Holladay were made at low luminance values only. According to the data given by Moon (1961, Figure 12.12) the measurements were restricted to an area below 3 lumen per square foot (about just over 30 lux). In spite of the fact that Moon has not given any further details on these studies and that references are lacking, it might seem that the remark of Moon is slightly premature. The results of the studies of König & Brodhun and Schreuder are depicted in the Figures 9.1.5 and 9.1.6.

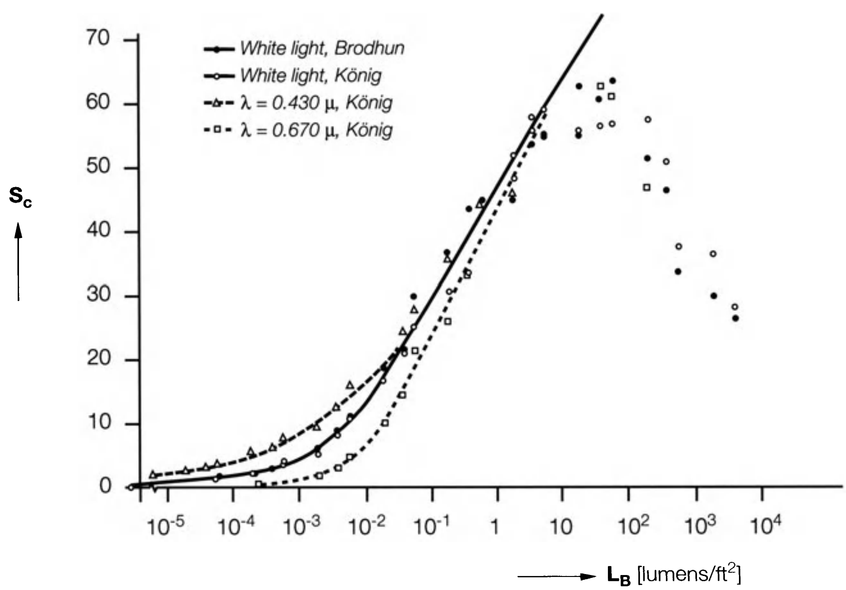


Figure 9.1.5: *The relation between the contrast sensitivity and the adaptation luminance. After Moon, 1961, Figure 12.13. Based on data of König & Brodhun, 1889 and König, 1903, p. 135.*

Note: the figure has been reproduced in its original form, including the idiosyncratic terminology and units of Moon.

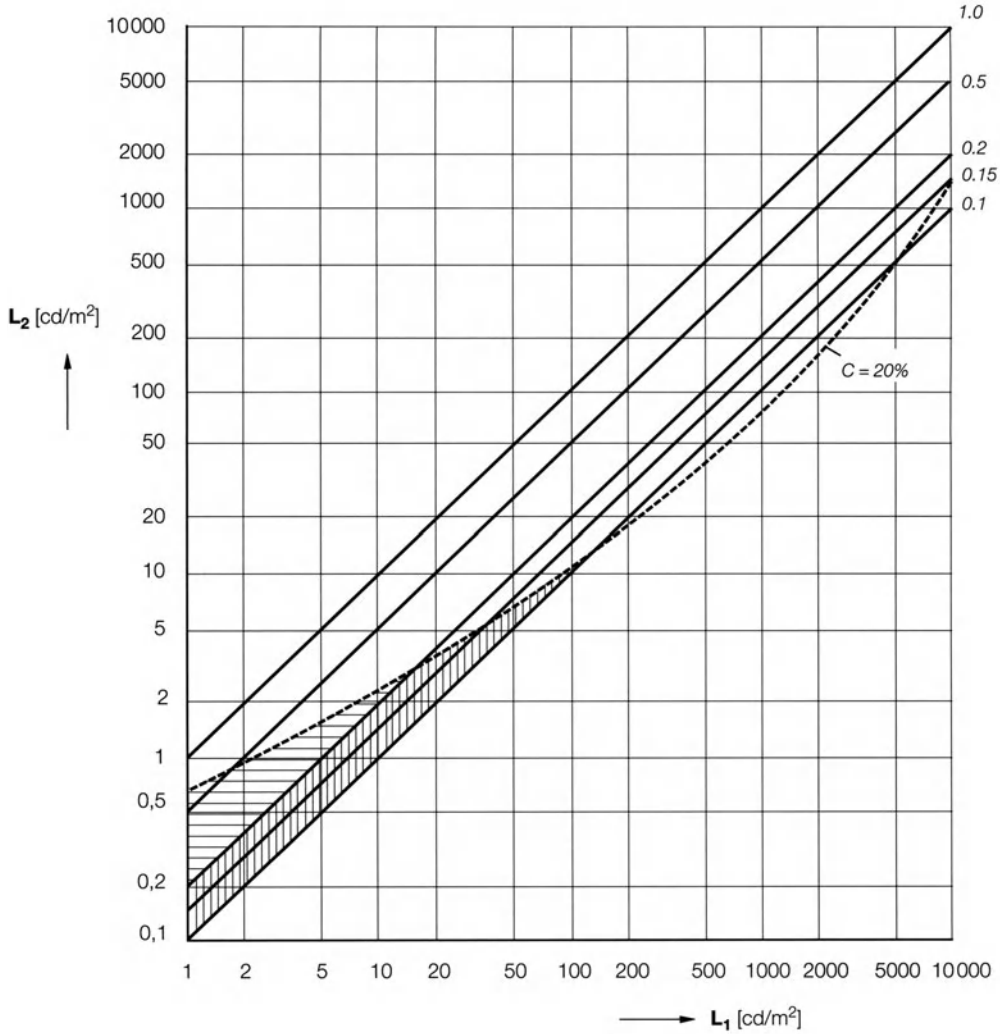


Figure 9.1.6: *The relation between the contrast sensitivity and the adaptation luminance. L_1 is the background luminance, L_2 is the luminance of the test object. After Schreuder, 1998, Figure 7.2.2. Based on data of Schreuder, 1964.*

In spite of the discrepancies at very high adaptation levels, it seems to be justified to use the CIE RSC-curve, as depicted in figure 9.1.4, for our considerations about the contrast sensitivity except for very high values of the adaptation level – say below 2000 cd/m^2.

It should be noted that the Standard RSC-curve is, in fact, only one of a complete family of curves. The Blackwell-studies made it abundantly clear that the results depend heavily on a number of parameters, the most important of them being:

(1) The time of exposure to the stimulus (the observation time). In the experiments, the observation time did range from very short to unlimited; in almost all cases, only the data for an exposure tine of 0,2 seconds are used;
(2) The size of the stimulus. In the experiments, targets were used that measured from 0,6 to 360 minutes of arc (Middleton, 1952, p. 87).
(3) The probability of detection (the percentage of 'hits' or correct answers). The method of research did allow to present data for quite different values of the probability of detection. For research of a more fundamental nature, usually the 50% detection values are used, whereas in practice, for reasons of safety and security, a much higher probability of detection is required. An increase of the probability of detection from 50% to 'almost' 100% would require an increase in the luminance difference with a factor of about 3,1 (Hentschel, 1994, p. 52)

It should be noted that the age and the gender of the observers was not a variable. All subjects were female between 19 and 26 years old. However, "A special short series of observations established a high probability that the sex of the observers had little effect on the threshold" (Middleton. 1952, p. 88). Although it is not clearly stated, it seems that they all were Caucasian with normal eye-sight, or eye-sight corrected to normal.

Other important parameters that were not included in the test were:
- the shape of the test objects; all test objects were circular disks. The Blackwell-data may be used for objects with a different shape as long as they are not extremely thin. The data may be used for rectangles where the long side is less than 7 times the short side (Middleton, 1952, p. 91, referring to Lamar et al., 1947; 1948).
- the colour ot the light. In sec. 9.1.7, we will come back to this point in the discussion of the visibility of coloured and non-coloured point light sources.

The report of the Tiffany studies as presented by Blackwell in the famous JOSA-article gives only the arithmetical means of all observations that were made at a particular measuring point. Data on the spread are not given; therefore it is difficult to judge the results in terms of statistical significance (Blackwell, 1946).

The fact that the measurements were restricted to adaptation levels below 300 cd/m^2 whereas the results were extrapolated to values of 10 000 cd/m^2 was discussed in an earlier part of this section.

(d) The transition between photopic and scotopic vision in contrast sensitivity

In sec. 9.1.2c, the relation between the luminosity and the luminance is discussed, as was investigated by Hopkinson et al. (1941). One remarkable aspect was mentioned: there is not a clear breach in the visibility process at the transitions from photopic to mesopic and from mesopic to scotopic vision.

In the earlier interpretations of the Blackwell data this fact was not always recognised. In some representations of the Blackwell data, a breach and not a smooth curve was given when the adaptation luminance is changed. As an example, we will give the results of the Blackwell-data as recalculated by Adrian (1969). The results are depicted in Figure 9.1.7.

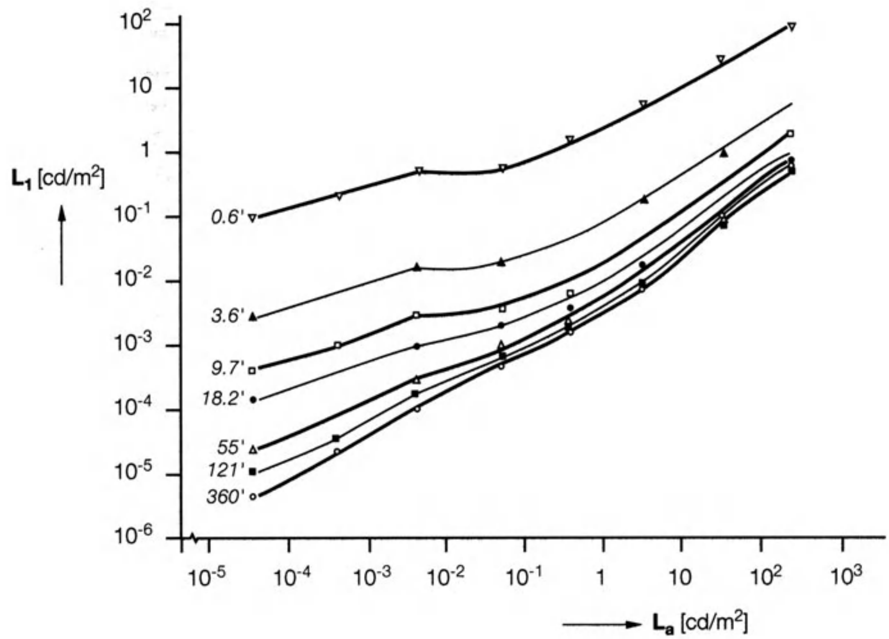


Figure 9.1.7: *The relation between the differential luminance threshold and the adaptation luminance for different sizes of the test objects and for a probability of observation of 50%. After Hentschel, 1994, figure 3.7. Based on Adrian, 1969. Data after Blackwell, 1946.*

How does that relate to the Tiffany Data? To begin with, it should be noted that the observers were free to select their own strategy of observation, allowing them to switch from parafoveal to foveal observation (Middleton, 1952, p. 88). This may be the best way to detect dim stimuli at low adaptation levels in the field, but leaving the direction of sight free does not allow us to know whether the observations were made in the rod-free fovea or in the parafovea with plenty of rods – in other words, the tests do not allow us to know whether the observations were made with cone or rod vision. It seems strange, therefore, that the Blackwell data are often quoted as showing clearly the transition from cone to rod vision – from photopic to scotopic vision. As an example of this reasoning we have depicted a part of the Blackwell results in Figure 9.1.8.

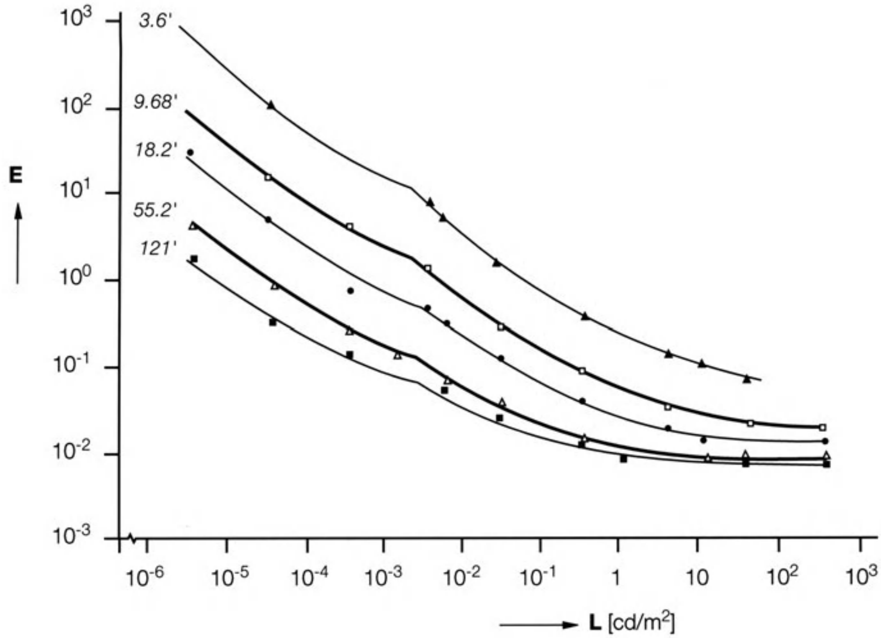


Figure 9.1.8: *Threshold of brightness-contrast for 50% detection for five stimulus diameters in minutes of arc. After Middleton, 1952, fig 5.2. Based on data from Blackwell, 1946.*

The graphs suggest a slight change in slope around adaptation levels between the luminance values of 10^{-2} and 10^{-3} cd/m^2. These slight changes seem hardly to support the following statement: "The first thing that strikes the eye is the discontinuity in all the curves at $2 \cdot 10^{-3}$ cd/m^2. This marks the transition from parafoveal to foveal vision. It was pointed out by Hecht (1947) that any curve of this sort must have a break, a fact that has not been realised by all experimenters, some of whom have attempted to draw smooth curves through all their data" (Middleton, 1952, p. 88-89). We may assume that Hecht referred to the transition between cone and rod vision, a transition that was at that time supposed to be sudden and complete, and occurring at one particular level of adaptation. The quote from Middleton is remarkable in the way that it seems to prove that, when a theory is adopted by the scientific establishment, all data are squeezed into it. Nowadays we know that the transition between cone and rod vision is not sudden and complete at all; the whole mesopic area is in between them, as is explained in detail in sec. 8.3.4c. And, of course, when something happens, it does not happen at $2 \cdot 10^{-3}$ cd/m^2 as is suggested by Middleton. This luminance value is clearly in the scotopic area of vision and not near any transition zone at all.

(e) Contrast sensitivity data

As has been indicated earlier, in spite of the criticisms, the Blackwell-data, particularly as presented in CIE (1981), represent by far the best set of data that is available at present as regards the contrast sensitivity. As indicated before, it can be stated as a conclusion that it seems to be fully justified to use the CIE RSC-curve, as depicted in

Figure 9.1.4, for our considerations about the contrast sensitivity except for very high values of the adaptation level – say below 2000 cd/m^2. For many practical purposes, it may be preferred to use the curves as they were redrawn by Adrian (1969). These curves are given in Figure 9.1.7.

9.1.4 The visual acuity

(a) Visus

If we would consider the contrast sensitivity as the most important visual function, the visual acuity would be the second. The most common description of the visual acuity is the reciprocal value of the smallest object or the smallest detail which still can be perceived. In optical instruments, this is usually designated as the resolving power. In medicine, often the term 'visus' is used. Visual acuity is usually defined as the angular measure of the smallest object that can be discerned. For healthy adults with good eyesight or with good glasses, the smallest object usually is smaller than one minute of arc. According to Hubel (1990, p. 46) it is about half a minute of arc. The limit of one minute of arc is often indicated as a vision of 100/100 or as 100%. This applies to the fovea.

The measurements made by Lythgoe (1932) have attained the status of a 'classic' in psycho-physics. They cover a range from 0,03 to 3000 cd/m^2 of adaptation luminance. The measurements were made in white light with a natural pupil and unlimited exposure time. Landolt C objects were used as test objects. These objects looks like the capital letter C; its gap is the actual test object detail to be detected. The shape is carefully defined. (Schreuder, 1998, p. 101; De Boer & Fischer, 1981, p. 14-16). The results are depicted in Figure 9.1.9, as represented by Walsh (1958/1965).

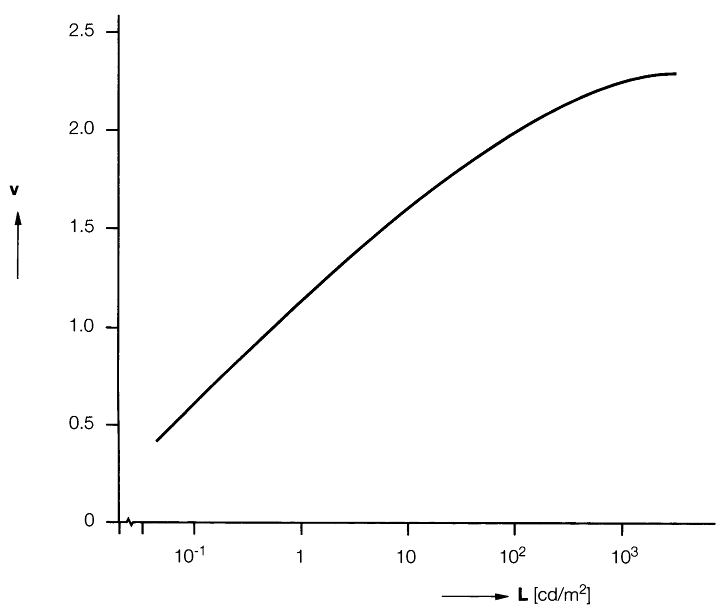


Figure 9.1.9: *Relation between visual acuity v and luminance. After Schreuder, 1976, figure 4, based on Walsh, 1958/1965, figure 39.*

A compilation of relevant measurements is given by Hentschel (1994, fig. 3.13). All measurements are made in white light with black Landolt-rings as test objects. They are therefore in this respect comparable. See the discussion furtheron in this section. No information is given about the exposure time, so one may assume that all data refer to unlimited observation time. The results are depicted in Figure 9.1.10.

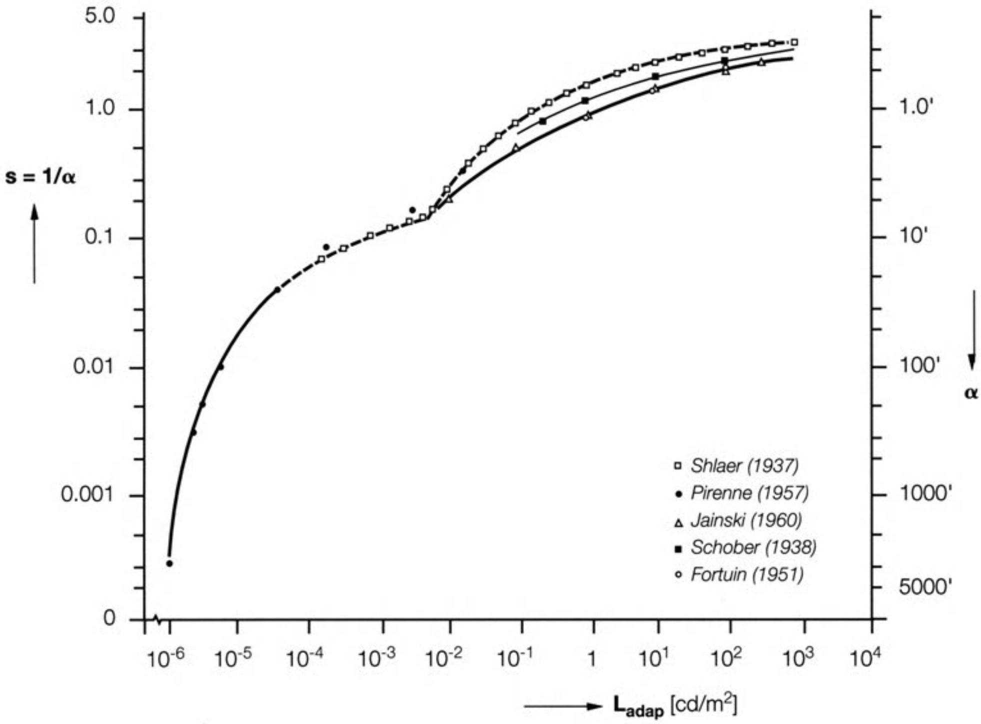
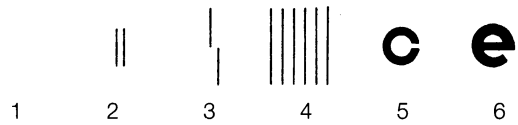


Figure 9.1.10: *The relation between visual acuity and adaptation luminance. After Hentschel, 1994, fig. 3.13. based on data of Shlaer, 1937; Pirenne, 1957; Jainski, 1960: Schober & Wittmann, 1938 and Fortuin, 1951.*

(b) Test objects

The test object that is used for the determination of the visual acuity is of crucial importance. A number of different types of test object that are commonly in use, are depicted in Figure 9.1.11. For the sake of comparison, the most common test objects for detection and for form discrimination are added in this figure. It may be noted that 'nonius' and 'vernier' actually mean the same.



igure 9.1.11: Some elementary test objects. After Baer, 1990, figure 1.47. 1: detection; 2: discrimination; 3: nonius acuity; 4: resolution; 5: Landolt ring; 6: form discrimination.

Each test object will lead to a different definition of the visual acuity and consequently to a different value. In Table 9.1.4, some data on the resolving power of the eye are given.

Object	Minimum angle (minutes of arc)	Retinal measure (μ)
two stars	1,0	4,3
two black bars on white ground	0,5	2,1
vernier (nonius)	0,15	0,65
spider web on dark ground	0,13	0,57

***Table 9.1.4:** The resolving power of the eye. After Moon, 1961, Table XLVIII.*

The type of test object must always be mentioned when describing the test results. The data given by Lythgoe (1932) and those compiled by Hentschel (1994) are all made with Landolt rings.

(c) *The visual acuity for point sources*

Point sources form an important class of test objects. As is discussed in sec. 9.1.7, point sources are also important in other aspects related to the limitation of light pollution. The colloquial definition of a point source is simply a source that is so small that no extension can be seen. Stars are point sources. However, this definition cannot be used in a more precise consideration of the visual detection of point sources. Due to the diffraction – and to other optical aberrations as well – a point source will never be seen as a mathematical 'point'.

There are two ways to look at electromagnetic radiation:
(1) As waves in the electromagnetic field with a small but finite wavelength that travel at the speed of light.
(2) As a stream of very small particles that travel at the speed of light. The particles are called photons.

The two ways to look at the radiation are mutually exclusive: it is either the one or the other. In optical imaging, always the wave model is relevant.

From theoretical optics it is well-known that, when light hits a screen after passing through a small circular aperture, a ring-shaped pattern will be seen. This pattern is called the diffraction pattern. For an arrangement with circular symmetry, the illuminance at a point P on the screen is given by the relation:

$$E = E_0 \cdot \left| \frac{J_1(2m)}{m} \right|^2 \qquad [9.1.11]$$

with:

$$m = \frac{\pi \cdot \delta}{2\lambda} \cdot \frac{r_0}{z_0} \qquad [9.1.12]$$

in which
δ: diameter of light source;
r_0: displacement of P in the screen from the axis;
λ: wavelength of the light;
z_0: the distance between the source and the screen;
J_1 (2m): the Bessel function of the first order;
E: illuminance in P;
E_0: illuminance for $r_0 = 0$;

The relation is given here in the form as presented by Moon (1961, equation 12.11, p. 425). The mathematical derivation is given by Feynman et al. (1977, Vol. I. Sec. 30-1, p. 30-2). See also Van Heel (1950) and Longhurst (1964).

For the calculation of the pattern it is assumed that a large number (n) of oscillators of equal strength are spread evenly over the aperture (Feynman et al. (1977, Vol. I. p. 30-1). Their phase (Φ) differs for different positions on the screen. This, of course, is the cause for the diffraction pattern to arise. The resulting intensity on the screen shows a pronounced maximum at phase zero – straight ahead. For increasing phase, the intensity on the screen passes through a series of equally spaced minima with maxima in between. The intensity in the minima is zero; the intensity of the maxima decreases rapidly with increasing phase. The intensity at the first maximum is less than 5% of that of the maximum at phase zero (0,0047; Feynman et al. (1977, Vol. I. p. 30-2). See Figure 9.1.12. Measurements of the retinal distribution are described by Vos et al. (1976).

For the practice of determining visual acuity an important test condition is called the 'minimum separable'. It is the minimum distance between two points of light – the 'two star' mentioned in Table 9.1.4. Crudely speaking, the apparent size of a point source is said as being equal to the width of the first spread-out maximum, that is the place where the first minimum occurs, or, more precisely, the diameter of the first diffraction ring. The minimum distance is determined by the refraction in the eye in such a way that the two objects seem to be situated at consecutive maxima, that are, as indicated earlier, equidistant in angular measure.

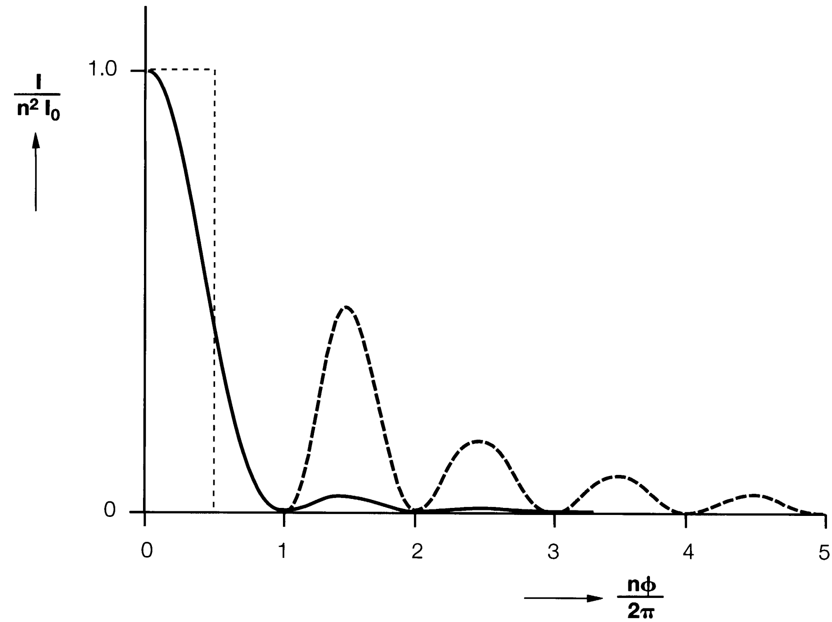


Figure 9.1.12: *The calculated refraction pattern. After Feynman et al., 1977, Vol. I. fig. 30-2.*

Using the pattern as given in Figure 9.1.12, the minimum separable can be calculated. See Figure 9.1.13.

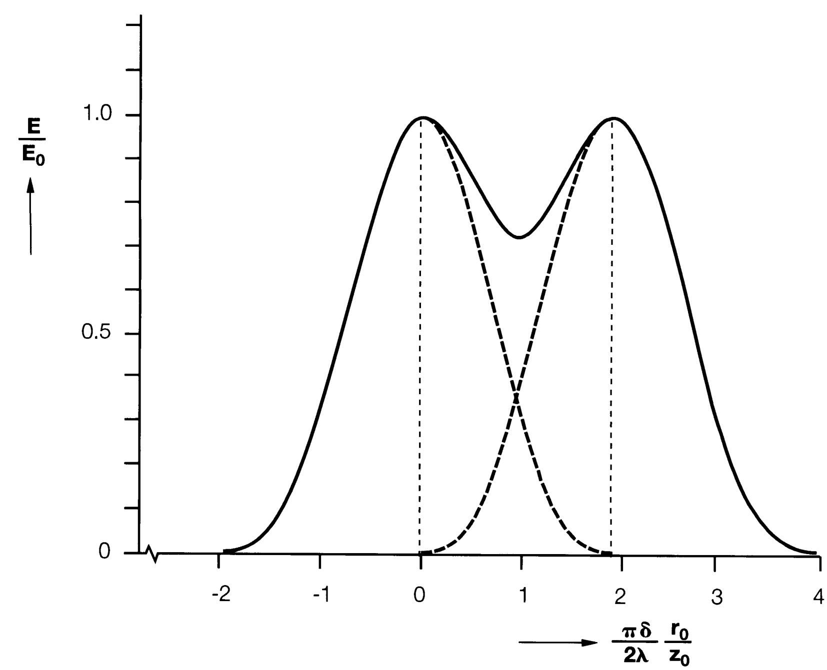


Figure 9.1.13: *The calculated retinal illumination caused by two light sources at minimum distance. After Moon, 1961, figure 12.17.*

The detection of point sources is discussed in detail in sec. 9.1.7.

(d) Visus and visual acuity

The visual acuity (or visus) is the most common measure for the quality of the visual system. The reason is not completely clear. Maybe it has to do with the fact that the visus is easy to assess without elaborate equipment, also by a general practitioner – the family doctor – and that is has some value of a diagnostic expedient. If something is wrong with your visus, there is a fair chance that there is much more wrong with your visual system, or maybe even with your general health situation. But as a scientific tool, the matter is different. It is often assumed that, if people cannot see details quite good, their general vision is impaired, and they should not be allowed at the wheel of a car. This, of course, is not completely true. As has been explained by Schreuder (1976, sec. 3.3.2; 1988), the visual acuity is in reality not a good measure for visual performance. In spite of that, driving tests, that are very lenient in most countries as regards most physical or psychological factors, are very strict as regards visus. There are a number of reasons for this misconception:

(1) Most real-life visual tasks are quite different from the detection of very small, colourless, high-contrast, stationary objects that are used in visus tests;
(2) The visus is determined for the fovea, whereas a large part of observations in real life is done in the periphery;
(3) Usually, the visual acuity is determined in white light, whereas the colour of the light has a considerable influence. This influence is discussed later in this section;
(4) Most methods of assessing the visus are not adequate and cannot withstand scientific scrutiny as is explained by Vos (1969). More in particular, when normal letters are used, form recognition will play a role. Form recognition is discussed in a further part of this section.

Because the density of the photoreceptors in the retina decreases with increasing eccentricity in the field of view, the visual acuity decreases as well with increasing eccentricity. See Figure 9.1.14. These data are represented also in an earlier section. See Figure 8.2.5.

A further reason of the decrease in visual acuity towards the periphery is the fact that the rods in the retinal periphery do not operate individually, but in clusters. The clusters are sets of rods that interconnect by neurons. They are called 'receptive fields' (Hubel, 1990, p. 39-46). The clusters tend to increase in size in the far periphery. This is one of the reasons that the visual acuity decreases with increasing eccentricity more rapidly that would correspond to the 'dilution' of the rod density towards the periphery. The visual acuity also depends on the size and the relative luminance of the surrounding field (Stevens, 1969, p. 12). This is related to the fact that the receptive fields have a central zone and a border zone (Hubel, 1990, p. 52). The clusters increase in size for lower adaptation luminances; at lower luminances, more rods are working together by means of changes in the neural interconnections. Thus, the visual acuity in the periphery decreases with decreasing light level. See also Hentschel (1994, p. 57). Some data representing the visual acuity are depicted in Figure 9.1.15.

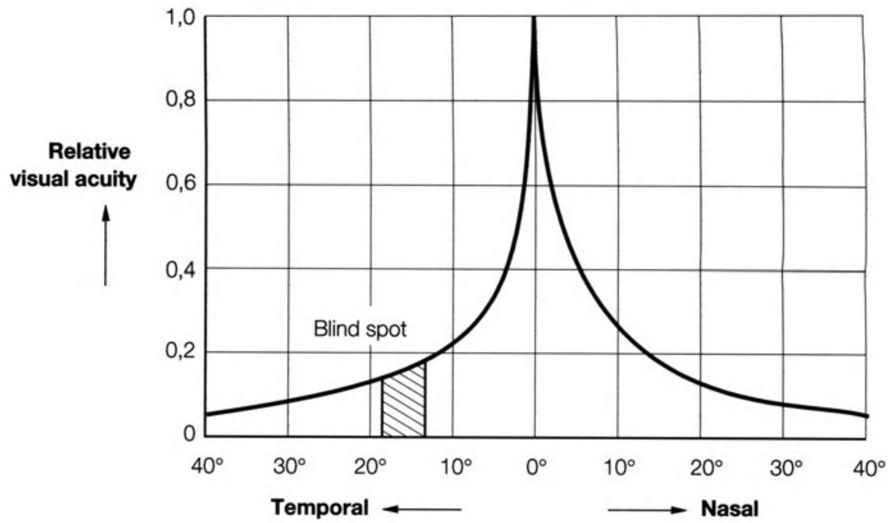


Figure 9.1.14. *The relation between visual acuity and the location on the retina. After Schreuder, 1998, Figure 7.2.3. Based on Hentschel, 1994, figure 3.12. Data from Wertheim (1894).*

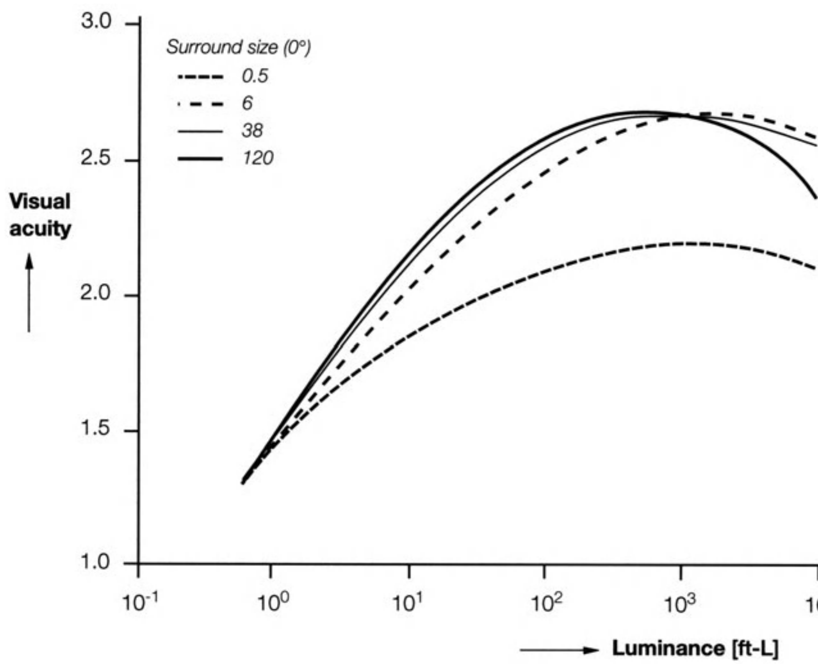


Figure 9.1.15: *Relation between luminance and visual acuity for different sizes of surrounding field. After Stevens, 1969. Fig. 1.5. Based on data from Foxell & Stevens, 1955.*

(e) *Visual acuity in relation to the shape of the test object*

In the earlier part of this section, the changes in the visual acuity with changing retinal location and with changing adaptation luminance are explained in terms of changes of the coupling of rods. The number of rods that work together in one cluster is not constant. However, this explanation does not clarify why the visual acuity changes with different lighting parameters for the cones as well. There are many interrelations between the cones; there is feed-back between the cones and the neurons, but basically, each cone has its own neuronal channel and its own cortical location (Hubel, 1990, p. 50; Feynman et al., 1977, secs. 35 and 36).

The first point to note is the shape of the test object. One might suppose that the tests would consist of the detection of a small object. This object ought to be really small, somewhere near the threshold of detection.

As is explained in sec. 9.1.1a, the threshold value is defined as the value at 50% of the cumulative probability distribution of the measurements. In order for the 50% to be included in the cumulative probability distribution, the measurements must be made with test objects that are larger than (or over) the supposed threshold value as well as with objects smaller than (or below) the supposed threshold. It the case of the determination of the threshold value of the visual acuity, this would mean that the size of the test object should be considerably smaller than one minute of arc. As is explained in sec. 9.1.7, when discussing the threshold value for the detection of point light sources, the threshold of detection of very small objects depends very much on whether its location is known or not. If the location is not known, the threshold may be ten times as high as when the position is known. It follows that the position of the test object must be known to the observer in measuring the visual acuity; if the position were unknown, the test would be an exercise in search patterns. This would involve heuristics as a stratagem. Heuristic stratagems are mentioned briefly in sec. 10.1.2. Interesting indeed, but not relevant at this stage. The consequence is that the test object must be a part – a detail – of a larger object. This is in line with the definition of the visual acuity, but it encloses a completely new phenomenon. The test may not be a test for the visual acuity any more, but for the detection of the form of the object! Form recognition and Gestalt observation are discussed in sec. 10.2.1, whereas the related phenomenon of pattern recognition is discussed in sec. 14.5.2d. The point here is that the visual acuity never can be completely separated from the form recognition. This implies that the outcome of the acuity test depends very much on the shape of the test object, and on the fact whether the observers know the object or not. The letters in the so-called ‘Snellen-chart’ are not particularly suitable for research, although they are very useful in the medical practice of the ophthalmologist for screening purposes. See Stilma (1995) and Vos (1969). As mentioned earlier in this section, for research purposes mostly the Landolt C objects are used as test objects. These objects looks like the capital letter C. The width of the letter is one-fifths of its outside diameter, and the gap is square. So the test object is easy to locate. The gap is the actual test object detail to be detected. The visual task is to locate the direction of the gap, which can be indicated in many ways, like e.g. up – down – left – right, etc. As mentioned earlier, the shape is carefully defined. (Schreuder, 1998, p. 101; De Boer & Fischer, 1981, p. 14-16).

(f) Visual acuity in relation to colour

Finally, the visual acuity depends significantly on the colour of the light. In the past, the colour of the light was considered an important aspect of road lighting and of vehicle lighting. As regards road lighting, this interest did stem from the time when only two 'families' of light sources were available for the lighting of traffic routes:

(1) High-pressure mercury lamps (colour corrected or not);
(2) Low-pressure sodium lamps.

In sec. 11.1, the physical characteristics of these lamp types are discussed in detail. The light-technical and colour characteristics are discussed in sec. 11.3.

The use of low-pressure sodium lamps was promoted for traffic routes, where the fact that their light is almost monochromatic is not considered as a disadvantage. Contrary to this, the higher visual acuity that is systematically reported was considered as an advantage, and so was the impression from studies that the light penetrated better through fog and haze, and caused less discomfort glare. Discomfort glare is discussed in sec. 9.2.3. The different aspects of the colour of the light for road lighting are discussed in great detail in De Boer (1967); Schreuder (1967); Van Bommel & De Boer (1980). The aspects of the colour of the light for vehicle headlighting are discussed in great detail in Schreuder (1976). See also sec. 12.2.

It is natural to expect that the visual acuity depends on the chromatic aberrations in the eye. These aberrations are discussed in sec. 8.1.2. Monochromatic light causes by definition no chromatic aberrations; light that contains only a few spectral lines will cause only slight aberrations, and so forth. When the most common gas discharge lamps that are used for outdoor lighting are grouped along the degree in which they approach light sources with a continuous spectrum, one finds the following sequence:

(1) Low-pressure sodium lamps (monochromatic);
(2) Uncorrected high-pressure mercury lamps (line spectrum);
(3) Corrected high-pressure mercury lamps (line spectrum with narrow bands);
(4) High-pressure sodium lamps (line spectrum with wide bands);
(5) Low-pressure mercury lamps (fluorescent tubes; multi-band spectrum);
(6) Incandescent lamps (continuous spectrum).

This sequence is precisely the sequence in which the visual acuity decreases. This is depicted in Figure 9.1.16. In this figure, the relative visual acuity in the light of low-pressure sodium lamps (Na); uncorrected high-pressure mercury lamps (HP); corrected high-pressure mercury lamps (HPL) and fluorescent tubes (TL) are compared. The light of incandescent (tungsten filament; Gl) lamps is taken as 100%.

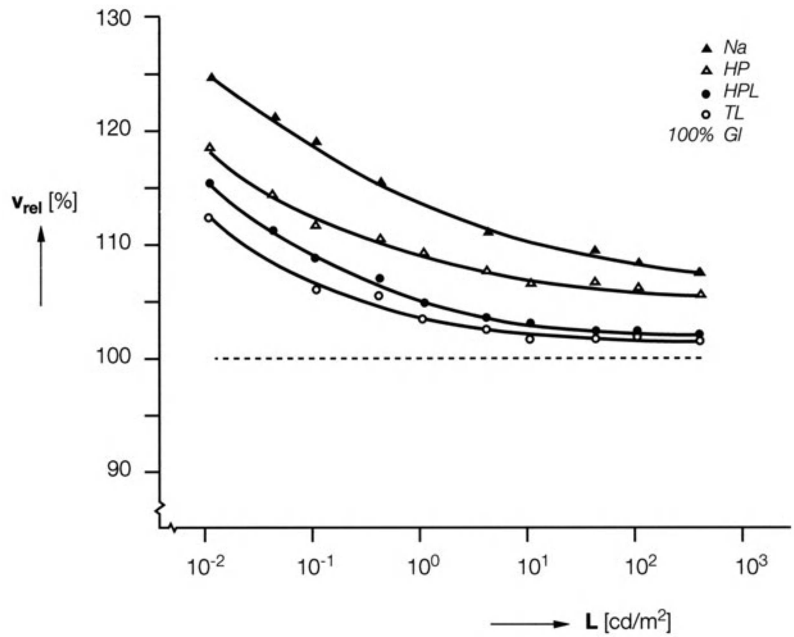


Figure 9.1.16: *Relation between the visual acuity and the adaptation luminance for different light sources. After Schreuder, 1976, figure 5. Based on data of Jainski (1960)*

It should be noted that much of the interest that was shown in the past to the differences in visual performance in different colours has disappeared. In outdoor lighting, the controversy between 'white' (mercury) and 'yellow' (sodium) lamps is not important any more because a number of other lamp types with widely different colour characteristics have been introduced. Most of these lamps are discussed in sec. 11.3. As for vehicle headlighting, a similar controversy between 'white' (standard) and 'yellow' ('selectiva') lamps is not important any more because European regulations prohibit the use of yellow headlamps.

It is interesting to note that the sequence of preference of lamps for outdoor lighting given here in this section as regards the visual acuity in relation to colour, may be found in other respects as well:

- considerations of discomfort glare;
- energy costs;
- preference for astronomical observations;
- preference for wildlife.

These different aspects are discussed in different other sections of this book.

9.1.5 The speed of observation; flicker-effect

(a) The discrimination in time

Many performance aspects of the visual system depend on the adaptation luminance. One of these aspects is the capability to discriminate time intervals. It seems that the integration time of stimuli increases when the adaptation luminance decreases. The integration time is the time interval where stimuli that enter the eye at different moments in time are observed as one single stimulus with an intensity greater than that of the individual stimuli. In this way, the system sensitivity can be increased (Gregory, 1965, p. 78). It might be considered as another adaptation effect. In this way, the retina behaves much like a CCD (Sterken & Manfroid, 1992, Chapter 13).

A consequence of this elongated integration time is that the response to a stimulus in low luminances is retarded compared to the response in higher luminances. This can be demonstrated very easily with what is commonly called the Pulfrich pendulum. One takes a normal pendulum, swinging from right to left and vice-versa. When looked at it straightforwardly, one sees just that: a pendulum, swinging from right to left and vice-versa. Now, one eye – e.g. the left eye – is covered with a dark filter (e.g. half of a pair of ordinary sunglasses). The left eye will adapt itself to a lower luminance. Consequently, the response to the stimulus is retarded. In the right eye, however, the adaptation stays unchanged. The response is not retarded like in the left eye. A simple geometric construction shows that the pendulum will appear to follow an elliptic trajectory. When the right eye would be covered by the dark glass, the pendulum would appear to travel in the opposite direction along the ellipse. With some training, the effect can be observed by simply partially closing one of the eyes. The Pulfrich-pendulum effect is depicted in Figure 9.1.17.

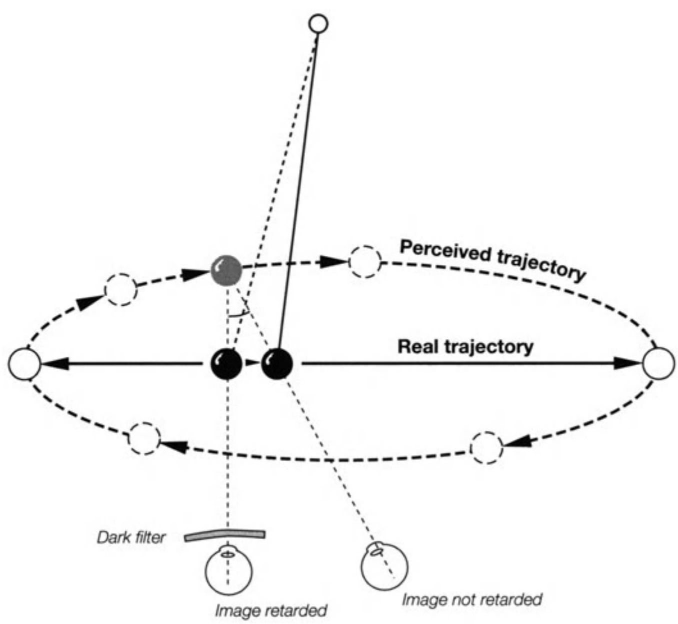


Figure 9.1.17: *The Pulfrich-pendulum effect. After Gregory, 1965, fig. 6.3.*

A very similar effect can be observed when looking at a double star with two components of considerably different magnitude. When one swings the head slowly side-ways, both stars seem to swing in the field of view. However, the amplitude of the brighter star seems to be larger than that of the dimmer star. The fact that the response to the stimulus is slower for the dimmer star than that for the brighter star may easily explain this phenomenon (see e.g Minnaert, 1942, Volume I, sec. 109, p. 150). It can be seen in any suitable double star; a good example is the well-known pair of Mizar and Alcor in Ursa Major. The magnitude of Mizar is 2,27 and that of Alcor is 3,95. They seem to be 12 minutes of arc apart (Schilling, 1992, p. 152). Minnaert suggests the use of a simple 'spy-glass' (Minnaert, 1942, Volume I, sec. 109, p. 150).

(b) The speed of detection

As is described in some detail in sec. 9.1.4e, in the past the colour of the light has been considered as being important in road traffic. In sec. 8.3.6, the more general aspects of the colour of the light are discussed in detail. One of the aspects that was discussed in the past was the speed of detection when using lamps with different colours. Although the discussion has been diminished in intensity more recently, the results may still be of interest when considering the reduction of light pollution.

For signalling lights and for automobile headlamps, the detection of the light itself is the subject of the studies; for lamps used in road lighting, attention was paid to the visibility of obstacles on the road.

In sec. 9.1.2a, the detection of flashing and of steady signalling lights is discussed. For the detection of the colour of the light, the intensity must be higher than the threshold value. For easy detection and for detection that involves searching for the light, much higher vales are needed.

Until very recently, all vehicle headlamps were tungsten filament lamps, or, as they are called more frequently but less accurately, incandescent lamps. In most countries, the lamps have no filter and thus emit light of a whitish-yellow colour. In the past, some countries permitted filtered light of a yellow colour. In France, the use of white light was prohibited. All this is history now since the European standards are obligatory in all countries of the EU. The yellow lamps were called selectiva-yellow lamps. A detailed study did not reveal any advantage of either type (Schreuder, 1976). As regards the speed of seeing this is supported by Reading (1966). Quoting measurements of De Boer (1959) and of Dunbar (1939), no differences in the speed of seeing were reported between filtered (yellow) and unfiltered (white) light (Schreuder, 1976, p. 38).

For considerable colour shifts, the speed of seeing depends on the colour of the light. This seems to be related to the fact that the regeneration in cone vision is not equally fast for the different visual pigments. This also results in the fact that after-images of different colours do not persists equally long (Minnaert, 1942, Volume I, sec. 94, p. 131-132). Furthermore, the flicker-fusion frequency for colours is lower than that for the brightness

(Hentschel, 1994, p. 69). This effect is used in the so-called flicker-photometer (Barrows, 1938, p. 123, quoting Rood, 1893). With the advance of high performance electronic photometers, the flicker-photometer is send to the museum. Its principle is, however, worth-while to look at.

(c) The flicker-fusion frequency

Related to the speed of seeing is the fact that periodic light stimuli seem to be steady when the frequency is above a certain value. This value is called the flicker-fusion frequency or FFF. The fusion frequency depends primarily on the adaptation luminance and on the retinal eccentricity (Moon, 1961, p. 451-452). Also the wave form has an influence (Hentschel, 1994, p. 60). The influence of the two major parameters is depicted in Figure 9.1.18.

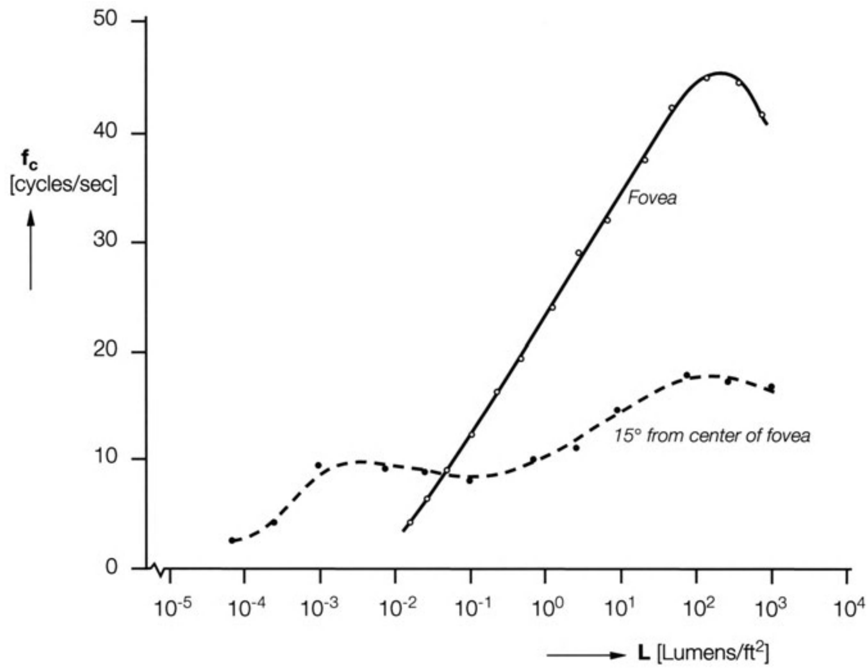


***Figure 9.1.18:** The flicker-fusion frequency for the fovea and for the periphery. After Moon, 1961, fig. 12.37 based on data of Hecht et al., 1934.*

Note to Figure 9.1.18. The adaptation luminance is expressed in lumens per square foot, which is actually a measure of the illuminance. For a surface with a reflectance of 0,8, the illuminance of 1 lumen per square foot corresponds to a luminance of about 2,74 cd/m^2.

It is interesting to note that over a wide range of luminances from about $3 \cdot 10^{-2}$ cd/m^2 to about 100 cd/m^2, the flicker-fusion frequency depends linearly on the logarithm of the adaptation luminance. This log-linear relationship is sometimes called the Ferry-Porter Law (Moon, 1961, p. 452, based on Ferry, 1892, and Porter, 1902).

More recent, or at least less ancient, research results are depicted in Figure 9.1.19.

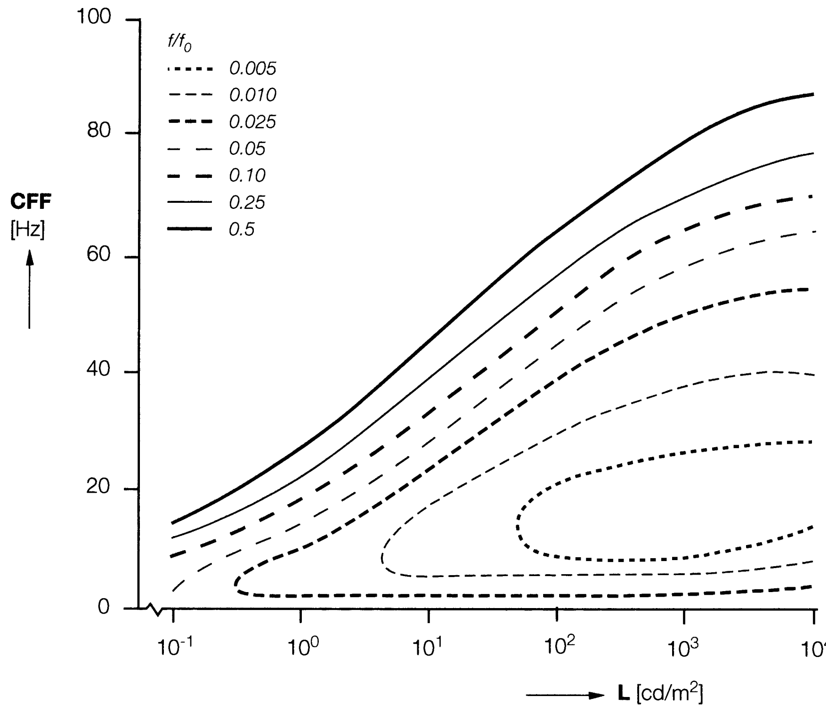


Figure 9.1.19: *The relation between the flicker-fusion frequency, the wave form and the adaptation luminance. After Hentschel, 1994, figure 3.14. Based on data of Kelly, 1961/1962.*

Note to Figure 9.1.19. The wave form is indicated by the parameter GW, the ground frequency ratio. This parameter is not defined by Hentschel, but it is indicated that for a square wave with equal light and dark period, it amounts to 0,637; for a sine wave it is 0,500, and for the light from a fluorescent tube it is about 0,15 (Hentschel, 1994, p. 60).

Light appears to be steady when the frequency is higher than the flicker-fusion frequency. Talbot's Law states that the effective intensity equals the time-average of the instantaneous intensity (sec.9.1.2a).

(d) Discomfort by flicker effects

When the frequency of the periodic light is below the flicker-fusion frequency, the flicker obviously can be perceived. It has been found that under certain rare conditions, flicker may cause epileptic attacks in people who are particularly susceptible for this. It was found, however, that, contrary to common belief, in practice no real problems arise. A survey of the relevant is given in Schreuder (1981). Flashing lights may cause stroboscopic effects. Just as with the epileptic attacks that were mentioned earlier, some people consider stroboscopic effects as a cause for concern. In reality, however, they cause problems in only a few very special cases (Baer, 1990, p. 66).

More problems are found in practical lighting applications. The flicker, when perceived, may cause considerable discomfort. In interior lighting, flicker from defective fluorescent lighting may cause the most nuisance when the frequency is close to the flicker-fusion frequency (Baer, 1990, p. 65; Collins & Hopkinson, 1957; Schreuder, 1964, p. 15).

At lower frequencies, some other effects seem to play a role. It has been suggested that interference with the α-rhythm of the brain may be responsible for the discomfort. See for the α-rhythm Greenfield (1997, p. 70) and Gregory, ed. (1987, p. 81). The low-frequency flicker effects are particularly disturbing in the lighting of long tunnels for road traffic. It was found that in a variety of conditions, the human visual system seems to acquire the highest sensitivity for the discomfort caused by flicker for frequencies between 5 and 10 c/sec (Kelly, 1961/1962; De Lange, 1957; Schreuder, 1964, p. 95). The measurements are described in summarized form in Schreuder (1967a; 1981) and Huijben ed. (2003).

Based on the earlier work of Jantzen (1960), extensive experiments were conducted on flicker effects with the emphasis on tunnel lighting (Schreuder 1964, sec. 5.3.; 1967a). The following conclusions were drawn (Schreuder, 1964, p. 96):
(1) A frequency of 2,5 c/s is a reasonable value for the lower limit of flicker disturbance;
(2) Frequencies over 14 c/s usually do not provoke any hindrance;
(3) The highest disturbance is found between 5 and 10 c/s;
(4) The hindrance depends very much on the modulation depth (Jantzen, 1960; Schreuder, 1964) and on the wave form (Collins, 1956; De Lange, 1957);
(5) The hindrance depends very much on the pulse-to-cycle ratio (Crozier & Wolf, 1941; Bartley & Nelson, 1961);
(6) For normal driving speeds, a centre-to-centre distance of tunnel lighting luminaires between approx. 0,75 and 9 m should be avoided, except when the modulation depth is small;.
(7) In tunnels, continuous line lighting is recommended.

These conclusions form the basis of almost all national and international recommendations and standards for tunnel lighting (CEN, 2001; CIE, 1973; 1984; 1990; 2003; NSVV, 1963 1990; Huijben ed., 2003).

In Japan, similar but more extensive measurements have been made (Saito & Narisada, 1968). A few of the results are summarized here:
(1) The duration of the exposure time to the flicker has little influence on the discomfort. See Table 9.1.5.

Time (seconds)	Degree of discomfort on relative scale
0,5	28
1	38
2	41
5	45
10	46
30	48

Table 9.1.5: *The influence of exposure time on flicker discomfort. Based on data from Saito & Narisada, 1968, fig. 8.*

(2) The size of the flickering light source seems to have more influence on the discomfort. See Table 9.1.6.

Size (degrees)	Degree of discomfort on relative scale
1	34
2	46
5	52
10	57
20	60

Table 9.1.6: *The influence of the size on flicker discomfort. Based on data from Saito & Narisada, 1968, fig. 9.*

(3) The modulation depth has an even larger influence on the discomfort. The modulation depth is expressed as the ratio (L_b/L_c) of the highest luminance (L_b) and the lowest luminance (L_c) in each period. In Table 9.1.7, data are given for two different waveforms a frequency of 6 c/sec.

Modulation depth (ratio L_b/L_c)	Degree of discomfort on relative scale wave form a	wave form b
2	22	26
5	30	44
10	48	60
20	61	75

Table 9.1.7: *The influence of the modulation depth on flicker discomfort. Based on data from Saito & Narisada, 1968, fig. 10.*

It can be concluded that the results reported by Saito & Narisada (1968) are very similar to those of reported by Schreuder (1964). The only real difference is that the frequencies of the 'area of annoyance' seem to be somewhat higher. According to Saito & Narisada (1968), the area of major discomfort is between 6 and 13 c/sec, compared to values of 5 to 10 c/sec. as found by Schreuder. For tunnel lighting this might have some minor consequences, but not for general lighting.

9.1.6 Detection of movement

The perception of movement is complex and is only partly understood. It is easy to understand how the movement of on object is detected when the eye does not move: the image of the object moves over the retina. However, if the eyes move as well, the visual system seems to be able to make a distinction between the movement of the retinal image due to the movement of the object itself and that of the eyes. It is clear that the muscles that govern the eye movement, play a role. It is equally clear that 'constancy' plays a role. As is explained in sec. 9.1.2d, constancy is understood as the phenomenon that the object – or the whole world – is observed as being stationary, even if the eye or the observer as a whole moves. Obviously, it is not enough to consider the eye-movement muscles, because constancy effects can be observed when the body is displaced without any muscular activity, e.g. in a train. It would seem that all sorts of feed-back mechanisms are involved, including the input by other sense organs and also including cognitive effects.

In the literature, one may find a number of elegant, simple, but convincing test that may demonstrate the role of the eye muscles (Gregory, 1965, chapter 7). A slight pressure on the side of the eye may move the eye ball slightly. Objects in the surroundings are seen to move as well. Apparently, the mechanical movement of the eye ball circumvents the constancy effect, contrary to eye movements that are made by using the normal eye-movement muscles.

Another aspect that seems worth-while to mention is the fact that, during eye movements, the transmission of signals from the eye is suppressed. The usual explanation is that this is necessary to avoid 'smear' over the field of view. There is an additional interesting effect. The eye movements seem to take no time; they seem to be instantaneous. From the physiology of the visual system it is well-known that the eye movements – like e.g. saccades – take about 0,2 seconds. This effect is easy to observe: when one looks, in a mirror, into the right eye and shift the view to the left eye, there is no apparent time for the shift. The transition seems to be instantaneous. This experiment stems from Van Essen (1968). See also Van Essen (1965). However, when a short, very intense flash is sent into the eye during the period of the saccade, it will be visible. It seems that the suppression of the signals is not absolute but limited to a certain intensity value. The flash is observed and located in the field of view, but not at the location of the flashing light source before, nor to that after the saccade. The light flash seems to fall at an arbitrary place. This effect is very easy to observe when one looks at the flashing beacon lights of a passing airliner.

The plane seems to fly straight on and stay on a steady coarse, but the beacon seems to wander all over the place. Details are given in Schreuder (1984).

Although there seem to be some similarities with the phenomena described here, the illusion of movement is in fact a rather different phenomenon. Under certain conditions, movements can be observed although the objects in the 'outside world' stay stationary. Some phenomena are described in detail in Gregory (1965, chapter 7, p. 99-104). When, in a completely dark surrounding, a dim point source of light is presented, the image seems to move around in an erratic way. The reason is still unknown. The erratic movement suggests some relationship with the saccadic eye movements that were cited earlier in this section. This idea in line with some early studies (Anon, 1857; 1942). These studies are quoted by Minnaert (1942, Volume I, sec. 107, p. 146). However, according to Gregory, the studies do not agree with the studies of Guilford and Dallenbach from 1928 (Gregory, 1965, p. 100). As no further information about these studies is given by Gregory, it is difficult to judge the value of this remark.

9.1.7 The detection of point sources

(a) The definition of a point source

The colloquial description of a point source is simply a source that is so small that no extension can be seen. Stars are point sources. However, when we consider more precisely the visual detection of point sources, this description is not good enough. When light passes through an aperture an hits a screen, the dimensions of the source on the screen are limited by the diffraction. The optical aspects of diffraction discussed in detail in sec. 9.1.4c. In this respect, there is no difference whether the source is viewed by the unaided eye or via an optical apparatus. In the first case, the aperture is the eye pupil and in the second case it is the entrance pupil of the optical system (Van Heel, 1950). In most telescopes the entrance pupil is the objective – lens or mirror – of the telescope.

In sec. 9.1.4c, a method to assess the diameter of the 'image' is given. This is usually supposed to be the diameter of the first diffraction ring. For the unaided eye the radius of the first ring is 1,916 (Moon, 1961, p. 426). Although it is not stated by Moon, we may assume that the unit is a micron. We may assume the focal length of the eye as 23,996 mm and the index of refraction of the optical media in the eye as about 1,38 (Hentschel, 1994, Table 1.1). The optical length of the eye is $23{,}996 \cdot 1{,}38 = 33{,}1$ mm. When the image of the point source on the retina is point is 0,001 916 mm, it covers an angle of $57{,}8 \cdot 10^{-6}$ radiant or about 0,194 minute of arc.

In sec. 9.1.4, a number of measures of the visual acuity is given (Hentschel, 1994, figure 3.13). It is found that for an adaptation luminance of 100 cd/m^2, the visual acuity corresponds with about 0,5 minutes of arc, for an adaptation luminance of 1 cd/m^2 about 1 minute of arc and for an adaptation luminance of 0,01 cd/m^2 about 3 minutes of arc. This corresponds well to the value of 'one minute of arc' that is generally used in practice (Vos et al., 1976; Schreuder, 1998, chapter 7). It is quite clear, therefore, that the eye is not 'diffraction limited' (Kuchling, 1995, sec. 26.2.6; Longhurst, 1964). The assessment of the diffraction pattern is not relevant for the human visual system. It may, however, be relevant for top-quality optical telescopes. The image can never be smaller than a certain limiting size, even with excellent diffraction limited optics (Kuchling, 1995, sec. 26.2.6; Longhurst, 1964).

A simplified approximation of the resolution of the eye and telescope is given in Kuchling (1995, formula 26.12, p. 388):

$$s = 0{,}61 \cdot \frac{\lambda}{r} \qquad [9.1.13]$$

with:
s: The resolution in angular measure;
λ: The wavelength of the light;
r: The radius of the effective aperture.

As an example, the resolution is determined for a number of different conditions, ranging from the unaided eye to very large telescopes. See Table 9.1.8. The resolution is determined for one wavelength only. The selected wavelength is 542,5 nm, corresponding to green-yellow light. This value is chosen because it corresponds to the wavelength for which the spectral energy distributions of CIE reference sources are normalised as 100% (De Boer & Fischer, 1981, figure 4.9, p. 102). In sec. 8.3.8e, the relative spectral energy distributions of a number of reference light sources selected by CIE are depicted in Figure 8.3.14. The wavelength of 542,5 nm is close to the wavelength of 556 nm. As is indicated in sec. 8.2.2, the wavelength of 556 nm. is by definition the maximum for the spectral sensitivity of the average normal eye for photopic vision (see e.g. Barrows, 1938, Table 1.1). The values of the resolution in the table correspond very well with those of Weigert & Wendker (1989, p. 67).

Radius r (mm)	**Example**	**Resolution s** (seconds of arc)
1	eye, small pupil	66,71
3	eye, extended pupil	22,24
5	theatre spy glass	13,34
10	small field glasses	6,67
100	small size amateur telescope	0,667
1000	large size amateur telescope	0,0667
5000	large size professional telescope	0,00133
50000	large compound telescope	0,000133

Table 9.1.8: *Values of the resolution s for λ = 542,5 nm*

A different definition of a point source is based on the studies of Blackwell that are discussed in sec. 9.1.3. The definition is: "A point source is a stimulus which affects the eye only in proportion to its intensity" (Middleton, 1952, p. 96). The size of a source that may be regarded as a point source based depends on the adaptation luminance. This is depicted in Figure 9.1.20.

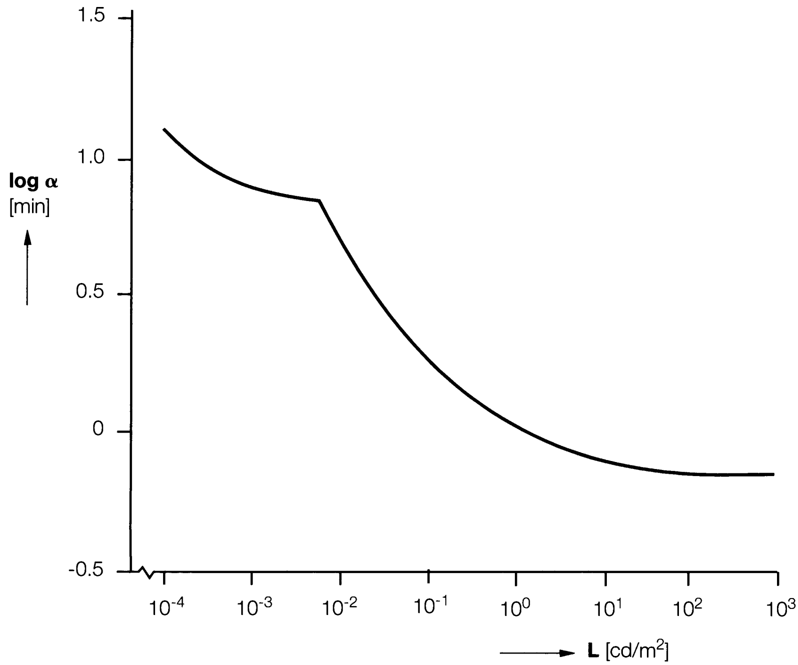


***Figure 9.1.20:** Critical visual angle as a function of the adaptation luminance. The region under the curve represents 'point sources'. After Middleton, 1952, fig 5.5, p. 90. Based on data from Blackwell, 1946.*

According to Figure 9.1.20, a light source seen in parafoveal dark-adapted vision may be as large as 10 minutes of arc and will still be considered as a point source (Middleton, 1952, p. 96). The same data are used by Douglas & Booker (1977, fig. 4.5, p. 4-22). Based on this assumption, the visibility of point sources is discussed in detail (Middleton, 1952, p. 96-99; Douglas & Booker, 1977, p. 4-22/4-23). We will come back to these discussions in a further part of this section.

A similar approach is followed by Moon (1961, p. 404). Again, a point source is defined on the basis of the fact that, for small objects, the detection is governed exclusively by the luminous intensity of the light source; its luminance is not relevant for the detection. This is the same definition as Middleton applied in order to use the Blackwell data. Moon refers, however, to Ricco's Law that is explained in sec. 9.1.2a. Ricco's Law means that two sections of the field of view of different size look equally bright, as long as the product of the diameter and the luminance is constant. In normal cases, Ricco's Law is valid for areas up to 6 degrees in diameter (Moon, 1961, p. 404). This implies that even quite large sources would classify as 'punctiform' – much larger, in fact, than is indicated by Middleton on the base of the Blackwell data. The reason is, of course, that the Blackwell data imply that the dimensions hardly can be discerned, whereas the Ricco data imply that the size, although clearly observable, is not relevant for the detection of the object. For the detection of stars, the Ricco data are therefore not relevant.

The Ricco approach is, however, used for establishing the recommended values for signalling lights. It is based on a number of studies (Adrian, 1963; Boisson & Pagès, 1963; Fisher, 1971; Hulscher, 1975; Rutley et al., 1965). For traffic lights, the reference distance is usually taken as 100 m. The angular size of a 20 cm and of a 30 cm lens is 6,7 and 10 minutes of arc respectively. This means that the dimensions of the light are easily visible; the visibility, however, is determined by the luminous intensity and not by the luminance. The standards and recommendations for road traffic control signals ('traffic lights') are equal for lenses with a diameter of 20 cm and 30 cm (Anon., 1964; 1973; CEN, 2000; CIE, 1980; 1988; NNI, 1966; 1972).

The same considerations are used for many other signalling devices that are used in road traffic, like e.g. number plates, retroreflectors on vehicles like e.g. cars, carts, pedestrians, bicycles, road markings, road signs etc. Some relevant publications on these areas are listed here. For obvious reasons, this listing is far from complete. For number plates see Schreuder (1985, 1988a); SWOV (1969, 1969a); IWACC (1986); for retroreflectors on vehicles see CIE (1987); OECD (1971); for retroreflectors on pedal bicycles see Blokpoel et al. (1982); for road markings see Anon. (1982); CIE (1983, 1988a); Meseberg (1990); OECD (1975); Schreuder (1981a, 1986) and for signalling lights on vehicle see OECD (1976); Schreuder (1976a); Schreuder & Lindeijer (1987); Wertheim (1986).

(b) The threshold detection of point sources

The Blackwell 'Tiffany' data, as described in sec. 9.1.3c, have been used to determine the detection of point sources. The results for fixed, achromatic sources are depicted in Figure 9.1.21. The thresholds are expressed in values of the illuminance at the plane of the observer. It may be noted that one lumen per square kilometre equals $1 \cdot 10^{-6}$ lux or one microlux. The results from measurements of Knoll et al. (1945, 1946) and of Green (1935) are included in Figure 9.1.21.

The results depicted in Figure 9.1.21 are well in agreement as long as the relative data are considered. It seems that the shift in the absolute values is related to differences in the experimental set-up of the different studies (Middleton, 1952, p. 98). The Tiffany data are given in a somewhat different fashion by Douglas & Booker (1977, fig. 4.4).

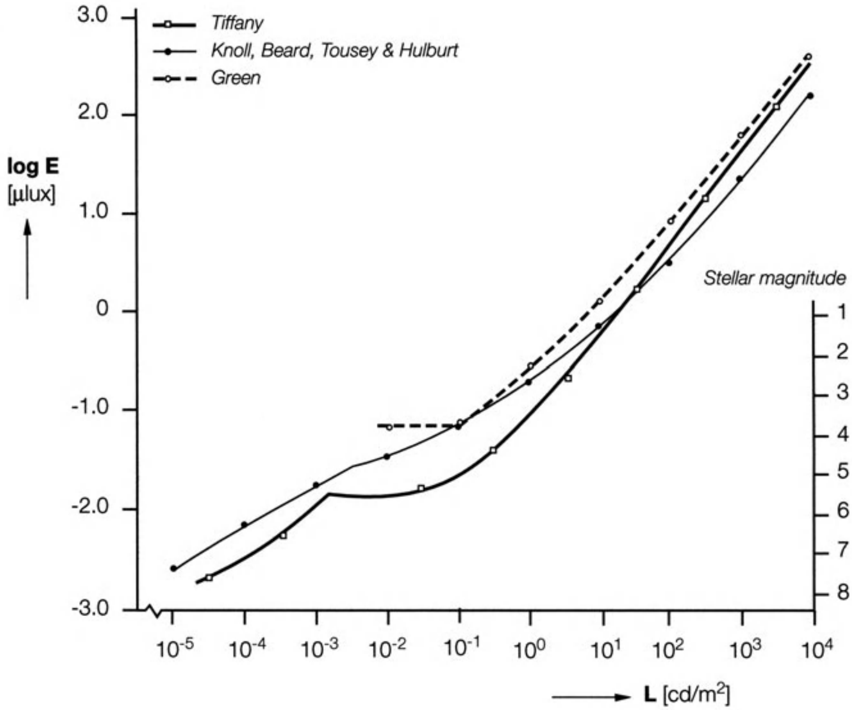


Figure 9.1.21: *The threshold illuminance for a fixed, achromatic source as a function of the background luminance. After Middleton, 1952, fig. 5.7.*

For easy reference, the Tiffany data from Figure 9.1.21 are given in Table 9.1.9.

Adaptation luminance (cd/m^2)	**Illuminance** (microlux)
1000	25
100	4
10	0,5
1	0,09
0,1	0,025
0,01	0,012
0,001	0,009

Table 9.1.9: *The threshold illuminance for a fixed, achromatic source as a function of the background luminance. After Middleton, 1952, fig. 5.7. Data from Figure 9.1.21.*

From these data the threshold of visibility of stars of different magnitude can be assessed. See Table 9.1.10.

Magnitude	E (lumens/km^2)	log E
-5	209	2,32
-4	83	1,92
-3	33,1	1,52
-2	13,2	1,12
-1	5,2	0,72
0	2,09	0,32
1	0,83	-0,08
2	0,331	-0,48
3	0,132	-0,88
4	0,052	-1,28
5	0,0209	-1,68
6	0,0083	-2,08
7	0,00331	-2,48
8	0,00132	-2,88

Table 9.1.10: *Stellar magnitude and illuminance. After Middleton, 1952, table 5.3.*

When comparing the data from the Tables 9.1.9 and 9.1.10, the threshold visibility of some stars in different surroundings may be estimated. A crude, first degree estimation is given in Table 9.1.11. In sec. 14.3.2, the threshold values of stellar visibility are discussed in more detail.

Adaptation luminance (cd/m^2)	lluminance (microlux)	Threshold stellar magnitude
1000	25	-2,5
100	4	-0,9
10	0,5	1,5
1	0,09	3,5
0,1	0,025	4,9
0,01	0,012	5,7
0,001	0,009	6,1

Table 9.1.11: *The threshold stellar magnitudes as a function of the background luminance. Data from Tables 9.1.9 and 9.1.10.*

The illuminance at a specific point for a specific point source is inversely proportional to the square of the distance. This is the 'inverse square law', the most fundamental relation in photometry (Schreuder, 1998, sec. 5.3.1; Helbig, 1972, para. 5.2). Details are given in sec.14.1.5d. As the visibility depends on the illuminance, it is possible to list the relation of the visibility of a point source and the distance. This relation is given in Table 9.1.12, based on data from Herrmann (1993, p. 30). As an example, the table is based on a point source of 1 cd. In a further part of this section it will be indicated what '1 cd' really means in practice. See also sec.14.1.4. It will be seen that it is really a weak source. For easy reference, the visibility is expressed in stellar magnitudes.

Distance (km)	Stellar magnitude
0,01	-10
0,1	-5
1	0
10	5
100	10
1000	15
10 000	20
100 000	25

Table 9.1.12: *The relation of the visibility of a '1 cd' point source and the distance. Based on data from Herrmann, 1993, p. 30.*

(c) *The supra-threshold detection of point sources*

As indicated earlier, the illuminance values presented in Figure 9.1.21 and Table 9.1.9 relate to the 98% probability of detection. They are applicable only when the observer knows precisely where to look for the light. "Even if the illuminance is twice the values in the figure and the table, the light will be hard to find. The illuminance value must be increased by a factor of 5 to 10 if the light is to be easy to find" (Douglas & Booker, 1977, p. 4-18, based on Tousey & Koomen, 1953). "Much greater increases are needed if the signal is to attract the attention of an observer who is not searching for it. Factors of 100 and 1000 are not excessive" (Douglas & Booker, 1977, p. 4-18, based on Anon., 1972). The 'increase' is expressed as the 'supra-threshold ratio' of the light.

The requirements for road traffic control signals can be compared to the supra-threshold ratios that are quoted above. In the recent European Standards, three classes of luminous intensity are defined to be applied on roads that differ as regards their degree of difficulty. The values are valid for all three relevant colours, viz. red, yellow, and green. The classes are 100, 200, and 400 cd (CEN, 2000, table 1). At the reference distance of 100 m, these intensity values correspond with illuminances of 10 000, 20 000 and 40 000 microlux respectively. As an example we will assume the adaptation luminance to be 1000 cd/m^2, corresponding to normal daytime conditions within built-up areas. According to Table

9.1.9, the threshold of detection corresponds to 25 microlux. For lights that agree to the European Standard, the supra-threshold ratio would amount to 400, 800, and 1600 respectively.

It is interesting to apply the concept of the supra-threshold ratio to the visibility of stars. When using the well-known photometric relationship as given by Herrmann (1990, p. 31):

$$\log\left(\frac{I_1}{I_2}\right) = -0{,}4\left(m_1 - m_2\right) \qquad [9.1.14]$$

we will find for a factor of 100:

$\log 100 = 2 = -0{,}4\ (m_1 - m_2)$, or $m_1 - m_2 = 5$

For a factor of 1000 we will find:

$\log 1000 = 3 = -0{,}4\ (m_1 - m_2)$, or $m_1 - m_2 = 7{,}5$

This implies that when a supernova is exploding somewhere in the Universe, it will be clearly conspicuous for a non-astronomer at a place where light pollution low, only when it has a magnitude of 1 or better. This is rather higher than the famous Supernova 1987a in the Magellanic Clouds, which did reach a magnitude of 2,8 at its maximum (Anon., 1988; Drummen, 2004). According to the conversion of magnitude differences into luminous intensity ratios, that is given in Table 14.3.12, a magnitude difference of 2,8 corresponds to a luminous intensity ratio of about 13. Clearly, astronomers know how and where they have to look!

Finally, it is interesting to give an indication of what different values of the luminous intensity actually mean for practical, day-to-day situations. As an example, some data are given in Table 9.1.13. Some data have been included in Table 8.3.7 in sec. 8.3.7c. The relation between the luminous intensity and the luminous flux is derived from the definition of the luminous intensity as given in sec. 14.1.4 (after Schreuder, 1998, sec. 5.2.4.; Hentschel, 1994, p. 33):

$$I = \frac{\delta\phi}{\delta\omega} \qquad [9.1.15]$$

The electric lamps are considered as uniform point sources. Assuming that the intensity is the same in all directions, the relation [9.1.13] can be integrated. The result is:

$$I = \frac{\phi}{2\pi} = \frac{\phi}{6{,}28} \qquad [9.1.16]$$

This relation is used in Table 9.1.13.

It is maybe of some interest to compare these data with those of the most common light source – the Sun. The luminous flux of the Sun is $2{,}6 \cdot 10^{28}$ lumen and its luminous intensity $2 \cdot 10^{27}$ cd (Sterken & Manfroid, 1992, p. 6). Its apparent visual magnitude is 26,78 (Sterken & Manfroid, p. 28) and its luminance about 10^9 cd/m^2, as the average over the full disk (Budding, 1993, p. 85).

Lamp family	Type	Note	Power (W)	Luminous flux (lumen)	Intensity (cd)
candle	wax	1	55	1	0,1
candle	stearin	2	80	10	1
LED white	50°	4	0,07		1,5
LED yellow	30°	5	0,04		6,3
hand-held small flashlight		14			10
kerosine	0.05 l/h	1	488	100	16
car sidelights					25
fluorescent	PLE*)	3, 6	11	600	96
incandescent	GLS	3, 6	60	730	116
EUR low beam headlamp		7, 8			500
US low beam headlamp		11			18 050
EUR HID low beam headlamp		12, 13			31 250
EUR high beam headlamp	max	9			100 000
area lighting	HOI-2000 W	10	2000		230 000
floodlighting	SON-TP	15	400		495 000

Table 9.1.13: *Light source characteristics. *) ballast included.*

Notes to Table 9.1.13:
(1) after Mills (1999);
(2) after Vermeulen (2000);
(3) after Philips Eindhoven (Anon., 1997);
(4) after Nichia Company (n.y.);
(5) after Hewlett Packard Company (n.y);
(6) see text;
(7) after Carlquist & Schreuder (1969);
(8) over the horizon;
(9) after Schreuder, 1976a;
(10) Imax 1250 cd/klm (Forcolini, 1993, p. 273); 183 000 lm (Anon., 1997, p. 1-188);
(11) after Bible & Chrysler (1995, Table 1);
(12) maximum under the horizon;
(13) after Huhn (1995, p. 97);
(14) after Anon. (2000);
(15) after Anon. (2000a).

(d) The conspicuity of distant luminaires

Many people, astronomers and naturalists alike, complain about the fact that distant luminaires are conspicuous in such a way that they cause ‘horizon pollution’. This effect is most noticeable when the distance between the site of observation and the light source – an urbanization or an industrial site – is somewhere between 3 and 10 km. At such distances, the direct light from the outdoor lighting luminaires is clearly visible and may cause considerable disturbance, whereas the light that is reflected of the ground is reduced strongly by trees and buildings. A clear example is given by Mizon (2002, fig. 1.62, p. 64), where, from the place where the picture is taken, the luminaires are clearly visible but not the reflected light. When the distance is much longer, say 100 km, the light sources themselves are not visible any more; all that remains is the sky glow. When the distance is much shorter, say under 1 km, the contribution of the reflected light is considerable and the sources are not longer the only visible proof of light pollution. Horizon pollution in general is described in some detail in sec. 3.3.4.

The data given in Table 9.1.9 allow us to estimate the amount of light that is needed to make the luminaires visible or clearly disturbing. As is described in sec. 7.1.4, CIE introduced a system of classification of street lighting luminaires (CIE, 1965, 1977). The CIE classification is the base for the luminaire classification that is proposed in Chapter 7 of this book. According to CIE, a luminaire is classified as 'cut off' when at 90 degrees (the horizontal direction) the light emission is less than 10 cd per 1000 lumen of the lamps (Schreuder, 1998, Table 7.3.2). As an example, we will look at a normal road lighting luminaire of a CIE cut-off class with a tubular high-pressure sodium lamp of 250 W with 28 000 lumen (Anon., 1997). The luminous intensity in the horizontal direction is 280 cd. For an adaptation luminance of 0,01 cd/m^2 – a quite dark surrounding – the threshold corresponds, according Table 9.1.9, to 0,012 microlux. The illuminance of that particular luminaire at different distances is given in Table 9.1.14. That table also contains the 'supra-threshold ratio', that is how much the illuminance exceeds the threshold value.

Distance (km)	Intensity (cd)	Illuminance (microlux)	Threshold (microlux)	Supra-threshold ratio
1	280	280	0,012	23 333
3	280	31	0,012	2 583
10	280	2,8	0,012	233

Table 9.1.14: *The illuminance at different distances and the supra-threshold ratio for a CIE cut-off luminaire.*

As is discussed in sec. 12.4.4, many people recommend the use of 'flat-glass' luminaires. In theory these luminaires would emit no light at all in the horizontal directions. Let us assume that this ideal situation is almost reached, and that the luminaires emit only 1 cd per 1000 lumen, that is only 10% of the light emitted by a good CIE cut-off luminaire. As is explained in several other sections of this book, this is a very strict requirement. In the example, the luminaire has again a tubular high-pressure sodium lamp of 250 W with 28 000 lumen (Anon., 1997; 2002). For 1 cd/1000lm, the light emitted in the horizontal direction amounts to 28 cd. As for the earlier example, for an adaptation luminance of 0,01 cd/m^2 the threshold corresponds to 0,012 microlux. The illuminance of this special luminaire at different distances is given in Table 9.1.15. Also, the supra-threshold ratio is given.

Distance (km)	Intensity (cd)	Illuminance (microlux)	Threshold (microlux)	Supra-threshold ratio
1	28	28	0,012	2333
3	28	3,1	0,012	258
10	28	0,28	0,012	23

Table 9.1.15: *The illuminance at different distances and the supra-threshold ratio for a luminaire with an extreme cut-off*

As can be concluded from the Tables 9.1.14 and 9.1.15, even luminaires with the strictest possible cut-off will still be quite conspicuous at a distance of as large as 10 km! One might put this in another way. The visual system is so sensitive that even very dim lights can easily be discerned. This is clearly so; otherwise, stars would not be visible! The fact that the luminaires are quite visible, however, does not imply that they may have a detrimental effect on astronomical observations. Still, they may look ugly and therefore we will need another term in stead of the term 'light pollution'. In sec. 3.3.4, the expression 'horizon pollution' is proposed to describe this effect. This term is generally in use to describe the ugly appearance – at day – of distant high-rise apartment buildings or overland power lines. Examples of conspicuous horizon pollution by lights are given in Cinzano & Elvidge (2003, Figure 3); Diaz Castro & De la Paz (2003, Figure 1); Wainscoat (2003, Figure 3), and Schwarz et al. (2003, Figure 4).

As a conclusion one can say that distant, normal, well-adjusted outdoor luminaires near the horizon have, in most cases, no negative influence on astronomical observations. If one wants them removed, this must be done on purely aesthetic grounds; it is not correct to use arguments about obstructions towards astronomical observations to do so. The same holds for much of the considerations about the sky glow of distant cities.

(e) The detection of colored point sources

The assessment of the detection of achromatic point light sources is, as has been explained in an earlier part of this section, based on the Tiffany data (Blackwell, 1946; CIE, 1981; Douglas & Booker, 1977; Middleton, 1952). Although in the foregoing sections, several weak points of these data have been indicated, they seem to very suitable for this purpose. Blackwell did, however, not study coloured objects so the assessment of the detection of coloured point sources of light must be based on other data.

The threshold of the visibility of coloured point sources of light fall in two categories.
(1) The achromatic illuminance threshold where the light is visible but where the colour cannot be recognised;
(2) The chromatic illuminance threshold where the colour of the light can be recognised.

The ratio between the achromatic threshold value and the chromatic threshold value is called the 'photochromatic ratio p' (Middleton, 1952, p. 102). In the past, the value of p has not been studied in great detail. In the fovea, it seems to be around 1 for red light and to increase to about 2,5 for blue light. Outside the fovea it rapidly increases (Middleton, 1952, p. 102, quoting Hill, 1947 and Holmes 1941). More specifically, it was found that the achromatic threshold for red light is about half of that of a white light, and the threshold of a blue light is about double. The differences between the achromatic thresholds of yellow, green, and white lights are small (Douglas & Booker, 1977, p. 4-26). In most practical cases, the chromatic illuminance threshold is somewhat higher than the achromatic illuminance threshold (Douglas & Booker, 1977, p. 4-26).

(f) The colour of stars

It is well-known that most of the brighter stars show a certain colour. It is generally assumed that the spectrum of almost all stars are almost perfect blackbody radiators, characterized by the effective temperature T_{eff}. "It is interesting to evaluate the colour for blackbodies, since many stellar sources have spectra resembling this ideal emitter" (Sterken & Manfroid, 1992, p.120). See also Budding (1993, p. 35). As is explained in sec. 11.1.1c, the colour of a blackbody radiator depends exclusively on its temperature. The traditional classification of stars in the Hertzsprung-Russell diagram is based on this assumption (Herrmann, 1993, p. 152; Illingworth, 1991, p. 215; Weigert & Wendker, 1989, p. 97-98). The standard stellar classification is given in Table 9.1.16.

Spectral type	Effective temperature (K)	Colour
O	40 000	blue
B	20 000	blue
A	9 000	blue-white
F	7 000	white
G	6 000	yellow
K	4 500	orange-red
M	3 000	red

Table 9.1.16: *The standard stellar classification. After Illingworth, 1991, p. 459.*

As is explained in sec. 14.2.3g, modern objective stellar photometry is based on the so-called UBV system (Budding, 1993, p. 45-51). See also sec. 14.2.3f. The system is based on three different assessments of the magnitude of a particular star. Originally, there were two; the visual (V) and the photographic magnitude. At the earliest times of stellar photography, the only material available was sensitive to blue light only. Based in this, the blue magnitude (B) is defined (Budding, 1993, p. 64). Later, the ultraviolet magnitude (U) was added. Sometimes, also yellow (Y) is added.

The actual system is based on the definition of three broadband filters:

(1) U (for Ultraviolet) with an approximative mean wavelength of 350 nm and a band width of about 70 nm;
(2) B (for Blue) with an approximative mean wavelength of 440 nm and a band width of about 100 nm;
(3) V (for Visual) with an approximative mean wavelength of 550 nm and a band width of about 90 nm.

The precise transmission data for the three filters are given by Budding (1993, p. 46, table 3.3). The filters are made of glass. Their precision is adequate for their job (Budding, 1993, p. 46). The normalised transmission functions are depicted in Figure 9.1.22.

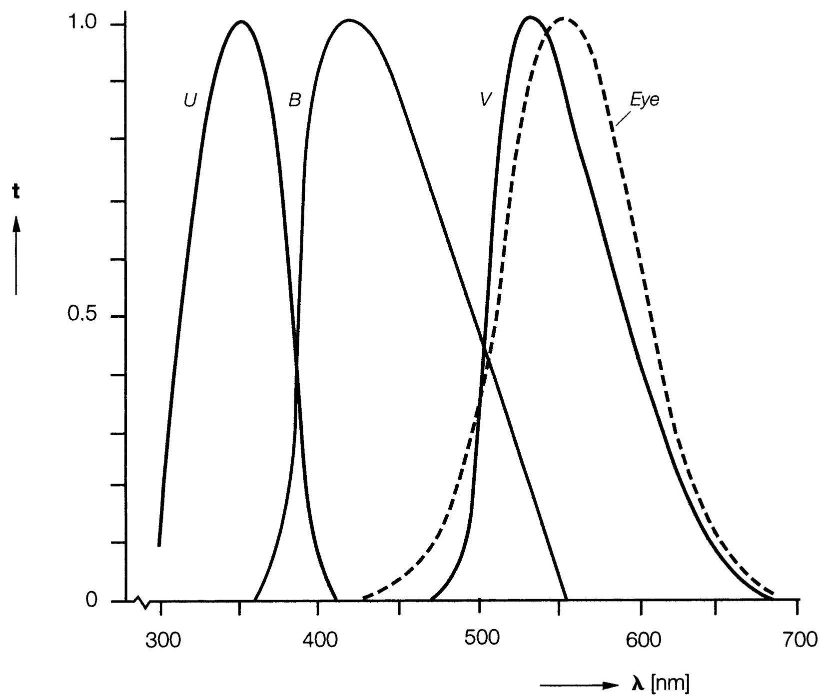


Figure 9.1.22: *Normalised transmission functions of the standard UBV filters, with the photopic spectral sensitivity curve of the eye added (after Budding, 1993. fig, 3.6).*

From Figure 9.1.22, it may be noted that the V-curve differs considerably from the photopic spectral sensitivity curve of the eye (the Vλ-curve) that is explained in sec. 8.2.2.

Ideally, the three magnitudes would be the same. In reality they are not, just because the stars have different colours. Any star can be characterized by the differences between the different magnitudes that are measured for this star. It is customary to use the differences in magnitude as measured by the B and V, and by the U and V filters. These differences are designated as (B – V) and (U – B) respectively (Budding, 1993, p. 46). For the quantification of the system, 10 stars are selected that serve as a unit of calibration for the system. These stars and their characteristics are given by Budding (1993, p. 48, table 3.4).

(g) Perceiving the colour of stars

The colours of stars are more difficult to see than their presence. In other words, there is a considerable difference between the achromatic illuminance threshold and the chromatic illuminance threshold that is explained in an earlier part of this section.

Most classical textbooks on astronomy, particularly those aimed at the general public, give few details about the threshold difference. This might seem peculiar because it is particularly the colours of the brightest stars that is an interesting sight to see for the casual night-sky observer.

In about 120 B.C., Hipparchus classified the stars that can be seen by the unaided eye in six classes, called magnitudes. The brightest were the stars of the first class, the faintest stars were of the sixth class. Later, this system was adopted by Ptolemy. The brightness of the stars were estimated during twilight, when, after sunset, first the brightest stars became visible and later the fainter stars. The magnitudes represent equal steps in visual perception (Sterken & Manfroid, 1992, p. 23). When comparing the magnitudes with photometric measurements, it was found that the visual system works logarithmical and not linear. It seems that it was Pogson who noted this for the first time (Sterken & Manfroid, 1992, p. 24). Pogson also selected the value of 2,512 as the photometric ratio between consecutive magnitudes (Pogson, 1856).

In the following considerations, data from a personal communication by Schaefer (2003) are used. According to Schaefer, the 'traditional' values for the limiting magnitude for night vision on stars is V = 6,0 magnitude, while the limiting magnitude for being able to see colors is V = 4,3. Here, the traditional value is the limit taken from the Almagest and many other sources, while the V = 4,3 magnitude corresponds to a star with 1500 nL of brightness. See for details and references the comprehensive review article of Schaefer (1993). The ways in which the estimate of the limiting magnitude of stars can be used for survey assessments of light pollution, are described in sec. 14.6.2b.

There are three main reasons why it is difficult to give a 'hard' figure for the difference between the achromatic and the chromatic illuminance thresholds for stars.

(1) There is a large difference between observers. This is the inter-observer variation that is well-known from all psycho-physiological experiments in vision. For star observation, this variation is increased considerably by the experience of the observer as a 'star gazer'. It should be noted that the values given here refer to observations with the unaided eye, but the situation is, in relative terms, identical when doing visual observations with a telescope. This is results from the fact that, as is explained in sec. 14.2.2b, the magnitude scale is essentially a logarithmic scale. More to the point, it is an interval scale. As is explained in sec. 9.2.3c, translations are permitted in interval

scales. Schaefer (2003) mentioned that the limiting magnitude is sometimes given as V = 6,5 magnitude, but that some individual people may even reach V = 8,2 or 8,4 magnitude. These reports are generally of the very faintest visible star, even though the observer missed many other stars of the same or brighter magnitude. It should be realised that the threshold for detection by the human eye is a probabilistic issue, where the probability of detection falls from near 1 to near 0 over a range of roughly one magnitude. See for a precise and accurate formulation of this function (Schaefer, 2001). Instead of quoting the extreme values, it is better to quote the 50% limiting magnitudes. The majority of people have 50% limiting magnitudes of V about 5 magnitude. The Almagest actually gives a magnitude limit of somewhere between V = 4,0 to 4,7 magnitude. It is likely that no stars fainter than V = 5,5 magnitude are included.

(2) Because stars are tiny, bright specks in a dark night-sky surrounding, one never can be certain whether the photopic or the scotopic spectral sensitivity curves apply. These curves are described in detail in sec. 8.3.4a. This implies that one never can be certain to what extent colour vision plays a role in the detection of stars and their colour.

(3) Stars differ markedly between themselves as regards their colour, but far less than the signalling lights that are used in road and rail traffic. The way the colour of stars is described, is explained in an earlier part of this section. But most stars have a relatively small range of colours of the order of about 1 magnitude expressed in (B – V). The colours range from pale yellow to white, with the difference being hard to tell even in bright sources. The end result is that few stars show detectable colours (Schaefer, 2003).

Despite some fuzziness in the issue is evident, Schaefer suggests that a magnitude difference of 1,1 for the threshold difference may be used as a guideline value (Schaefer, 1996, Appendix). Asking amateur astronomers might result in a somewhat larger difference. A simple experiment to show this, is to take people out under a dark sky and ask them to identify stars with colours, and people stop getting colours right at a difference of about 2,5 magnitude (Schaefer, 2003). When one asks the opinion of experienced amateur astronomers, one may get the answer that the colours for only the 20 or 30 or so of the brightest stars can be seen with the unaided eye. Others may indicate that the difference is somewhere between 2 and 4 stellar magnitudes.

As can be seen form Table 14.3.12, a difference of 1 stellar magnitude is equivalent to an intensity ratio of 2,5; a difference of 2 stellar magnitudes is equivalent to an intensity ratio of 6,31 and a difference of 4 stellar magnitudes to a ratio of 39,8 (Schreuder, 1994, table 2, based on data from Weigert & Wendker, 1989). Whatever the value of these opinions, one thing is clear; the difference between the achromatic illuminance threshold and the chromatic illuminance threshold is much larger than one should expect from the results of the measurements of quoting Hill (1947) and Holmes (1941) that have been quoted earlier in this section. According to these measurements, the difference should correspond to a ratio of somewhere between 1 and 2,5 but not between 6 and almost 40. It seems possible, that this difference might be explained, at least in part, by the fact that coloured stars are 'almost' white, whereas coloured light signals usually have a very saturated colour (CEN, 2000; CIE, 1986; 1988).

9.2 Dazzle and glare

9.2.1 Blinding glare

Glare is related, as the word says, to phenomena that hamper or even obstruct visual observations. Glare has three aspects:
(1) Absolute glare or blinding glare;
(2) Disability glare;
(3) Discomfort glare.
When the intensity of the light stimulus is over the maximum value where the visual system can process visual information, one speaks of blinding glare. The stimulus does not contribute to the visual information that is acquired from the surroundings, but it obstructs the processing of useful information. One is, to a certain extent, really 'blind'. As is explained in sec. 8.2.3d, the stimulus value where blinding glare takes place, depends on the adaptation luminance; see Table 8.2.2 and Figure 8.2.3. In extreme cases, the eye may even suffer damage (Van Norren, 1995). It might be noted here that Vos proposed a further subdivision of 'sorts of glare' where he introduced a 'glare cube' that contains eight different sorts of glare (Vos, 1999, p. 40-41, Fig. 5). Apart from the glare angle, the temporal effects have also been included so that the system could also cover flashing lights. Time must learn whether such a complicated system is viable. In this book we will use only the three sorts of glare indicated earlier in this section.

Blinding glare occurs rather frequently in daily life:
- when, in the dark, an opposing car does not switch back to low beam headlights;
- when leaving a road tunnel at daytime;
- when leaving a dark cinema hall in full sunshine;
- when driving on a wet, shiny asphalt road surface against a low sun;
- when walking (or skiing!) on snow in full sunshine;
- when sunbathing on a tropical beach in full sunshine.

There is not much that can be done against blinding glare. In particular, sunglasses may reduce the glare, but the relevant stimuli, that are already too weak to be detected, are reduced in strength even further. The end effect of wearing sunglasses is often a further reduction of the visual performance. Their main benefit is that eye-strain may reduce – apart from the possibility of avoiding eye-contact with others. Some people even seem to think that wearing sunglasses makes them more interesting or even more sexy! The same applies to tinted windscreens in cars. In most countries, the use of tinted front windshields over their complete area is prohibited just for this reason.

9.2.2 Disability glare

(a) Physiological glare

Disability glare is often called 'physiological glare' because its effects are of a physiological nature. It occurs when the field of view contains a strong light source in another location than the direction where the object, that must observed, is located. The light source is called the glare source. The light from the glare source is scattered within the ocular media when it strikes the eye. It causes a light veil that seems to stretch over the complete field of view. The scatter is not equally strong in the different part of the eye. Vos (1963) in his fundamental study did make a comparison that is still valid. Other studies did suppose that there were neural effects as well (Schouten, 1937; Schreuder, 1964). In dealing with disability glare, however, we are only concerned with the aggregate effects.

In practice, usually not only one, but a number of glare sources contribute simultaneously to the glare effect. Additionally, many glare sources are extended and do not represent point-sources. As long as the glare is caused exclusively by the physical phenomena of light scatter, it is obvious that the effects of the different sources are additive, and that the effects of large sources may be integrated. The total equals the sum of the parts. In practice, this is usually the case. This fact is often quoted as strong support for the 'straylight theory' of glare (Vos, 1963). In some cases, e.g. near the entrance of a dark traffic tunnel in a surrounding of snow in the full sun, discrepancies have been found, suggesting that the stray-light theory of glare is not sufficient to explain all glare phenomena (Schreuder, 1964, 1998).

The veil influences the contrast in the field of view. As is explained in sec. 5.1.1, the luminance contrast is usually defined as:

$$C = \frac{L_o - L_b}{L_b} \qquad [9.2.1]$$

with:
G: The contrast;
L_o: The luminance of the object to be perceived;
L_b: The luminance of the background of the object.

The veil can be expressed in luminance values in the way that is described in another part of this section. It is called the veiling luminance L_v. Because the veil extends over the complete field of view, all luminances in the field of view become larger. To all luminances, the veiling luminance has to be added. This implies that the contrast becomes smaller as can be seen from [9.2.2]:

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{(L_o - L_b)}{(L_b + L_v)} \qquad [9.2.2]$$

C' is always smaller than C: the nominator in [9.2.1] and [9.1.2] is the same, whereas the denominator is greater. Usually, C' is called the visible contrast and C the intrinsic contrast.

(b) The Stiles-Holladay relation

As long as the glare considerations are restricted to the purely physical entoptic stray-light effects, one may use the ocular stray-light factor L_{seq} instead of the more general veiling luminance factor L_v. Because the ocular stray light can be described by an equivalent luminance factor, L_{seq} is the equivalent veiling luminance, and can be expressed in cd/m^2, just as if it were a luminance outside the eye. Because that is, of course, not the case, the luminance must be considered as being 'equivalent'.

The veil depends on the angle between the directions for the eye to the object and to the glare source respectively. This angle is called the glare angle Θ. When we assume that the object is observed foveally, the glare phenomena display the same circular symmetry as the eye itself, because, as is explained in sec. 8.1.1, the fovea lies in the axis of symmetry of the eye. The glare does not depend of the azimuth angle ϕ as is explained in Figure 9.2.1. When the glare source is seen in the fovea and the object somewhere else – not a common geometry in visual observation – the same is true. If, however, both object and glare source are seen outside the fovea, the axial symmetry does not apply any more. The implication is that none of the glare formulae that are explained furtheron in this section, may be applied. Thus, in those cases, the disability glare cannot be assessed.

The geometry that is used in glare assessments is depicted in Figure 9.2.1.

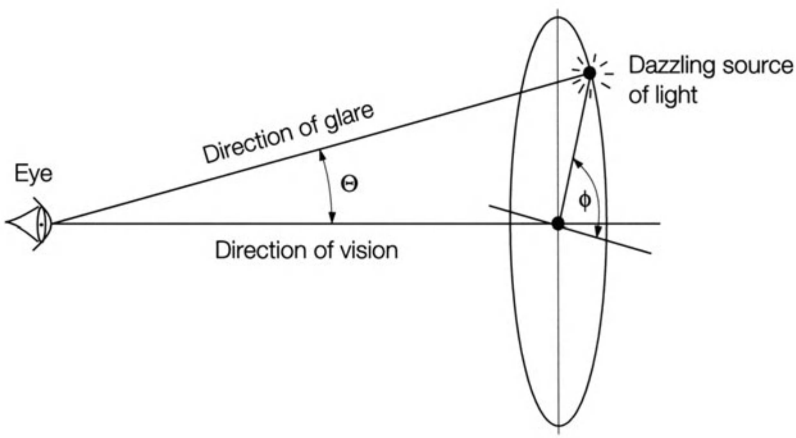


Figure 9.2.1: *The geometry used in glare assessments. Θ: glare angle; ϕ: azimuth angle. After Schreuder, 1998, Figure 7.3.1.*

The Θ-dependence has been the objects of many extensive studies over many decades. Surveys may be found in CIE (2002); Vos (1963, 1983, 1999, 2003); Vos & Padmos (1983); Vos et al. (1976); Schreuder (1964, 1981, 1998). The first proposal that was applied on a large scale was that of Holladay (1927). This proposal is very simple: the glare depends on the illuminance that hits the eye and on the square of the glare angle. The relation is written in the way that was proposed by Holladay, Stiles and Crawford. It is usually called the 'Stiles-Holladay relation' (Stiles & Crawford, 1937; Adrian, 1961):

$$L_{seq} = k \cdot \frac{E_e}{\theta^2} \qquad [9.2.3]$$

with:
L_{seq}: The equivalent veiling luminance (cd/m^2);
E_e: The illuminance on the plane of the eye pupil (lux);
Θ: The glare angle (degrees);
k: A factor that depends on the age and on other parameters. It usually taken as 10. This factor will be discussed in more detail in another part of this section.

It should be noted that 'time' is not an important parameter for disability glare, because the decrease in contrast takes place simultaneously with switching on the glare source. It is not possible to get accustomed to disability glare, contrary to discomfort glare that is discussed in sec. 9.3.3.

From here on, research on disability glare followed two distinct pathways. The first was to refine the Θ-dependency. This will be discussed in this part of this section. The second was to find out what could be done against glare. Here, one might find out that people concerned with the environment chose to investigate the way to reduce glare at the source: make the lighting installations less glaring. The other way was that of industry. They considered that if contrasts do become smaller by glare, the solution is to increase the adaptation luminance so that the threshold contrasts are lower. For industry this has two advantages: they do not need to adapt their lighting equipment (luminaires, lamps etc.) and they could argue that the luminance level must be increased, which is good for the sale of lighting equipment, electricity etc. These points will be discussed in another part of this section. Nowadays the first, the environmentalists, appear to have the upper hand, but this was not always – and is still is not always – the case. This approach is discussed in another part of this section.

(c) The Θ dependency

Although the Stiles-Holladay relation is far from exact, it is still widely in use in its original form in many practical applications. For road lighting, the Stiles-Holladay relation is sufficiently accurate. Glare angles below 2° seldom occur. Therefore, in most cases, this relationship is used both for roadway lighting (CIE, 1976, 1977, 1995) and for tunnel lighting, e.g. in the determination of the required light levels in the entrance of long tunnels (CEN, 2001; CIE, 1990, 2003; Huijben ed., 2003). There is, however, some difference of opinion about the Θ-range over which it may be used. "In the main practical glare angle domain, roughly between 3° and 30°, the description could be reliably used" (Vos, 1999, p. 38). Many researchers are more generous and allow a domain between 3° and 60° (Adrian, 1993) or even 2° and 60° (Huijben ed., 2003). For road and tunnel lighting, the lower limit is acceptable. For other lighting applications, however, the lower limit is often too large. This is the case for glare by the headlights of opposing cars. For normal road geometries of a two-lane two-way road of 7 m wide and a distance of 200 m between the opposing vehicles, where glare begins to be bothersome, the angle is about 0,015 radian or about 0,85 degrees. Here, the Stiles-Holladay relation cannot be applied. Another case is the observation of stars near glare sources. Here also, very small angles may apply. For this reason, the moons of Jupiter cannot be seen by the unaided eye, although their magnitude is high enough, being about 5th or 6th magnitude (Thomas, 1944, p. 268). This is considered as belonging to nature; similar conditions may easily arise in a surrounding of artificial light, where the limitation is considered as an aspect of light pollution. So, there are plenty of reasons to try to extend the range of Θ-angles where the glare relations may be used.

Many proposals have been made to define another value for the dependency from Θ other than the square that is used in the Stiles-Holladay relation, particularly for smaller values of the glare angle. Often, an exponent of about 2,8 was found (see e.g. Hartmann & Moser, 1968; Hartmann & Ucke, 1974; Schreuder, 1981; Vos, 1963). The glare angle domain was extended to about 10 to 15 minutes of arc. Vos has proposed a new formula that was based on the knowledge at the time. It was aimed in particular at the entrance lighting for long road traffic tunnels (Vos, 1983; Vos & Padmos, 1983). The formula is an extension of the Stiles-Holladay relation, as a term containing Θ^{-3} is added. The original formula contained a further term where Θ showed up in the exponent. This formula proved to be too complicated for practice, so an abbreviated form of the 'new Vos formula' is used:

$$\frac{L_{seq}}{E_e} = \frac{10}{(\theta + 0{,}02)^2} + \frac{10}{(\theta + 0{,}02)^3} \qquad [9.2.4]$$

in which E_e is the illuminance at the plane of the eye. This equation is valid for L_{seq} in cd/m^2; E_e in lux, and Θ in degrees.

It is well-known that the eye media become turbid with increasing age (Schreuder, 1998, sec 7.5). Since disability glare is the result of scatter of light in the eye, the glare is bound to increase with age as well, the main reason is the steep increase of cataract with age (Mann & Pirie, 1950; Stilma, 1995a). Cataract is the most common visual disturbance. In 1990 from the 15 million inhabitants of the Netherlands, 760 000 suffered from cataract in a disabling way (Schreuder, 1998, table 7.5.1.; Voorn, 1995, table 1-3).

Fisher & Christie (1965) proposed to take account of the age dependence by exchanging the constant factor k in equation [9.2.3], the Stiles-Holladay relation by:

$$k = d + 0{,}2A \qquad [9.2.5]$$

with A the age in years and d a factor depending on the geometry. According to Schreuder (1998, p. 111), d = 4,2. This means that if we take, according to Adrian (1963), k = 9,2 for 25 year old observers, k would be 14,2 for 50 year old people and 19,2 for 75 year old people (Schreuder, 1998, p. 111). Although is has not been mentioned anywhere at all, it seems safe to assume that the Fisher-Christie relation applies to healthy individuals, i.e. individuals who do not suffer from cataract in a disabling way.

(d) The three-step CIE Standard Glare Observer

In analogy to the CIE Standard Observer, discussed in sec. 8.2.2, Vos proposed to introduce a CIE Standard Glare Observer. In fact, he proposed "to define a three-step Standard Glare Observer, depending on then glare angle and on the accuracy wanted" (Vos, 1999, p. 38). The fist step is an observer who follows the Stiles-Holladay relation [9.2.3]. The relation may be used, as said earlier, in the angle domain from 3° to 30°. The second step involves allowing for the age influence. It is called the 'Age adapted Stiles-Holladay CIE Glare Observer':

$$\frac{L_{seq}}{E_e} = \frac{10\left(1+\left\{\frac{A}{70}\right\}^4\right)}{\theta^2} \qquad [9.2.6]$$

with L_{seq} and E_e as in [9.2.4] and A the age in years. The useful angle domain is as before from 3° to 30°. The formula is given in Vos (1999, equation 2) and is based on data from IJspeert et al. (1990). See also CIE (2002) and Vos (2003).

When the age dependence according to Fischer and Christie is compared to that according to Vos, considerable differences appear. In Table 9.2.1, the factor k from [9.2.3] is given according to Fischer and Christie (with d = 4,2) and according to Vos, more in particular for very young and very old observers.

Age (years)	**k according to Fischer & Christie**	**k according to Vos**	**Ratio**
10	6,2	10,0	0,62
20	8,2	10,0	0,82
30	10,2	10,3	0,99
40	12,2	11,1	1,10
50	14,2	12,6	1,13
60	16,2	15,4	1,05
70	18,2	20,0	0,86
80	20,2	27,1	0,74
90	22,2	37,3	0,60
100	24,2	51,6	0,47

Table 9.2.1: *Factor k from [9.2.3] according to Fischer & Christie (1965; with d = 4,2) and Vos (1999).*

The useful angle domain can be extended from 0,1° to 30° by adding an extra term to equation [9.2.6]:

$$\frac{L_{seq}}{E_e} = \frac{10}{\theta^3} + \frac{5\left(1+\left\{\frac{A}{62,5}\right\}^4\right)}{\theta^2} \qquad [9.2.7]$$

If the useful angle domain needs to be extended to a large glare angle of about 100°, the colour of the pigment of the iris in the eye must be taken into account. This is the third step. Although the influence might be considerable, up to a factor of 10, it is not clear in which way this aspect can be taken into account in lighting design. It seems, therefore, that the 'CIE Standard Glare Observer' as proposed by Vos, will be a tool for research rather than for lighting design purposes. For this reason we do not include the rather complicated formula. See Vos (1999, equation 4).

There is one more thing to mention. According to Vos, wavelength dependencies are of the second order magnitude (Vos, 1999, p. 40). In view of what has been explained in sec. 8.3.2 while discussing the influence of the colour of the light on visual perception, this statement might seem to be a little rash. However, Vos concludes in a slightly different wording: "The equations can be taken to hold for the normal glare situation, i.e. with white light" (Vos, 1999, p. 40).

(e) Reduction of glare from lighting equipment

As was indicated earlier in this section, another approach to reduce the effects of disability glare is to reduce the glare at the source; make the lighting installations less glaring. For many, this seems the most logical thing to do. In sec. 6.2.3c, the Upward Light Ratio ULR is discussed, that indicates the amount of light that is emitted by luminaires above the horizon. In that respect, the glare is also included. The reason is that in an angle region close to, but below the horizon, the requirements to reduce light pollution and the requirements to reduce glare are very similar. In sec. 7.1.4, the consequences of these considerations on the preferred light distribution and on the classification of the light distributions of luminaires, are discussed in detail.

(f) Counteracting glare; TI

A theoretical approach to counteract disability glare is to increase the contrast just as much as the contrast is decreased by the glare. This may be a possible solution in some indoor lighting installations when the contrast can be changed, e.g. television sets, computer monitor screens, plasma display screens etc. In most indoor and in almost all outdoor situations, however, the objects to be perceived and their surroundings are 'just there', so that a change of the contrast by the operator is not possible – with the exception, of course, of shifting from high-beams to low-beams.

There is another theoretical approach that is often used in road traffic lighting. As long as the adaptation luminance is in a region where the contrast sensitivity threshold gets lower with increasing adaptation level, a loss of contrast can be compensated by an increase in adaptation level. This was the leading thought behind the decision to express the disability glare in road lighting by the 'Threshold Increment' TI (Van Bommel & De Boer, 1980, p. 21-23).

In order to explain the role of the luminance compensation, we will use, as an example, the curve given by Van Bommel & De Boer (1980, figure 1.5). This figure is based on data from Adrian (1969) that in its turn is based on the original Blackwell data (Blackwell, 1946). This figure is depicted in Figure 9.2.2. It is in fact the RSC-curve for 8 minutes of arc from CIE (1990a). The exposure time is not indicated, but it may assumed to be 0,2 seconds.

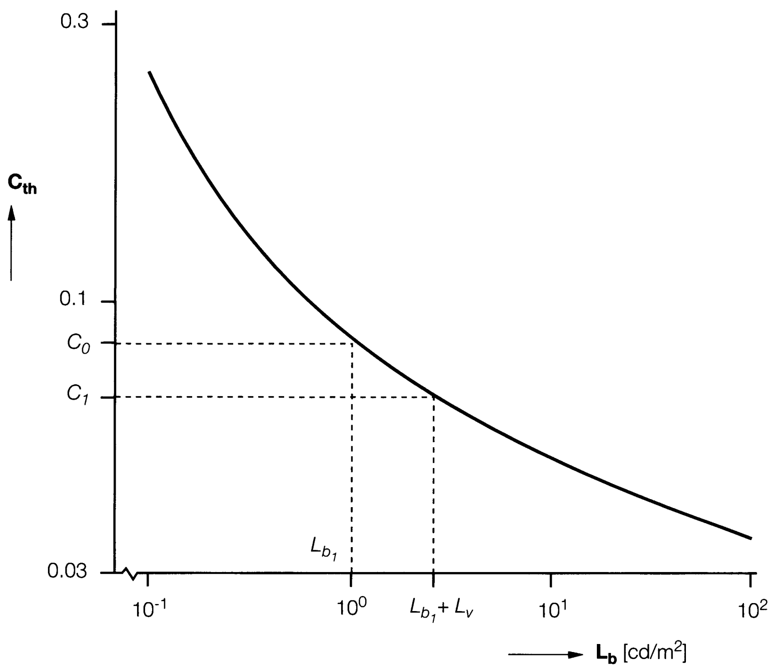


Figure 9.2.2: *The relation between the threshold contrast and the adaptation luminance for an object measuring 8 minutes of arc. After Van Bommel & De Boer, 1980, figure 1.5. Based on data from Adrian 1969.*

From Figure 9.2.1, it follows that for an adaptation luminance of 1 cd/m^2, the threshold contrast C = 0,081 and for an adaptation luminance of 3 cd/m^2, the threshold contrast C' = 0,061. As an example, we take a road lighting installation with an average road surface luminance of 1 cd/m^2. For normal road lighting installations, the average road surface luminance is a good approximation of the adaptation luminance. Now, glare is introduced. Let is assume that the glare intensity is such that an increase of the adaptation luminance to 3 cd/m^2 is sufficient to compensate for the loss of visibility. The question is, which value of the veiling luminance is acceptable if the loss of visibility can be compensated by raising the average road surface luminance (or the adaptation luminance) from 1 cd/m^2 to 3 cd/m^2.

In an earlier part of this section, the usual definition of the luminance contrast is given:

$$C = \frac{L_o - L_b}{L_b} \qquad [9.2.1]$$

When a veiling luminance is added, all luminances increase by the same amount:

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{(L_o - L_b)}{(L_b + L_v)} \qquad [9.2.2]$$

with:
L_o: The luminance of the object to be perceived;
L_b: The luminance of the background of the object;
L_v: The veiling luminance.

In our example, $C = 0{,}081$ and $C' = 0{,}061$. From [9.2.1] it follows that, with $C = 0{,}081$, $L_o - L_b = 0{,}081\ L_b$, or $L_o = 0{,}92\ L_b$. With $L_b = 1$ cd/m^2, $L_o = 0{,}92$ cd/m^2. In a similar way we find, using [9.2.2]: $C' = 0{,}081 / (1 + L_v) = -\ 0{,}061$. From this it follows that $0{,}061\ L_v = 0{,}02$, or $L_v = 0{,}328$. Thus, if the veiling luminance is 0,328 cd/m^2, the loss of the visibility that results from the glare can be compensated by raising the average road surface luminance from 1 cd/m^2 to 3 cd/m^2.

From here to the assessment of the TI, the path gets very confusing indeed. Usually, the next steps are just stated without much further comments. According to Van Bommel and De Boer: "The CIE (1976) states that for the luminance range 0,05 cd/m^2 $< L_b <$ 5 cd/m^2, the threshold increment is approximated with the formula:

$$TI = 65 \cdot \frac{L_v}{L_{av}^{0.8}} \qquad [9.2.8]$$

where:
TI: The relative threshold increment (percent);
L_v: The equivalent veiling luminance (cd/m^2);
L_{av}: The average road surface luminance (cd/m^2).

A third road lighting parameter is thus the threshold increment TI" (Van Bommel and & De Boer (1980, p. 22).

(g) Compensating for glare

The final remark of this quote is significant for the course the discussion about disability glare has taken. The original idea of compensating the loss in visibility due to glare by an increase of the average road surface luminance, is abandoned: all one does is add a number to the existing quality requirements for road lighting installations that is supposed to represent the glare that is to be tolerated. Recommendations almost always select a TI value of 10% as a the maximum for the permissible disability glare. This value is required for almost all road types as well as for road tunnels (CEN, 1998, 2001; CIE, 1977, 1990, 1995, 2003; Huijben, ed., 2003; NSVV, 1990a).

It is interesting to pick up the original idea about the introduction of the Threshold Increment. First we will look at the relation between the veiling luminance L_v and the TI. Using equation [9.2.8] for the value of L_{av} equal to 1 cd/m^2, an example is worked out in Table 9.2.2.

L_v (cd/m^2)	TI (%)
0,01	0,65
0,02	1,3
0,03	1,95
0,05	3,25
0,08	5,2
0,1	6,5
0,2	13
0,328	21,32
0,5	32,5
0,8	52
1	65

Table 9.2.2: *The relation between the veiling luminance L_v and the TI for L_{av} = 1 cd/m^2*

Table 9.2.2 shows that for a TI of 10%, the veiling luminance should be not more than about 0,15 cd/m^2. The value of L_v = 0,328 is included in the table, because it is part of the example given earlier in this section.

Using again equation [9.2.8], it is possible to assess the required average road surface luminance L_{av} needed to counteract the loss in visibility due to a glare level that corresponds to a specific value of TI. The results are summarized in Table 9.2.3. The TI values selected for this example are: TI = 1%, 3%, 10%, and 30%. This range covers all normal road lighting conditions.

L_v	L_{av}' for TI = 1%	3%	10%	30%
0,001	0,03	0,008	0,002	0,0005
0,002	0,08	0,020	0,004	0,0011
0,003	0,13	0,033	0,007	0,0018
0,005	0,25	0,062	0,014	0,0035
0,008	0,44	0,112	0,025	0,0063
0,01	0,58	0,15	0,033	0,0083
0,02	1,39	0,35	0,078	0,0198
0,03	2,30	0,58	0,130	0,033
0,05	4,36	1,11	0,25	0,062
0,08	7,85	1,99	0,44	0,112
0,1	10,38	2,63	0,58	0,148
0,2	24,68	6,25	1,39	0,352
0,328	45,81	11,6	2,58	0,653
0,5	77,60	19,6	4,36	1,105
0,8	139,6	35,4	7,8	1,99
1	184,6	46,7	10,4	2,63

Table 9.2.3: *The required values of L_{av}' for specific values of L_v and TI.*

It is clear from Table 9.2.3, that the required values of L_{av}' depend very much on the value of TI that is selected for the particular lighting installation. For TI = 10%, the veiling luminance should be below 0,1 cd/m^2 in order to avoid excessive high values of the road luminance. The value of $L_v = 0{,}328$ is included in the table, because it is part of the example given earlier in this section.

In order to assess what will happen in a real road lighting installation, we will give a simplified example. What we need is to know the L_v – or the L_{seq}. Using the Stiles-Holladay relation that has been given earlier in this section in equation [9.2.3], the total value of L_{seq} is calculated per installation. The installations are supposed to have SON 250 Watt lamps with 25 000 lumen, a mounting height of 11,5 m (reduced height 10 m) and a spacing of 40 m. For simplicity, the cut-off values are approximated, using four different cut-off classes that are discussed in sec. 7.1.4. They do not agree precisely with those classes, however. The result is summarized in Table 9.2.4.

Mast no.	cd/klm	Distance (m)	L_{seq} (cd/m^2) FCO	CO(1)	CO(2)	SCO
1	5	80	0,004			
1	10	80		0,008		
1	20	80			0,159	
1	30	80				0,239
2	5	120	0,004			
2	10	120		0,008		
2	20	120			0,0159	
2	30	120				0,0048
3	2	160	0,0016			
3	5	160		0,004		
3	10	160			0,008	
3	20	160				0,0159
4	1	200	0,0008			
4	5	200		0,004		
4	10	200			0,008	
4	20	200				0,0159
total per installation			**0,0104**	**0,024**	**0,1909**	**0,2756**

Table 9.2.4: *The total veiling luminance for four example installations.*

According to Table 9.2.4, the veiling luminances are:

- for a full-cut-off installation: 0,0104 cd/m^2;
- for a good cut-off installation: 0,0240 cd/m^2;
- for a medium cut-off installation: 0,1909 cd/m^2;
- for a semi cut-off installation: 0,2756 cd/m^2.

When we compare those data with the values given in Table 9.2.3, we can approximate 0,0104 by 0,01 cd/m^2; 0,0239 by 0,3 cd/m^2; 0,0478 by 0,05 cd/m^2 and 0,0797 by 0,8 cd/m^2. If we leave out the TI values of 1% as unrealistically low and 30% as unrealistically high, Table 9.2.3 will be reduced to Table 9.2.5.

Installation	L_v	L_{av}' for TI = 3%	10%
FCO	0,01	0,15	0,033
CO (1)	0,03	0,58	0,130
CO (2)	0,05	1,11	0,25
SCO	0,08	1,99	0,44

Table 9.2.5: *The required values of L_{av}' for specific values of L_v and TI.*

In conclusion, it is easy to see that a full cut-off road lighting installation is not only favourable as regards the reduction of light pollution, but also as regards disability glare. Should one choose to counteract the loss in visibility due to glare, a full cut-off installation would require much less additional road surface luminance as compared to normal cut-off, or semi cut-off installations. This might result in considerable economic advantages as well.

(h) The Contrast Reduction Ratio

As we have explained in an earlier part of his section, the end effect of disability glare is that the perceived contrast C' is always smaller than the intrinsic contrast C as a result of the veiling effect of the entoptic straylight.

This was expressed as follows:

$$C = \frac{L_o - L_b}{L_b} \qquad [9.2.1]$$

and

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{(L_o - L_b)}{(L_b + L_v)} \qquad [9.2.2]$$

with:
L_o: the luminance of the object to be perceived;
L_b: the luminance of the background of the object.
L_v: the veiling luminance.

Obviously, C' is always smaller than C. As a convenient measure of the degree of disability glare, we will introduce the 'Contrast Reduction Ratio' CR, defined as:

$$CR = \frac{C}{C'} \qquad [9.2.2.a]$$

With [9.2.1] and [9.2.2], CR becomes

$$CR = \frac{C}{C'} = \frac{(L_o - L_b)/L_b}{(L_o - L_b)/(L_b + L_v)} = \frac{(L_b + L_v)}{L_b} = 1 + \frac{L_v}{L_b} \qquad [9.2.2.b]$$

This means that CR is always larger than 1. It seems that this way to characterize disability glare is particularly suited for cases where the TI definition cannot be used, e.g. in lighting installations other than street lighting or in cases where L_v is large, such as in automobile headlights.

9.2.3 Discomfort glare

(a) Psychological glare

Glare is related to phenomena that hamper or even obstruct visual observations. Three aspects of glare have been mentioned:

(1) Blinding glare;
(2) Disability glare;
(3) Discomfort glare.

The first and the second aspects have been discussed in detail in sec. 9.2.2. Now we will devote our attention to the third aspect, the discomfort glare. Discomfort glare is characterized by the fact that glare sources in the field of view cause disturbing effects and discomfort, but that a decrease in the visual performance is not experienced, at least not as a short-term effect. Discomfort glare is often called psychological glare because its effects are of a psychological nature, and because it is similar to 'real' or 'disability' glare. In the past, discomfort glare was considered as much more important that disability glare in almost all aspects of outdoor lighting, notably in road and street lighting (CIE, 1965, 1977, 1995; NSVV, 1957; 1974/1975; 1977; De Boer, ed., 1967).

However, in most modern recommendations the picture is different: disability glare is considered as the main or even as the exclusive glare aspect to be taken into account (NSVV, 1990a). It was often argued that the glare of vehicle headlamps is so strong that it is futile to try to reduce the glare from road lighting installations. In sec. 10.2.1b, when discussing Small Target Visibility, it is shown that allowing glare helps to reduce the installation and the running costs of the lighting – quite a different story! (See Keck, 1993). Furthermore, it has been argued that, if disability glare is absent, there will be no discomfort glare because the discomfort glare is dominant (De Boer, 1967, quoting De Boer, 1951). Also it is often assumed at the two are closely interrelated. Because this is not always correct, we will come back to this assumption later in this section. If it were correct, there would be no reason to bother about two different kinds of glare. Finally, it is sometimes stated that reducing discomfort glare is just a matter of luxury on which no money ought to be spend. It is interesting to note that in interior lighting, all attention is focussed on the reduction of discomfort glare. See e.g. Baer (1990); Hentschel (1994); De Boer & Fischer (1981); Stevens (1969) and Weis (1996). We will come back to this point as well later in this section. In many more recent CIE-recommendations, both aspects of glare are considered (CIE, 1995). However, the most recent international recommendations deal again exclusively with disability glare and disregard discomfort glare (CEN, 2002). Because the new Standard for the Netherlands is based directly on this CEN-document, discomfort glare is also disregarded here (NSVV 2002, 2003, 2003a).

The relation between discomfort glare and disability glare in the luminance region that is relevant to most outdoor lighting is discussed in Adrian (1966). See Figure 9.2.3.

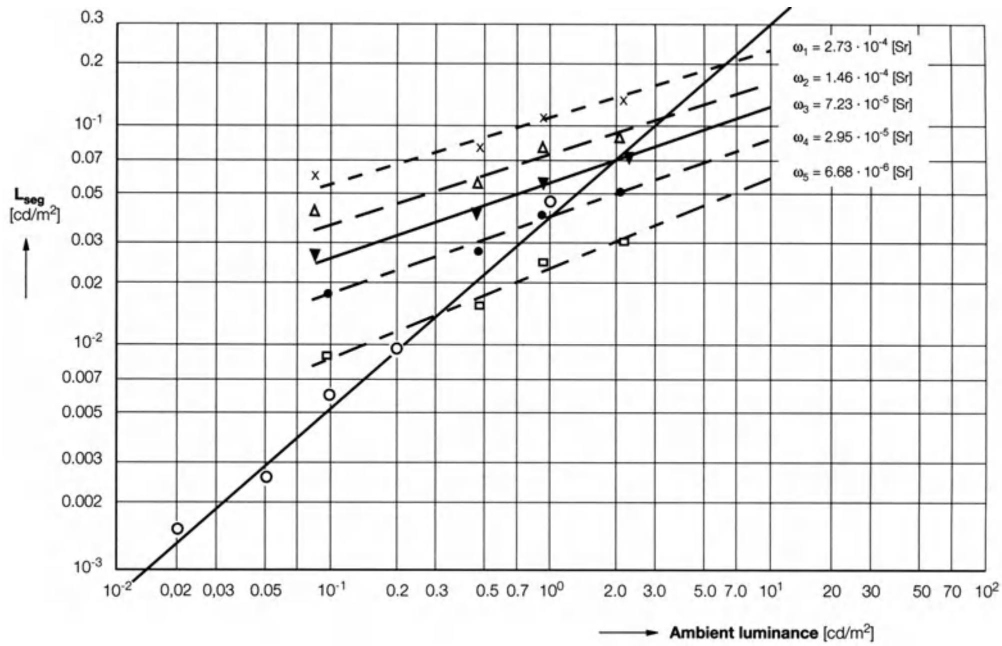


***Figure 9.2.3:** The relation between discomfort glare and disability glare. After Schreuder Figure 7.3.2. Based on Adrian (1966).*

Figure 9.2.3 shows clearly that there is some sort of relation between the two glare aspects; however, the slope of the two sets of curves is quite different, so the two are not directly proportional. As may be directly experienced by being outdoors, in very well-lit streets, discomfort glare is predominant even when disability glare is almost absent, whereas in poorly-lit streets the opposite is true. Disability glare can be considerable even when discomfort glare is hardly noticeable or absent. Thus, in poorly-lit streets, reducing discomfort glare to a degree that it is not noticeable any more, may cause hazardous situations for traffic, particularly for pedestrians who, contrary to cars, have to do without any lighting of their own. This aspect is often overlooked by those people who advocate low levels of street lighting on the grounds that high, or even mediocre, lighting is not only a waste of energy and a source of light pollution, but causes objectionable glare as well (Crawford, 1991, 1992, 1994; Mizon, 2002). It is clear, that this short-sighted idea is not supported by the facts.

(b) Discomfort glare in road lighting

Discomfort glare in road lighting has been a subject of intensive research for many years. The first studies were made in static models (De Boer, 1951; De Boer & Van Heemskerck Veeckens, 1955; De Boer et al., 1959). In later years, Schreuder made many measurements of discomfort glare in a scale model where actual driving could be simulated.

The results are given in De Boer & Schreuder (1967) and Schreuder (1967). They are summarized in Adrian (1971), De Boer (1967) and Van Bommel & De Boer (1980, sec. 1.3.3). The results have been validated in driving test in real streets (Cornwell, 1971; De Grijs, 1972; Economopoulos, 1978). Based on these studies, a rather complicated formula is defined that relates the degree of discomfort glare to a number of geometric and photometric characteristics of a road lighting installation. The formula is created by Schreuder (1967; see also Adrian & Schreuder 1968; 1971; De Boer & Schreuder, 1967). In 1976 it is accepted by CIE as the Glare Mark Formula (CIE 1976). Usually, G is called the 'Glare Control Mark'. Furtheron in this section, we will explain what G precisely means. Later, the formula is incorporated in the CIE recommendations for road lighting, be it in an annex (CIE, 1995, Appendix B). The formula is represented here in the form as given by Van Bommel & De Boer (1980, p. 27). See also Baer (1990, p. 76).

$$G = 13{,}84 - 3{,}31 \log I_{80} + 1{,}3 \left(\log \frac{I_{80}}{I_{88}} \right)^{0{,}5} - 0.08 \log \frac{I_{80}}{I_{88}} + 1{,}29 \log F + C + 0{,}97 \log L_{av} + 4{,}41 \log h' - 1{,}46 \log p \qquad [9.2.9]$$

with:

G: The Glare Control Mark;

I_{80}: The intensity under 80° with the downward vertical;

I_{88}: The intensity under 88° with the downward vertical;

F: The apparent light-emitting surface of the luminaire as seen under 76° with the downward vertical;

C: A colour factor. C = 0,4 for low-pressure sodium lamps and C = 0 for all other light sources (CIE, 1976 ; Van Bommel & De Boer, 1980, p. 58);

L_{av}: The average road surface luminance;

h': The reduced mounting height of the luminaires (the actual mounting height minus 1,5 m which represents the eye height of the observer);

p: The number of luminaires per km.

The range of validity of this formula is given by

- $50 < I_{80} < 7000$ (cd);
- $1 < I_{80}/I_{88} < 50$;
- $0{,}007 < F < 0{,}4$ (m^2);
- $0{,}3 < L_{av} < 7$ (cd/m^2);
- $5 < h' < 20$ (m);
- $20 < p < 100$;
- one or two luminaire rows in the road axis direction.

At the time of the introduction of this formula, it proved to be difficult to use in practice. Several graphical methods have been proposed to assess G. See e.g. Schreuder (1967, p. 149-152); Adrian & Schreuder (1986, 1971); Baer (1990, p. 77); Hentschel (1994, p. 181-185). With the use of personal computers, such graphical methods are not needed any more.

Several simplifications have been proposed over the years. CIE suggested the following formula to be used for outdoor sports and area lighting (CIE, 1994, formula 3.3):

$$GR = 27 + 24 \cdot {}^{10}\log\left(\frac{L_{LV}}{L_{VE}^{0,9}}\right) \qquad [9.2.10]$$

with:
GR: Glare Rating where GR = (10 – G);
L_{LV}: The veiling luminance from the luminaires (cd/m^2);
L_{VE}: The veiling luminance from the environment (cd/m^2).

For road lighting, classification systems for luminaires have been proposed to simplify the design process. These classification systems for road lighting luminaires are discussed in detail in sec. 7.1.4.

Einhorn (1994) has proposed a simple way to assess the discomfort glare for street lighting in residential areas:

$$L_K = A \cdot h^2 \qquad [9.2.11]$$

with:
L_k: The borderline value of the luminaires (kcd/m^2);
A: The flashed area of the luminaires (m^2);
h: The mounting height (m).

The proposal never was published. See also Schreuder (1998, p. 114), where a slightly different form of the proposal is given.

(c) *The scaling of experiences*

The end result of the calculations according to equation [9.2.9] or of the graphical assessment is the Glare Control Mark G. Usually, G is expressed in the well-known nine-point scale. It is basically an ordinal scale where to each number a 'glare experience' is allotted. The most common way to connect the two is given in Table 9.2.1.

G	Glare experience
1	unbearable
2	
3	disturbing
4	
5	just admissible
6	
7	noticeable
8	
9	unnoticeable

Table 9.2.1: *Glare Control Mark and Glare Experience (After CIE, 1994, Table 1, p. 3)*

Before the nine-point scale became commonplace, other scales were in use. The simplest was the concept of the Borderline Comfort-Discomfort (BCD), which is, of course, a two-point scale. In the 1940s and the 1950s, this concept has been used in the North-American literature. The Glare Control Mark G = 5 represents the BCD. De Boer has introduced a four-point scale (De Boer, 1951). The nine-point scale has the advantage of being symmetric around the BCD-border, which avoids at least some of the biases that are common in subjective appraisals.

Basically, the nine-point scale, as well as the other scales that are mentioned earlier, are ordinal scales where to each number a 'glare experience' is allotted. An ordinal scale is one of the four possible ways to group entities, the other three being the nominal scales, the interval scales, and the metric scales. They have the following characteristics:

(1) A nominal scale is a scale of items that does not include any quantitative measure. An example is the alphabetical order;
(2) An ordinal scale is a scale where items are scaled according to their magnitude, irrespective of how much their quantitative difference is. All one can say is that a higher class represent larger items, but it is not possible to say how much larger. An example of an ordinal scale is the distribution of medals in sports championships. All one can say that the gold medalist was faster/higher/stronger that the silver medalist, and so forth, but not how much. Therefore, many think that championship competitions are rather dull. As regards the Glare Control Mark scale, one may say that level 3 represents more glare than level 5, but not how much more. There is no way to ascertain whether the difference between the levels 5 and 3 is equal, larger or smaller than the difference between the levels 7 and 5. In other words, arithmical actions with the items are logically forbidden. More to the point, is it not permitted to take the average of several items. If, as an example, one installation is appraised by two observes as '6' one as '7' and one as '8' is it fundamentally wrong to say: "the installation scores as 27/4 = 6,75". In spite of these objections, this is precisely what always has been done. There is no justification other than the practical suggestion that the discrepancies are not so large as to cause disasters;
(3) An interval scale is an ordinal scale where the differences between the levels are equal. An example is the temperature scale of Celsius. The difference between 5° and 7° is the same as between 8° and 10°. However, one is not allowed to say that 40° is twice as warm as 20°. Additions and subtractions are permitted in an interval scale but multiplications are not;
(4) A metric scale is an interval scale with a real 'zero' point. The zero point of the Celsius scale is just a convention, whereas the zero of the Kelvin-scale is 'really' zero. The Kelvin scale is, contrary to the Celsius-scale a metric scale. Another example is the length: a piece of string of 2 meter is twice as long as a piece of string of 1 meter. In a metric scale, additions and subtractions, but also multiplications are permitted. Details on the different scales and their underlying theories are given in Blackburn (1996, p. 236).

As a final remark, it is clear that expressing items in an ordinal scale or in an interval scale or in a metric scale is a quantitative action. However, expressing items in a nominal scale is a qualitative action.

(d) Age effects in discomfort glare

The age effects of discomfort glare never have been studied in great detail. One source may be the paper by Vos & Van Bergem-Jansen (1995). In sec. 4.5.5, a description is given of the measurements of the light pollution around greenhouses in the Netherlands (Van Bergem & Vos, 1991). See also Van Bergem-Jansen et al. (1996). The survey in which the hindrance of the light pollution was assessed, contains some details on discomfort glare and on its possible age-effects. The discomfort glare is expressed with the obsolete concept of the Borderline Comfort-Discomfort (BCD). It was found that the typical luminance of 50 cd/m^2 of greenhouses is well below the BCD that, according to Putnam & Faucett (1951) is about 2000 cd/m^2 for a source size of 10^{-2} steradians (Vos & Van Bergem-Jansen, 1995, p. 50). These values are typically determined for young observers. According to Bennett (1977), the BCD decrease with age as follows: BCD = 86 000/a with BCD in cd/m^2 and the age a in years (Vos & Van Bergem-Jansen, 1995, p. 50). This negative age-effect is difficult to understand because disability glare clearly increases with age. That particular increase in easily understood by the ongoing cataract in the eye. See Mann & Pirie (1950 pg 142) and Stilma (1995a). Age effects are described in some detail in Schreuder (1998, sec. 7.3.3). The age-effects in disability glare are discussed in sec. 9.2.2c. See also Adrian (1995) and Fischer & Christie (1965). A decrease of discomfort glare with age is not confirmed by other studies like e.g. those of Rex & Franklin (1960) and Olson & Sivak (1984). They found only small, if any, influence of age (Vos & Van Bergem-Jansen, 1995, p. 50). Finally, no age influence was found in the subjective appraisal of the hindrance by greenhouses. (Vos & Van Bergem-Jansen, 1995, p. 51).

(e) Discomfort glare in other areas of lighting

De Boer introduced the following general relationship to describe the discomfort glare:

$$G_M = \frac{L_S^m \cdot O^n}{L_A^r \cdot p^q} \qquad [9.2.12]$$

with:
G_M: The glare mark;
L_S: The luminance of the glare source;
O: The solid angle of the glare source at the observer's eye;
L_A: The adaptation luminance;
p: A position factor.

The formula is published in this form by De Boer & Fischer (1981 p. 74). See also Vermeulen & De Boer (1948). It has been noted that the values that had been found for the empirical exponents m, n, r and q "are somewhat different as expressed by several authors; it appears that the test procedure itself influences the results" (De Boer & Fischer, 1981, p. 74).

Baer has expanded this formula (Baer, 1990, p. 60, equation 1.38):

$$G = 2 \cdot \sum_i \frac{L_{BL}^{1,6} \cdot O_{BL}^{0,8}}{L_u} \cdot \frac{1}{p^{1,6}} \qquad [9.2.13]$$

with:
G: The glare mark;
L_{BL}: The luminance of glare sources (cd/m^2);
O_{BL}: The flashed area of glare sources (steradian);
L_u: The luminance of the surroundings (cd/m^2);
p: A position factor. p = 1 if the observer looks right into the glare source; p depends in a complicated way on the viewing angle;
i: The specific glare light sources. The notation is somewhat sloppy.

The equations [9.1.12] and [9.2.13] have been developed especially for interior lighting where the time the observers are subjected to the glare is quite long. In an office, it usually is several hours. In many glare conditions, however, the 'time of exposition' or exposure time can be short. In the meeting situation between cars on a dark road it is only several seconds, whereas in most fixed road lighting situations it is seldom longer than a few minutes. Therefore, for a generally applicable glare relationship, the exposition time needs to be taken into account. It might be noted that one may get accustomed to discomfort glare, but never to disability glare.

(f) The need for a general discomfort glare formula

It is striking that each area of light application seems to have its preferred method to assess discomfort glare. In the literature, at least four different methods can be found, each with its own glare formula to calculate the glare and with its own design methodology:
(1) Vehicle headlighting – glare by low beam headlamps;
(2) Road lighting – glare by fixed road lighting luminaires;
(3) The lighting of outdoor sports facilities – glare by lighting fixtures, both as regards the spectators and the sport participants;
(4) Indoor working areas. Here the glare in offices, factories and other facilities are again treated in different ways.

Major publications for these four areas are:
(1) For vehicle headlighting: Schmidt-Clausen & Bindels (1974); De Boer & Schmidt-Clausen (1971);
(2) For road lighting; Adrian & Schreuder (1968; 1971); CIE (1976); De Boer (1951, 1967); De Boer & Schreuder (1967); Schreuder (1967, 1998); Van Bommel & De Boer (1980);
(3) For the lighting of outdoor sports facilities: CIE (1994); Folles (1979);
(4) For indoor working areas Baer (1990); De Boer & Fischer (1981); Hentschel (1994).

It is easy to add a few more areas where discomfort glare might cause problems. In most cases, little serious study has been made in those areas. A few examples: residential areas;

hotel lobbies; daytime situations etc. Usually, they are not judged as regards discomfort glare.

There are two main reasons to look for a general approach for discomfort glare, irrespective of the particular traditions in the specialized areas of lighting design:

(1) It is always the same human being who suffers from the adverse effects of discomfort glare;
(2) In all cases, discomfort glare is described by the same geometric and photometric characteristics of the lighting installation.

In the general discomfort glare approach that will be discussed here, the same geometric and photometric characteristics of lighting installations will be used. The difference for the specialized areas of lighting design will be expressed in different weighing factors for these characteristics.

(g) A proposal for a general discomfort glare formula

When considering a proposal for a general discomfort glare relationship, the best place to start seems to be the Baer variant of the De Boer formula. Earlier in this section, this formula is given as equation [9.2.13]. For a proposal for a general discomfort glare relationship, the formula is slightly re-written:

$$G = K \cdot \sum_i \frac{L_{BL}^{1,6} \cdot O_{BL}^{0,8}}{L_u} \cdot \frac{1}{p^{1,6}} \qquad [9.2.13a]$$

with:

K: A constant. In [9.2.13], K = 2. For the general discomfort glare relationship, K will be taken as the relevant variable;
G: The glare mark;
L_{BL}: The luminance of glare sources (cd/m^2);
O_{BL}: The flashed area of glare sources (steradian);
L_u: The luminance of the surroundings (cd/m^2);
p: A position factor;
i: The specific glare light sources.

In order to find out whether it is feasible to construct a general discomfort glare formula, we will start to introduce a number of simplifications in [9.2.13a]:

(1) The factor p is too complicated to handle, so we assume that while in the glare situation, the observer will look once-in-a-while directly into the glare source. More importantly, we assume that those periods determine the discomfort feeling. So we take p = 1;
(2) G = 5; we assume that in all cases there is a wish to be at least at – or preferably above – the BCD;
(3) We will look at one glare source at the time, so the summation can be deleted.

A time factor must be added:

(4) The total time in the glare condition t_1;
(5) The total time for looking straight into the glare source t_2.

As a further simplification we assume that only the fraction $F = t_2 / t_1$ is relevant, not the time intervals t_1 and t_2 themselves.

In general, it can be stated that discomfort glare will increase when:

- the illuminance on the eye increases (E_{eye});
- the viewing frequency increases (F);
- the size (length) of the luminaires decreases (D);
- the adaptation luminance decreases (L_{adap}).

A general formula would somewhat look like the following relation:

$$G = K \cdot \frac{E_{eye} \cdot F}{L_{adap} \cdot D} \qquad [9.2.14]$$

We will have to add exponents to the individual factors. These may be taken from the Baer-formula [9.2.13]:

- the exponent of E is the same as that of L: it amounts to 1,6;
- the exponent of D is the same as that of O: it amounts to 0,8;
- the exponent of L_{adap} is the same as that of Lu: it amounts to 1;
- for reasons of additivity, we assume that the exponent of F amounts to 1.

Earlier we did chose for G = 5.

Finally, the formula will be:

$$5 = K \cdot \frac{E_{eye}^{1,6} \cdot F}{L_{adap} \cdot D^{0,8}} \qquad [9.2.15]$$

In order to see whether K depends on the glare situation, and to estimate the variations of K for different situations, we will calculate K for a number of example cases from [9.2.5]. The examples, together with their estimated parameters, are listed in Table 9.2.2. The estimated values of K are listed in Table 9.2.3.

Type of lighting	**E_{eye} (lux)**	**F**	**L_{adap} (cd/m^2)**	**D (degree)**
daytime sun	100 000	0,001	3000	1
sun on snow	100 000	0,0001	10 000	1
living room	20	0,01	10	0,1
hotel lobby	5	0,1	3	0,1
repair workshop	100	0,01	30	10
factory	500	0,001	100	10
office	1000	0,01	300	10
sports field	500	0,1	100	1
lit road	10	0,01	1	1
unlit road	1	0,3	0,1	0,1

Table 9.2.2: *A number of example cases used for the estimation of K*

K	Type of lighting
0,15	daytime sun
0,24	sports field
0,26	unlit road
1,81	hotel lobby
5	sun on snow
6,57	living room
12,56	lit road
15	office
59,72	repair workshop
151,57	factory

Table 9.2.3: *Estimated values of K for different types of lighting in increasing order of K.*

(h) Conclusions as regards the use of discomfort glare as a design criterion

When we look at Table 9.2.3, it is clear that for different types of lighting and thus for different glare conditions, the situation is quite different even if one considers in all cases the Borderline Comfort-Discomfort. In other words, the glare discomfort depends on the situation and the type of lighting. When we take into account that, as has been indicated elsewhere, it is not possible to 'get accustomed' to discomfort glare, any proposal for a general discomfort glare formula must include this effect. However, the values in Table 9.2.3 refer only to a small number of examples. Any minor change in the parameter values selected for these examples might change the outcome considerably or even drastically.

As a conclusion it is therefore better to state that discomfort glare may be helpful for comparing different, but similar lighting installations. However, discomfort glare does not seem to be suitable for a general quality characteristic for the design of lighting installations on which fixed, numerical criteria can be based. It seems best, to do as has been done in street and road lighting: do not use discomfort glare any more as a design criterion. If glare has to be taken into account, as it must be done in all outdoor lighting installations, it is safest to restrict the design method to the assessment of disability glare.

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10 Fundaments of visual and behavioural functions

Essentially, this chapter is about human motivation: about what makes people do what they do. Motivation triggers behaviour; in order to understand behaviour, the motivation must be understood. In all behaviour that differs from unconditional reflexes, there is always a moment where consciousness is involved: at a certain moment, it is decided to do something. Decision processes are discussed in this chapter as well. This chapter deals with consciousness and the related concepts of conscience and ethical behaviour. The survey is slanted towards the subject matter of this book. All this is needed because most outdoor lighting is installed to prevent crime and violence, and to counteract their results. In order to know in how far these lighting efforts are justified, it is essential to know more about the consciousness of the those people involved – not only the criminals.

In earlier chapters, the phenomenological aspects of vision and visibility have been discussed as well as aspects of visual performance and task performance. This chapter deals with a number of basic concepts that are related to sensory perception more in general. The philosophy of information processing is briefly discussed. These philosophical considerations not only determine in how far sensory information may be used as a basis for the acquisition of scientific knowledge, but also in how far sensory perception is useful as a source of information for daily life.

Perception is transfer of information from an object into the consciousness. A four-level model of human consciousness is presented. One level is that of the instincts. Humans, like almost all animals, have many different instincts, one of which is the instinct of acquiring and defending a territory. It seems that this instinctive aspect is of particular interest for light pollution: light pollution is considered as a breach into ones's own territory. That may help to explain the vehement aggression that is often seen in objecting to light pollution.

Until recently, most considerations have been related to animal behaviour. For the subject matter of this book, it is human behaviour we will have to concentrate on, and particularly the role of human instinctive behaviour on aggression, focusing on street violence. The reason for this interest is clear: road lighting – a major source of light pollution – is installed with the reduction of street violence in mind.

The reason to pay attention to the language-aspects of the rational level of the consciousness is that reasoning, and more in particular reasoning by means of verbal language, allows us to get rid of the conscience. The conscience serves as a gauge to find out whether a specific action is 'good' or 'bad' – whether it should be pursued or refused. In particular, this is relevant for instrumental aggression. Language provides a means to 'rationalize away' the conscience. The reason to pay attention to visual illusions is that they once more make very clear that visual information – or any sort of sensory information for that matter – can give only a very rudimentary picture of reality. However, true knowledge requires a fundamentally different source of information.

10.1 The philosophy of information processing

10.1.1 Out there and in here; the problem of knowledge

One might wonder what is the point to discuss the philosophy of information processing in a book that focusses on the engineering aspects of artificial sky glow. There is some need, however, to do so. When we discuss visual perception, we assume that this process gives us relevant information about the things, the objects, that are perceived. If we have no interest in the objects, there would be no point in trying to make them perceivable by means of lighting – and without lighting, the problems of light pollution would by definition not exist. There is another reason as well. As is made very clear indeed in studying the psychology of human beings, there is more in reality, more within the human consciousness, than the rationality of science alone. Some of these points have been touched upon in sec. 9.1.2b, where 'behaviorism' is discussed. We will need all this here in this book, because only then, while taking the non-rational considerations of the human spirit into account, do we have a chance to be clear about what really goes on, when people are bothered by light pollution. As we will see, not much of that expectation is coming true.

Casual observations lead us to believe that many, if not most, people seem to look for true and solid knowledge about the Cosmos and about all that is in that Cosmos. Similar casual observations lead us to the idea that there is something outside us ('out there') and that there is also something inside us ('in here'). The concept of two 'worlds' – one out there and the other in here is explained very clearly and in great detail in Happold (1975). In secs. 9.1.2 and 10.2.2, it is explained that sensory perception is not a really good help to acquire true knowledge, so it seems that the only way to get that knowledge is to go to the inside ('get in'). Further in this section we will also come back to this point when discussing the nature of science.

Getting 'in' presents, of course, a problem. There are no real clues whether the things one might find there will be the same as the things other people might find when they go 'in'. There is even no sure way to know there is a 'real' reality 'out there'. It is even not clear what a 'real' reality actually means, or whether there is any sense at all in speaking about 'real' and 'unreal' realities. Nevertheless, most people seem to be convinced that the findings will be very similar to those of other people, and indeed, that there is a 'real' reality out there, with other people in it. However, when it comes to acquire true and solid knowledge, it seems that the answers can only be found 'in here'. And true, solid and objective knowledge about things is what we expect the sensory perception to provide.

According to the empirists, all knowledge is the result of sensory perception (Kohnstamm & Cassee, eds., 2002, p. 177). Contrary to the assertions of natural sciences, "Philosophical theories are not tested by observations, they are neutral with respect to particular matters of fact." (Ayer, 1969, p.7). And also "Naive realism leads to physics, and physics, if true, shows that naive realism is false. Therefore, naive realism, if true, is false, therefore it is false" (Ayer, 1969, p. 92, quoting Russell n.y., p. 15). These verbal niceties seem to lead nowhere; for this reason they are quoted here. Not all things said by The Masters make sense.

It goes without saying, however, that this chapter is not the place to discuss in detail the philosophical finesses of the 'problem of knowledge'. There are some points that are directly relevant for the subject matter of this book. These points go back directly to the definition of science. Engineering is usually understood to be the art of the pragmatic application of the findings of science.

10.1.2 The nature of science

The term 'science' is often used in a loose, even sloppy way. In fact, the term is not very useful because no strict definition can be given. Sometimes, science is defined as organized knowledge (Medawar, 1984, p.3). The limits of science always have been a matter for discussion: "The cosmic insight of the natural sciences is not any longer a part of the natural sciences. It is a view on the relation between human beings and nature and not a view on nature" (Heisenberg, 1955, p. 21).

Things improve when we speak of 'natural science' instead. Natural science can de defined in an operative way by stating: "Natural science is the collective of actions that are performed by the exclusive use of the method of natural scientific research". The method of natural scientific research is firmly anchored in what philosophers usually call positivism and empirism. Both terms have a lot in common. We use here the very brief descriptions given by Kohnstamm & Cassee, eds. (2002). According to positivism, all knowledge originates from sensory perception (Kohnstamm & Cassee, eds., 2002, p. 182). Empirism adds to this that human beings do not have any inborn capability of knowledge. All knowledge is the result of sensory perception (Kohnstamm & Cassee, eds., 2002, p. 177). This idea is not new, as may be seen from a quotation from Leonardo da Vinci, written around 1500: "All our knowledge has its origin in our perceptions" (Richter, ed., 1952, p. 4). The method of natural scientific research is essentially inductive. "Induction is a process of reasoning that takes us from empirical premisses to empirical conclusions supported by the premisses but both deductible from them" (Blackburn, 1996, p. 192). Mathematics use deductive processes: "Deduction is a process of reasoning in which a conclusion is drawn from a set of premises" (Blackburn, 1996, p. 96). In an inductive process, both the premisses and the conclusions are empirical in nature, i.e. they stem from sensory inputs. It should be noted that in a more precise fashion, the terms induction and deduction refer to logic and not to science (Blackburn, 1996, p. 221). It may be noted that some consider science as deductive: "Science is deductively ordered. It parades principles, laws and other general statements from which statements about ordinary particulars follow as theorems " (Medawar, 1984, p. 3). It might be noted that 'experiments' are not mentioned in this quote.

Around the 1920s, a group of scientists came together in Vienna. As a result, they are known as the 'Wiener Kreis' (The Vienna Circle). They explained their views on the "Scientific conception of the World" in a pamphlet of 1929 (Anon., 1973). The Vienna Circle was very clear as to what belongs to the natural sciences (or the scientific world-conception as they call it), using the method of logical analysis. "The metaphysician and the theologian believe that their statements denote a state of affairs. These statements say nothing but merely express a certain mood and spirit. To express such feelings for life can be a significant task. But the proper medium for doing so is art, for instance lyric poetry or music" (Anon., 1973, p. 8-9). This view, of course, is only adhered to in several Western European countries and that only since the 17th Century – actually since Descartes made them fashionable as a part of his theories were a strict distinction was made between body and mind (Anon., 2003, p. 39). The Aristotelian conception of sensory perception may serve as an example that this was not always the case: "Sensory perception is a literal sharing of form with that which is perceived" (Blackburn, 1996, p. 25). The Aristotelian philosophy is summarized in a clear way in Bambrough, ed. (1963).

In recent times, doubts did arise against the strict distinction between body and mind. Unfortunately, in the wake of the discoveries in neuro-physiology and in brain anatomy, many people advocate that 'mind' is just a part of the 'body'. In sec. 8.1.5d, the following was quoted: "The conscious picture of the surroundings is the result of the concerted efforts of all parts of the visual cortex" (Bergsma, 1997, p. 62). Standpoints that reach much further are represented in Crick (1989, 1994), Dennett (1993), Edelman (1992), or Weinberg (1993). This, by the way, is nothing new. The nineteenth century biologist Thomas Huxley states: "The thoughts to which I an giving utterance, and your thoughts regarding them, are the expression of molecular changes" (Augros & Stanciu, 1984, quoting Huxley from Alburey Castell, ed., 1948).

In the process of establishing premisses and of applying inductive processes, a number of assumptions is made. The nature of an assumption is that it is seldom made explicit; only few philosophers or scientists were smart enough – or courageous enough – to realise this and to make them explicit. A group who did this was the Vienna Circle. They used three main assumptions in natural sciences:

(1) The first quite common assumption is, that the Universe is comprehensible – when one takes enough trouble, one could understand the whole Cosmos with everything in it ("The scientific world-conception knows no unsolvable riddle"; Anon., 1973, p. 8). Usually, a more restricted view is taken that the Universe is not only comprehensible but also that it can be described in mathematical terms. "Mathematics itself is never the explanation of anything – it is only the language in which we express our explanations" (Weinberg, 1993, p. 44). Not only that; it is generally assumed that, if two conflicting theories are presented, the most 'elegant' is the 'most true' (Maxwell, 1998). Of course, one theory being more true than another is sheer nonsense. There is even a 'theory' for it: 'Ockham's razor' – the more stupid because Ockham said something quite different: "Entities are not to be multiplied beyond necessity" (Blackburn, 1996, p. 268). In modern words, it is a plea for clean thinking, not for different levels of truth. In spite of this, the assumptions are quite common: "So physicist are faced with two distinct theories, each profoundly separate and different from the other. For physicists, who believe that nature should be ultimately simple and elegant, it was a puzzle; they could not believe that nature could function in such a bizarre fashion" (Kaku & Trainer, 1987, p. 11-12).

(2) The second quite common assumption is, that the syllogistic logic is universally valid – the logic of the excluded middle (Blackburn, 1996, p. 129); the logic of the rules of causality (Blackburn, 1996, p. 58-59). Often, this is summarized as the Aristotelian logic (Blackburn, 1996, p. 221; p. 368; Diemer & Frenzel, eds., 1970, p. 139- 144). This view was expressed already by Leonardo da Vinci: "In nature there no is effect without cause; understand the cause and you will have no need of the experiment' (Richter, ed., 1952, p.6);

(3) The third quite common assumption is, that the principles of reductionism are universally valid – the total equals the sum of the parts (Weinberg, 1993).

It should be stressed here that these three assumptions are clearly not universally true. It is very easy to find many exceptions of them in daily life. Therefore, the Vienna Circle were very clear in excluding all these considerations from the scientific conception of the world. It did not seem to bother them, as it does not seem to bother modern scientists, that they were in the end speaking of a very limited area of human endeavour. Just a few examples:

- it seems that the statement that the Universe is comprehensible only refers to the human intellect and not to the Universe;
- many people will experience that the syllogistic logic has little or no meaning for the relation between people or between groups of people;
- reductionism holds for algebra only – and probably even not all the time.

Based on the assumptions, one may construct a view about the nature of science – it would be better to say: about the nature of natural science:

(1) Take a premise. One does not have to bother too much where the premise is coming from, as long as it is open to sensory observation – as long as it is empirical. Even that is not always required: "Every once in a while mathematical abstractions, experimental

data, and physical intuition come together in a definitive theory" (Weinberg, 1993, p. 3);

(2) Perform observations. One does not have to bother too much about the nature of these observations as long as they are empirical. Usually they are not fully systematic; they are heuristic in nature;

(3) Set up a hypothesis, a theory or a paradigm on the basis of the observations about the premise. In practice, hypotheses, theories, and paradigms seem to mean about the same. The hypothesis has to fulfill certain requirements, such as being internally consistent and not being in conflict with the assumptions indicated earlier about being comprehensible, logical and reductionist;

(4) Set up a crucial experiment "held to decide with certainty between two rival hypotheses about some matter" (Blackburn, 1996, p. 89). According to some scientists, this is not going far enough. They require that hypotheses must be open to falsification. "The virtue of science is not that it puts forward hypotheses that are confirmed by evidence to a high degree, but that its hypotheses are capable of being refuted by evidence. That is, they genuinely face the possibility of test and rejection through not confirming to experience" (Blackburn, 1996, p. 136, quoting Popper, 1934).

(5) This method is supposed to give an indication of truth. In view of the assumptions used underway, this assertion does not seem tenable at all (Maxwell, 1998). However, some physicists seem to believe that there is even an ultimate truth in physical theory "Advocates of superstrings even claim that it could be the ultimate theory of the universe" (Kaku & Trainer, 1987, p. 3). Indeed, 'ultimate'! It is hopefully sufficient, however, to solve most practical physical and engineering problems.

10.1.3 The nature of sensory perception

As has been stated earlier, natural science relies on experiments that lead to results that can be observed by the senses. It is usually assumed that this statement allows for equipment like e.g. measuring devices or computers to be inserted between the object to be studied and the observer. It must be noted that this extension of the statement is not self-evident, but it seems that neither philosophers nor scientists are bothered by it. Now a strange thing can be observed: it seems that philosophers – and theoretical physicists alike – believe that sensory input has some sort of 'truth' of its own right. "Science is not just a catalogue of unrelated facts. It is a creation of the human mind, with its freely invented ideas and concepts. Physical theories try to form a picture of reality and to establish its connections with the wide world of sense impressions. Thus the only justification for our mental structures is whether our theories form such a link" (Einstein & Infeld, 1966, p. 294). The link they refer to is the link between the inventions of the human mind and the sensory perceptions. The idea is similar to that of phenomenology: "Phenomenology denotes, according to Kant, the description of experience in abstraction from its internal content" (Blackburn, 1996, p. 284). What it comes down to is: you may think whatever you like, the only truth is in that part that corresponds to the sensory perceived outer world. The rest is just a 'figment of the imagination'. However, in sec. 10.2.2, when discussing visual illusions, it will be explained that it is probably better to reverse the idea: whatever you think you may regards as true; when it corresponds with sensory perceptions you are just lucky. Sensory processes are fraught with errors and therefore the results of sensory perception must be treated with the greatest care. See also sec. 10.1.1.

This means that we have to be satisfied by an approximation. Sensory perception – visual or with other senses – will in all likelihood provide useful information about the world 'out there' but one never can rely on it in order to come to hard conclusions about the outer world. Whatever the case, the information ends up in the consciousness. Having perceived objects in the outer world makes us conscious about the presence and the nature of these objects, even if the knowledge is only in part and not complete.

10.1.4 Consciousness

(a) Models

Models are a useful tool to make an approximations or a similarity to reality (Schreuder, 1998, p. 95). There are many types of models. The first distinction is between colloquial models and formal models. Colloquial models are just what it says: a model. In formal models, not only the model itself but also the language and the axioms need to be formalized (Nauta, 1970, p. 177). These ideas are worked out in more detail in sec. 10.3.1a. A model is a projection of reality; a model can also be used as a paradigm. A paradigm is a thematic programme for a research project. Conventionally, models are split in two categories:

(1) Descriptive models;
(2) Predictive models.

As the word says, descriptive models just describe the reality, whereas predictive models allow to make predictions about the result of manipulations of the reality. In a predictive model, the parameters in the reality are depicted in the parameters in the model. The parameters in the model are a transformation of the parameters in reality. Any manipulation of the parameters in the model corresponds to equivalent manipulation of the parameters in the reality; therefore, a predictive model can be used to predict – as the word says – the effects in reality of a particular manipulation in the model. Models are described in more detail in Feynman (1990); Hollin & Howels (1992); Nauta (1970); Schreuder (1973; 1985; 1993; 1998, sec. 10.1.3)

Models can be any of many kinds. A common type of models in science is the mathematical model. The description of Nature in mathematical terms is nothing but a model; that it fits, means only that the model is self-consistent and does not say anything at all about the essence of Nature (Feynman, 1990, sec. 2). As is suggested in sec. 10.1.3, it seems to say only something about the structure of the human mind. Other models are scale models of buildings, computer models of almost everything, etc.

We will list here some of the more important characteristics of models. First comes the most important one:

(1) Models do not give any information in how far the concepts of reality are true. There are no 'true' or 'false' models; there are only 'clever' and 'dumb' models. Clever models 'work' and dumb models don't. Models are not 'correct' or 'wrong'; they may be adequate or inadequate.

The second important characteristic is that:

(2) The most suitable model should be used. This is a variation of 'Ockham's razor' that is mentioned in sec. 10.1.2 (Blackburn, 1996, p. 268). As an example, the 'world model' of Ptolemy is much more suitable for solving the day-to-day problems of ordinary people, even of today, than the Copernicus model – let alone the Einstein model or the 'superstring model'. Only for scientists they may make some difference (Kaku & Trainer, 1987; Weinberg (1993).

Other important characteristics are:

(3) Models rely on experiments (sensory observations) for their support. As sensory observations are fraught with inaccuracies, the support can never be more than 'adequate' or 'acceptable';

(4) This implies that at any moment in time, the need may arise to change the model, to adapt it, to extend it or to throw it over board altogether. Thus, we are completely free to select and use any model we like. Even cultural aspects are sometimes used to propose another selection of the models to be used: "By presenting astronomical developments through the ages as a cultural continuum, we will be emphasizing astronomy as a global heritage. The West must give up its fixation with ancient Greece. Time did not stand still between Ptolemy and Copernicus. On their part, cultures with memories of past contribution, should use tradition as a source of inspiration and then selectively break away from it to enhance modern science." (Kochlar, 2001). This, of course, holds not only for astronomy but for all natural sciences, for philosophy and religion and finally for all human knowledge and insight in general.

It should be noted that they all are called 'models', because they all miss something essential: they depict reality, but they are not reality themselves!

(b) Consciousness and memory

In spite of the fact that many learned as well as many popular books are devoted to consciousness and, particularly in recent times, to the possible neurophysiological and biological basis of consciousness, definitions are hard to find. "First, consciousness is impossible to define" (Greenfield, 1999, p. 210). Or: "It is almost impossible to say what consciousness is" (Blackburn, 1996), p. 76). What can be done in stead of defining consciousness is to give a broad description of it, wide enough to encompass what our ideas about it and precise enough to be useful. For this description, we will start with some observations that are likely to be shared by most people.

A first thing that one might notice is one is 'conscious' of only a very limited items simultaneously at the same moment in time. The number of these items seems to be around eight or so. So it seems that the actual content of consciousness is very limited indeed, limited to only a few bits of information in terms of information theory (Shannon & Weaver, 1949; Wiener, 1950, 1954). At the other hand, one will be well aware of the fact that the number of items one may can choose from to be conscious about is vast – maybe even unlimited. This aspect is closely linked with the concept of attention that is discussed in sec. 10.2.3, a concept that in its turn is closely related to the concepts of arousal, awareness and vigilance (Schreuder, 1998, sec. 8.1).

As an example, Table 10.1.1. gives a overview of the capacity of different sensory channels in the human organism.

Stimulus	Number of receptors	Nerve fibers	Neurons	Conscious information processing
light	$3{\cdot}10^8$	$3{\cdot}10^6$		
sound	$3{\cdot}10^4$	$2{\cdot}10^4$		
pressure	$5{\cdot}10^6$	$1{\cdot}10^4$		
pain	$3{\cdot}10^6$		10^{10}	10-100 (bits per second)
heat	$1{\cdot}10^4$	$1{\cdot}10^6$		
cold	$1{\cdot}10^5$			
smell	$1{\cdot}10^7$	$2{\cdot}10^3$		
taste	$1{\cdot}10^7$	$2{\cdot}10^3$		

Table 10.1.1: *Information processing in humans. After Anon., 2000. Based on Schmidt-Clausen, 1997.*

In the psycho-physiological literature, these effects are usually described as the short-term memory (Gregory, ed., 1987, p. 713-714) and the long term memory (Gregory, ed., 1987, p. 455-464). In computer terminology, the first is the working memory, the second is the RAM. So, consciousness has at least two parts: a ready, short term part that is always available and related to the momentary activity and a reserve, longer term, part that can be called upon at will at each moment.

But there is more. Human behaviour is influenced to a large degree by the input from other parts of the inner being, parts that have some similarity with consciousness but missing precisely that which makes out consciousness (Hess et al., 1992, p. 112-113). Freud termed that the 'subconsciousness' (Freud, 1916, 1962). As a matter of fact, it is the basic principle of the psycho-analytic therapy to transfer contents from the subconsciousness into the consciousness (Brown, 1967).

(c) Five ways of life

A second observation that several people seem to share is the fact that there are several types (or levels, or 'tastes' if you wish) of consciousness that have little in common and that can operate almost independent of each other. There is some likeliness to the different chakra levels of oriental philosophy. Leadbeater, in his classic work, lists them as follows:

(1) The root or base chakra;
(2) The splenic chakra;
(3) The navel chakra;
(4) The heart chakra;
(5) The throat chakra;
(6) The brow or frontal chakra;
(7) The crown or coronal chakra. (Leadbeater, 1977, p. 7).

They seem, according to the findings of neurobiology, to correspond closely to parts of the brain (Edelman, 1992; Sagan, 1980). There seems also to be a parallel to the phylogenetic evolution of life, and particular of animal life. There is little room for doubt about the fact that life evolved gradually from the simple to the complex; the discussions focus on the mechanisms involved. We will come back on the concept of evolution, and on several aspects of its essential concept 'time' in sec. 10.1.5a. And finally, a number of these levels seem to correspond to five different levels of 'living': vegetative living – instinct – emotion – reason (or ratio), and intuition.

The relationships between different levels of consciousness at the one hand and brain locations at the other hand are not one-to-one projections. When considering the possible allocation of functions to brain areas, it has been found that such relations usually are rather vague. Some allocations are very specific (Greenfield, 1997). However, a closer look at human behaviour suggested that the allocation of functions to areas of the brain usually is far from specific. It might be better to speak of 'systems' (Damasio, 1994, p. 15; Greenfield, 1997, p. 39). "Experience does not err, it is only your judgement that errs in expecting from her what is not in her power" (Richter, ed., 1952, p. 5).

(d) A four-level model of consciousness

Now we go back to the concept – be it not defined properly – of consciousness. There seems to be enough material now to propose a model of human consciousness (Schreuder, 1996). Because the model is based on the fact that there may be discerned four different levels of consciousness, the model may be called the 'four-level model of consciousness'. In the description of it, the chakra levels according to Leadbeater (1977) are added as well as an indication of the parts of the brain that seem to be active when actions find place that correspond to the different levels of consciousness (after Sagan, 1977 and Schreuder, 1996). In this section, five levels of human activity are listed; the first is, as shall be explained, not a conscious level properly speaking, so the actual model consists of four levels. Hence the term. The four levels of the model are:

(1) The level of instincts;
(2) The level of emotions;
(3) The level of the ratio;
(4) The level of intuition.

The sequence in which these levels are listed is not arbitrary. They range from the simple to the complex, from the primitive to the developed. When we take the stages of development into account of the animals where the levels may be discovered, or the stages of development of the human being from embryo to adult, one might also say that they range from the lower to the higher. However, the most appropriate way to express the sequence of the different levels is to consider them as sets – as in 'set theory', where each lower level is considered as a sub-set of the higher level. See for sets and set theory Daintith & Nelson (1989, p. 293).

(e) Vegetative aspects

The vegetative level (the root or base chakra) represents activities that seem to be totally unconscious. They include bodily functions like e.g. digestion. They are common to all living beings, plants and animals alike. It should be noted that many believe that these processes are not really unconscious for those who have more insight. See e.g. the well-known tetralogy of Castaneda (1975, 1976, 1976a, 1978) or the famous autobiography of Yogananda (1977). It is not clear to which part of the human brain – if any at all – these activities do correspond. Reflexes do not involve the brain at all; they are processed in the spinal cord (Greenfield, 1997, p. 43-44; 134). The upper part of the spinal chord is somewhat expanded and forms the 'medulla'. The medulla is involved in the regulation of a number of bodily functions such as the bodily temperature, the breathing, the heart beat and the digestion as well as a number of other functions (Vroon, 1989, p. 135). It must be noted that these functions can almost all be influenced, additionally, by reflective action or by voluntary action. Some are also influenced by some non-image forming effects of light falling into the eye (sec. 4.5.2). Digestion is also governed by the autonomic nervous system (Greenfield, 1997, p. 135).

10.1.5 The first level: the level of instincts.

(a) Theories about time

The first point to consider when discussing the theories behind the instinct-concept is to establish what instincts are and where they come from. Whatever definition of instinct is used, they all have in common that they are inherited from one generation to the next: they are hereditary. It is customary to connect heredity to genetic aspects that are supposed to be located in the chromosomes. For our further discussion it is of some importance to find out how they get there. The most common notion is that instincts, just as all other hereditary traits, get into the chromosomes because with these traits, living creatures are better off than without them. "If we are willing to ignore the possibility of divine intervention, the only known process by which such complexity can have arisen is evolution by natural selection" (Mithen, 1996, p. 42). Many do not agree, however: "It is necessary to invoke supernatural spiritual creation for the qualities of the human mind" (Mithen, 1996, p. 268, quoting Eccles 1989).

The strange thing is that these two ideas are often presented as opposites: either the long-drawn effects of survival of the fittest or instantaneous creation. There is of course no reason why some sort of non-physical intervention would not take a long time as well. It seems to be better to leave the question whether 'divine intervention' is involved or not, out of the debate. If not, one would have to begin with a precise definition of 'divine'; as is explained in sec. 10.1.9g, this is precisely what never can be done about divine. For the purpose of this book, it does not matter what is exactly the process how the information gets into the chromosomes. What matters is that it is plausible to assume that it takes a long time for any change in the hereditary patterns to get ingrained in the hormone outfit of living creatures and probably just as much time to get it out.

Theories of evolution imply time as an essential dimension: first, there was condition A, and afterwards there was condition B. Traditional evolution theories are based on evidence from biology, or rather, from paleontology. They are based on fossils. The same applies to cosmology, be it that the fossils look different. The problem with fossils is that they are here in the present. They may tell us something about the past, but they are not the past (Reeves, 1989; Van Woerden, 1989).

Hawking (1988) gives probably the best survey of the different theories of time that were used in physics over the centuries. In modern physics, time is a mathematical construction without any reality. It is nothing but a coordinate. See e.g. Gribbin (1992, p. 45). Newton had a different idea. Time is absolute, it is an objective flow that goes on relentlessly from minus infinity – the absolute past – to plus infinity – the absolute future. The speed is of the flow of time is not cannot be influenced by any physical cause. But how do you know that? Only by comparing it to something you know that flows steadily. The daily rhythm is the only useful thing. Fortunately, Earth revolves round its axis rather smoothly. Irregularities are far too small to be detected by the senses alone, but we know – and Newton knew – that they exist. So, the continuous flow of time is an assumption, or rather an axiom. When time is just a coordinate, it is separate from things that happen in time. One might argue whether coordinates can exist without anything in it. It is not sensible to believe that, because coordinates are just a convenient tool, invented by mathematicians to bring some order in phenomena that would seem to be chaotic otherwise. In terms of models, coordinates are a descriptive model (sec. 10.1.4a).

Over the centuries, the question whether time as such does exist without anything in it, has been answered in different ways (Hawking, 1988, p. 9). As Hawking explains, Newton left the question alone by assuming that the Universe was eternal as well. Augustinus said: "Time is a property of the Universe that God created, so time did not exist before the beginning of the Universe" (Hawking, 1988, p. 9). This point of view is similar to that of most modern cosmologists who postulate that the Universe started long ago, but at a fixed time, with the Big Bang. There was no time before the Big Bang (Hawking, 1988,

p. 10). Not all cosmologists seem to share this opinion. However, the Steady State Universe as postulated by Hoyle and his colleagues (Hoyle, 1958), seems to be difficult to compromise with the results of observations (Hawking, 1988, p. 50-51). A more recent variation of this, the idea of Multiverse as defended by Rees, does avoid these conflicts by stating that there are almost an infinite number of separate Universes from which we may pick the one which suits us (Rees, 1997). It seems a rather strange way to avoid the difficulties that seem to exist when considering special effects in the Cosmos. It this case, it is about the 'fine tuning' of natural basic constants, in classical Darwinism it is the clever adaptation of animals and plants to the environment, and in modern neurosciences it is the riddle of consciousness. The philosophical point behind these considerations is that many scientist abhor any sort of 'plan' in the Cosmos, because they come to the erroneous conclusion that a 'plan' automatically means 'God' – and to allow God in any consideration is considered as the most deadly sin in science.

Newton and Augustinus seem to agree on one point: time is a separate coordinate; what happens in the Universe can be scaled along this coordinate axis in a linear way: first this and then that. This seems to be a direct contradiction of the theories put forward by Einstein. Einstein introduced in the special theory of relativity the four-dimensional space-time continuum. See for a succinct but very clear description Feynman et al (1977, Vol. 1, Chapter 25, p. 1-21). Again, coordinates do not represent reality, only a set of coordinates that may be used to describe situations. The postulate of Einstein is that any occurrence may be represented by a set of these four coordinates; the characteristics of the occurrence are invariant for any linear coordinate transformation. That is something completely different from the four-dimensional block model of the Universe that is proposed by some physicists and that is supposed to represent reality. In that model, time as such is non-existent; future and past are all included in the block. This would mean that the Universe is completely predetermined and that there is no place for chance occurrences.

It should be stressed that this does not only contradict the cosmological standpoints that we have indicated above; in a more fundamental way, it is in direct conflict with the principles of quantum dynamics. Feynman has expressed this succinctly: "*We do not know how to predict what would happen in a given circumstance* and we believe now that it is impossible" (Feynman et al., 1977, Vol. 3, p.1-10; italics by the Feynman). One should note the word 'believe' in this quotation. It would also imply that there is no place for a free will. The free will, however, is not a concept that can be treated in experimental natural sciences.

According to the Hindu philosophical, or rather spiritual, systems, history has a closed-loop character, without, however, being exactly circular. Time cannot fold back on itself. In an exactly circular Universe, one can never count the number of full circles that has been made, because the circles would be identical, and offer no means to distinguish the one from the other. Hindu philosophy states that a human being might be subject to go through the cycle of life and death many times, even millions of times, but still, if you do really your utmost, you may break the circle and reach the state of 'moksha' or enlightenment

(Hinnells, ed., 1984, p. 214). So there really is no periodic Universe, only a 'nearly periodic' Universe. This is briefly explainde for Hinduism in Hinnells, ed. (1984, p. 215) and for Jainism in Hinnells, ed. (1984, p. 258). It should be added that there seem to be some limits to this (nearly) periodic Universe. "According to ancient Hindu cosmology, the universe began with the all-pervading resonance of the magic syllable om (Von Baeyer, 1993, p. 29). Whatever we may think about that, for the Hindus the Universe did begin. A similar idea may be found in the Gospel of Saint John: "In the beginning was the Word, and the Word was God; and the great dark emptiness trembled with the promise of incarnation. Or did it? No trembling of any kind can occur in the absence of a medium – something to do the trembling" (Von Baeyer, 1993, p. 29).

This brings us to the concept of vacuum. That gives other problems, also as regards the concept of time. "But the introduction of a shadowy something, like the ether, into the otherwise pristine emptiness of the vacuum produced a contradiction" (Von Baeyer, 1993, p. 32). After many unsuccessful attempts, an answer was given by Feynman by stating that "negative-energy solutions of the Dirac equation describe electrons travelling backwards in time" (Von Baeyer, 1993, p. 35). By introducing a definitely counter-intuitive definition of the concept of time, it did not solve the vacuum-problem. The only reassurance is that it is highly unlikely to meet in daily life, any object that travels backward in time.

There is more to that, however. The idea that the Universe is completely predetermined and follows the laws of Newton and Einstein, implies also that time is reversible. Often, the billiard table is used as an example. If we disregard friction, it is always completely possible to reverse time. All laws of Newton, as well as all laws of Einstein, are invariant for the direction of time. Mind the condition: "If we disregard friction". However, in real life, friction never can be eliminated, and thus has time a direction.

Until now, we discussed the mathematical tool. Now we need to discuss events that happen in reality. Events are characterized by the fact that first they do not exist, then they exist, and then they do not exit any more. They have a beginning, an existence and an end. They have a history, and histories use time as their yardstick.

Taking into account phenomena like friction, that was mentioned earlier, gives rise to a completely different concept of time. This is the time concept of irreversible processes. "They have special place in nature. They are related to a very important law of physics, known as the second law of thermodynamics; this, put at its simplest, tell us that things wear out" (Gribbin, 1992, p. 146).

An example that is sometimes used, is about a sand castle on the beach. In the beginning, it is neat and smooth. When time elapses, grains of sand are taken from it by wind and water, until at the end only a shapeless little hill remains, and still later, nothing at all. When filmed, each grain of sand will evidently follow the laws of classical physics. When the film is shown in reversed order, still each grain of sand seems to follow these laws, but gradually, from 'nothing' seems to emerge a nice and smooth sand castle. This, of course, never happens in real life. The reason is not that the grains of sand disobey the laws of classical physics, but that the probability of a castle emerging from 'nothing' is exceedingly small. It would take many, many multiverses for this to happen.

This probability is called 'entropy'. More precisely, entropy is "The thermodynamic probability W where W is the number of microscopically different states of a system that give the same macroscopically determinable state" (Illingworth, ed., 1991, p. 156). When in a closed, reversible system energy flows, the entropy is unchanged. In a closed, irreversible system, when energy flows, the entropy always increases. The increase is determined only by the beginning and end states, and does not depend on the way the end is reached (Illingworth, ed., 1991, p. 1556). A rigorous mathematical treatment of the entropy concept is given by Feynman et al. (1977, Vol. 1, Chapter 44, p. 10-12, and Chapter 45, p. 6-9).

(b) Theories about instinct

In the preceding part of this section, it is suggested that we may assume that it takes a long time for any change in the hereditary patterns to get ingrained in the hormone outfit of living creatures and probably a time just as long to get it out. The implication is that, as will explained further in this section, the hereditary outfit of modern human beings is almost the same as that of our ancestors of a distant past of say one or two million years ago.

Many people seem to think that instinct and aggression are synonyms. This is, of course, not true at all. Levelt, in his study about aggression in road traffic, concentrates on just two ways of getting aggressive: to take revenge for injustice – real or perceived, or to gain profit – either in psychological or in material sense (Levelt, 1997). Instinct behaviour is not mentioned, neither is frustration.

Schreuder, in his original study on motivation, indicates that often an 'original doctrine of instincts' has been used (Schreuder, 1973). According to Fletcher (1968), this algorithm was originally stated by Darwin. This paradigm (the word 'doctrine' seems to be a little far fetched) has three elements:
- instincts are innate;
- instincts are internally controlled,
- instincts are goal oriented (Kortlandt, 1970).

A fourth element might be added:
- instincts are species specific (Van Essen, 1971; also Van Essen, 1965).

This algorithm needs to be extended as a result of the studies in ethology and psychoanalysis (Fletcher, 1968, p. 29). This extension needs to be only marginal (Fletcher, 1968, p. 288). The programme of Fletcher (1968, p. 67; p. 288) is rather limited to the answers to two questions only (slightly abbreviated):

(1) Among animals, we find numerous examples of complicated sequences of behaviour which are performed without previous experience; how are we to account such behaviour?
(2) To what extent are the features of such behaviour discernible and of importance in the nature of man?

The answers can be summarized as follows: (1): impossible; (2): a lot. This seems rather discouraging and very general. No wonder that many other authors agree to these conclusions, e.g. Barnett (1970, p. 259).

There seems to be some difference with the opinions of the psychoanalysts. The instinct theory of Freud is summarized by Graumann (1969a, p. 16). That theory seems to come down to the statement that instincts are not much more than a way to fulfill internal drives. These drives seem to have a physiological aspect and are not purely instinctive (Fletcher, 1968, p. 173: Graumann 1969a, p. 16). It seems that this is in fact nothing more than the idea that human beings – just as animals – only act as a result of conditioned reflexes (Cofer & Appley, 1964). In sec. 10.4.1, the concept of motivation, as well as the related concept of motive, will be discussed in detail when considering decision making processes.

So, the psychoanalysis does not seem to give an answer on what instincts are and how they work. In spite of that, animal instincts are often considered as being valid for human beings as well. So, the second question of Fletcher (1968, p. 288) is usually answered in a positive sense, in spite of the following remark: "Humans did not inherit any important motoric mechanisms; humans are better capable to adapt their behaviour to changes in the environment than any other animal species; human instinct seem to be restricted to experiences mainly in the form of ineradicable impulses, comprising an extremely important and extensive part of his mental life; setting the major ends of activity, and exerting a powerful and far-reaching influence upon the more conscious and rational aspects of individual and social life". (Fletcher, 1968, p. 286-287)

Instinctive behaviour is related to brain activities, but, just as in other similar cases, a straightforward one-to-one relationship between specific instincts and specific brain locations does not seem to exist. Instincts like those of reptiles – sometimes indicated as 'primitive instincts' correspond to brain stem activities. Sagan (1977, p. 58; 62-65) calls it the R-brain or R-complex. More elaborate instinctive behaviour seems to be closely related to activities of the hypothalamus and the thalamus, parts of the brain located near the brain stem (Frijda, 1988).

(b) Classification of instincts

Instincts – at the splenic or sex chakra level – in itself are not conscious but the actions based on instinct are. Human beings have instinct in common with almost all animals, some bacteria included. According to behavioristic psychologists, there are just two instincts: looking for food and looking for shelter. A concise description is given by

Krech et al., 1969. They act via unconditional reflexes (Hebb, 1985; Skinner, 1956, 1972). Looking a little more careful at human and particularly at animal behaviour, shows clearly that several more instincts are important, so there are at least seven – in a sequence that is deliberately non-random:
(1) Looking for food;
(2) Looking for shelter;
(3) Selective behaviour in relation to procreation (Barnett, 1970; Fletcher, 1968);
(4) The establishment of the hierarchy between members of the group (Schreuder, 1973);
(5) Territorial defence (Tinbergen, 1951, 1968; Lorenz, 1954, 1968);
(6) Care for the offspring (Van Lawick-Goodal, 1971);
(7) Ethical behaviour may be instinct-based, as is suggested in more recent studies (De Waal, 1996).

The list can be subdivided in clusters in several different ways. The first subdivision is related to survival aspects:
(1) Instincts that have to do with the survival of individuals;
(2) Instincts that have to do with the survival of the species.
It seems that the second is the stronger of the two: when there is a conflict between them, the survival of the species gets priority treatment. There are many examples of this; a well-known example is the behaviour of lemmings who commit suicide at a large scale if food is becoming so scarce that the survival of the species is at risk. Some of the most unscrupulous dictators, like Hitler and Stalin, made use of this priority of instincts by proclaiming that the People or the Party was more important than the individual.

A second subdivision is related to social aspects:
(1) Instincts related to the individual group member (looking for food; looking for shelter);
(2) Instincts related to the group (the hierarchy between members of the group; territorial defence);
(3) Instincts related to the species (selective behaviour in relation to procreation; care for the offspring; basic ethical behaviour).

(c) The group-concept

The second of these three cluster has a central place in our considerations. As will be explained later, the social aspects lead directly to considerations of aggressive behaviour. Aggressive behaviour – more in particular street violence – is directly related to the lighting of public spaces. The central issue in these social aspects is the concept of the group. The group is the nucleus of human society, and not the family nor the tribe, clan or nation. This can easily be observed, more in particular in pre-agricultural societies. The dominance of the group in still existing societies is described in detail in Shostak (1981) and Blainly (1982); extinct societies are described by Leaky & Lewin (1977, 1992). In the present day industrialized or post-industrialized societies, the prevalence of the group may be a little more difficult to see (Krech et al., 1962). A group may be characterised by a feeling of 'we'; it is more than a network of interrelations (König, ed., 1969, p. 113). Typically, a human group consists of about thirty people of different families, different age groups and so on.

It might seem that for a group in general, this number is an optimum for the group to function as an independent building block for society; for specialized groups, the number is often somewhat smaller. The 'group' as part of a platoon of soldiers, the football team, the hunting team of hunters-gatherers is about ten. It might be surmised that ten is about the largest number that easily can be reached while speaking at a normal voice, but this, of course, is pure speculation.

The group has two distinct instinctive aspects that are directly relevant for our considerations. The first is the establishment of the hierarchy between the members of the group. All groups have a pecking order. One can even define a 'group' in this way: a bunch of individuals without a pecking order is not a group in the strict sense of the word. It is easy to see, e.g. in group therapy sessions or when hostages are taken in a hijacking, that a pecking order seems to 'crystallize out' spontaneously, and almost immediately.

A pecking order is characterized by the fact that one individual is at the top, and that there is a strict order who is number two, number three etc. Pecking orders are absolutely incompatible with democracy. The concept of pecking order stems from chicken stalls where chick A may peck on chick B but not the other way around; both chicks A and B may peck on check C etc. Some pecking orders seem to be circular in nature: number last is the only one who may pick on chick A! (Van Lawick-Goodal, 1971). It is evident that the establishment of the pecking order will involve a lot of violence. In principle, the violence stays within the group, but as a result of the selection of an alternative goal it will lead to violence outside the group as well. The selection of an alternative goal is explained in sec. 10.1.6d, when discussing displacement aspects. See also Krech et al. (1969, p. 757). This is a well-known aspect of youth gang violence. In this contexts, it should be noted that the instinct related to sexual preferences may result in violence as well. However, as a natural defence against inbreeding, almost always the sexual bonds are not inside but outside the group. This implies that most violence will usually not reach the group level. Aggression and violence are discussed in detail in sec. 10.1.6.

The second instinct-aspect of the group is the establishment and defence of the territory. Each group has its own territory. Basically, the territory consists of the part of the land that supplies the food for the group. However, as can be seen even by the most casual observation, territories mean much, much more. Over the ages, a territory means things like the soul of the nation (our Nation!), the basis of the religion (our Religion!), the core of individuality (my Individuality!), the epitome of democracy (our Democracy!). In short, territory stands for everything I am and you are not – for everything I am proud to have and that I do not allow you to have. Not only for adults but also for children and even for toddlers. It should be stressed that not only groups, but also individuals, clans, tribes, and nations each have their own territory. Claiming, establishing, and defending territories is one of the most basic instincts. It pervades almost all aspects of daily life of animals and human beings alike. It has been the object of very detailed studies at all possible levels. So much so that it is impossible to give even the most crude outline of these studies. We will therefore abstain from any reference to the literature.

When discussing territories, the most striking aspect is the vehement reaction that invariably is provoked by even the smallest of infringements of the territory. In another part of this section it is pointed out that this defensive reaction to territorial infringements is most probably the central cause for the vehement reactions to any form of light pollution. In sec. 10.1.6, when discussing aggression, it is explained that the violence that results from these defensive reactions is probably the most important contributing factor in street violence.

(d) Unconditional and conditional reflexes

Many aspects of animal behaviour can be described in terms of unconditional reflexes. More important for our studies are the conditional reflexes. Conditional reflexes are the automative or reflective reactions on a stimulus that is the result of training, education or experience. Sometimes it goes even further and involves personality aspects (Maslov, 1954, 1968). Again as regards conditioned reflexes, human beings have a lot in common with almost all animals. Teunissen describes an elegant experiment that shows that single cell, animals like paramecium shows conditioned reflexes that would not look bad for a Pavlov-dog (Teunissen, 1947, p. 129-130). Driving a car is mostly a matter of conditional reflexes. Schreuder (1997) has argued that driver education and training essentially is the transfer of certain behavioural clusters from conscious decisions into conditioned reflexes. Reflective behaviour is discussed in detail in psychological textbooks like Gleitman (1995); Krech et al. (1969); Straub et al., eds. (1997).

Living organisms, animals and human beings alike, communicate a lot on the level of instincts. Three of the main groups of instinct that were indicated earlier in this section, refer directly to the relation between individuals: the sexual preference and mating behaviour, the territory defense, and the establishment of the hierarchy between individuals. Any dog owner can observe directly how the communication between dogs works: it is a combination of body language and sounds. These simple observations are thoroughly supported by a large amount of animal studies, like those of De Waal (1996) and Van Lawick-Goodal (1971) for chimpanzees, Tinbergen (1951, 1968) for other animals like e.g. sea gulls, and Lorenz (1968) for ducks – just to name a few. Human beings do all this, and may add the specifics of clothing (Schreuder, 1973).

(e) Sexual preference and mating behaviour

Instincts develop in line with the development of species. For human beings, one must reckon with a development over several millions of years. As was explained earlier in this section, one may discern two main types of instincts: those related to the survival of the species and those related to the survival of the individual. The instinctive aspects concerning the preservation of the species primarily related to the selection of mates for optimal reproduction. This aspect is generally accepted by those who accept the idea of evolution. There is no need to be more specific and to proclaim the universal validity of such doctrines as the 'survival of the fittest' (Darwin, 1890) or of the 'selfish gene' (Dawkins, 1989).

In almost all species, physical strength and endurance scores the highest in male individuals. This leads to a set of instinctive patterns that establish the hierarchy – or the 'pecking order' – between male individuals, such as has been explained earlier in this section. The details may differ somewhat for different animal species, but the pattern is clear: right from birth, male individuals strive for hierarchy by means of physical contest. See De Waal (1996) and Van Lawick-Goodal (1971). De Waal (1996) points out that, at least in chimpanzees, is accompanied by a strong and often very just social order that is enforced by the dominant individuals. In most animal species that have a more or less strict sexual code like almost all mammals, humans included, a similar hierarchy is established between the female individuals, where the relevant variables are not primarily physical strength and endurance, but rather inventiveness and motherly care.

Until now, most considerations have been related to animal behaviour. For the subject matter of this book, we will have to study the role of human instinctive behaviour on aggression, more in particular on street violence. The reason for this interest is that road lighting – an important source of light pollution – is installed with the reduction of street violence in mind.

(f) Instincts in humans today

Even the most casual observations will show that human beings, both newborn and adults exhibit a large number of fixed patterns of behaviour that follow on, and are the effect of, specific stimuli. Even unborn babies show such behavioral patterns. It is not the place here to discuss them in detail, nor is the place to discuss whether they are instincts or conditioned reflexes. It is equally easy to observe that human beings, contrary to almost all animals, have an immense capacity to adapt their behaviour to the external circumstances and conditions. Humans are very flexible. It is often stated that reacting in a very flexible way to variations in the environment is the primary characteristic of human beings. In other words, human behaviour seems to be determined in part by innate – instinctive – patterns and in part by influences of the environment. It is customary to attach the words 'nature' and 'nurture' respectively to the two. Obviously, the effects of the free will, of rational decision making and of non-physical influences are disregarded. We will come back later in this section to the question in how far these omissions can be justified.

For centuries, the nature-nurture controversy raged through philosophy and social sciences. It is not the place here to discuss this controversy. As we suggested above, both seem to be of great importance for human behaviour. In this section, the instinct aspects are discussed; in sec. 10.1.8, the environmental aspects; in sec. 10.4.2, the rational decision making processes, and in sec. 10.1.9 the role of the free will. That means that we will not join the discussion as to whether nature or nurture is the more important or whether it is possible that the one or the other does not have any significance at all.

(g) Gender-specific instincts in human beings

As is explained earlier, belonging to a group – or a 'band' as is it is sometimes called – is important for human beings. There is some support for the opinion that the division of the gender-specific instincts that have been mentioned in an earlier part of this section, is related to the food economy of the band. "Throughout all contemporary gatherers-hunters there is a consistent division of labour between men and women: hunting for meat is a male pursuit, whereas gathering plant foods is the responsibility of the women" (Leakey & Lewin, 1979, p. 208). "Another universal among hunters-gatherers is that the meat is shared with the whole band. By contrast when a woman brings home her collection of plant foods she is providing for her immediate family only" (Leakey & Lewin, 1979, p. 99). Basically, these observations are made in contemporary hunter-gatherer societies. It will be assumed that the characteristics of contemporary hunter-gatherer societies are equally valid for ancient, historic or prehistoric hunter-gatherer societies. There is some proof for this (Leakey & Lewin, 1977; Johanson & Edey, 1982) and one would find it difficult to disclaim it. It is difficult to find grounds for the suggestion that the societies of ancient hunters-gatherers differ essentially from contemporary hunter-gatherer societies.

Another point is the fact that, as is mentioned in sec. 10.1.5a, it is likely that any genetically determined pattern of behaviour, whether it is instinctive of not, will take a very long time to evolve and an equally long time to be erased.

It is sometimes assumed that the biological origin of these gender-specific instincts go back to the earliest history (Bronowski, 1973; Chatwin, 1987; Matthiessen, 1962; 1972). Whether to call it human or pre-human history is a matter of taste. This biological origin is thought to be based on the fact that man can move swiftly and therefore have a chance to catch fast-moving food, whereas women cannot move so fast because they suckle babies often until the age of three or four (Shostak, 1981). They have to carry them."The burden of carrying infants on food gathering expeditions is great" (Leakey & Lewin, 1979, p. 208). What happened to the ways these instinct were implemented in more recent history is not important for the present discussions because we deal here with the prevalence of the 'original' instincts and their effects on present-day life, and more in particular on present-day aggressive behaviour. Details of the evolution of instinctive behaviour in the agricultural and the much more recent industrial revolution is explained in detail in Schreuder (1994). See also Childe (1942; 1959).

It is important to note that these major changes in human societies did not begin much earlier than some 10 000 years ago; this may seem a long time but, as is explained in sec. 10.1.5a, this period is very short when compared to the time needed for instinctive or other genetically determined pattern of behaviour to evolve or to get erased.

In the strong social order that is explained earlier, also sexual fidelity as part of the sexual prerogatives might be important. See again De Waal (1996, 1998) and Van Lawick-Goodal (1971) and more in particular Goodenough (1998).

10.1.6 Aggression

(a) Defining aggression

Before we go into the details of the second level of the four-level model of consciousness, the level of emotions, it is necessary to discuss the related concept of aggression. The concept of aggression is difficult to define in a general way. One may find the following description: "Attack on another, usually, but not necessarily, as a response to opposition" (Drever, 1968, p. 11). Another is: "An unprovoked attack on a person or a state" (Smith & O'Loughlin, 1948, p. 24). Still another: "A kind of direct attack upon the obstacle or barrier" (Krech et al., 1969, p. 758). In still another way, aggression is described as hostile behaviour that is directed against Nature in general; against animals (inter-species aggression); against other human beings (intra-species aggression); against the 'self' (Schreuder, 1973. sec. 3.4). There are probably many more descriptions around. The problem is that they seem to have very little in common. In this book, we will use the following description: Aggression is hostile and violent behaviour directed against other parties, either human or non-human. Mostly, the violence is physical, but it may be verbal or of another nature. Aggression can be spontaneous or premediated.

(b) Aggression as a consequence of instinctive behaviour

Sometimes, aggression is considered just as one of the many instincts. A closer look will show that it is probably better to consider aggression as a consequence of instinctive behaviour rather than of an instinct in its own right. More in particular, is has been suggested that aggression is related to two of the instinctive patterns that are related to the fact that human beings usually act in groups. The two group aspects that have been discussed in sec. 10.1.5, are, firstly, he establishment of the hierarchy between the members of the group – the pecking order – and secondly, the establishment and defence of territory. We will come back to the fact that sexual preferences at the one hand and greed at the other hand also may result in violence.

A central item in many aggression theories is that, in agreement to Freud (1915), aggression by itself is neutral in a psychomoral sense. "These drives by themselves are not good nor bad", quoted by Denker (1966, p. 41). See also Van Essen (1970). Not everyone seems to agree. Storr (1969, p. 34) states that aggression is at the same time both necessary and undesirable. Also being dependency and aggression seem to be closely related (Storr, 1969, p. 58). The same ambivalence is expressed by Mitscherlich: "There is a need to make a distinction between two forms of aggression. The two are, however, closely interrelated in a genetically sense" (Mitscherlich, 1956, quoted by Lincke, 1969, p. 41). Aggression is considered by Nietsche a positive drive as the 'Slave revolt in morals' (Nietsche, 1885, p. 83) and also because "the resentment itself creates new values" (Nietsche, 1887b, p. 25).

Contrary to the idea that aggression is neutral in a psychomoral sense, is the conviction that aggression is 'bad'. A link to conscience is postulated. These notions are often at the root of many decisions regarding law-enforcement measures, particularly as regards aggression and street violence. In sec. 10.1.9f, when discussing conscience, a few words are devoted to the notions of virtue and sin.

A completely different point of view was fashionable in the 1950s, 1960s, and to some extent even in the 1970s. In the wake of the equally fashionable flirting with communism, particularly the brands of communism of Mao, Castro and Che Chevara, people wanted to blame the explosion of aggression that was found in the Western world on the society in general, but more in particular on the capitalist society. Usually, the term was 'the environment', which at that time signified the society rather than nature, as it is now. See Hoefnagels (1969) and also Marcuse (1970, p. 24), who seems to believe that aggression is a positive reaction towards society, and more in particular towards automatization. Many went even further and blamed all sorts of psychotic behaviour, not only aggressive behaviour, on society (Redl & Weinemann, 1967; Laing, 1970, 1971). As a prelude to the 'selfish gene' hype that was en vogue in the 1990s, many authors blamed hereditary traits for aggression (Van Bemmelen, 1948, Kloek, 1968, Nagel, 1959).

(c) Theories about the cause of aggression

What behaviour is considered as being aggressive, how aggression can be described, whether is should be curbed and, if so, by what means seems, surprisingly enough, to depend on the prevalent fashion in biological thinking and on the prevalent political ideology. In the 1950s, war and aggression were considered as unavoidable and belonging to human nature. Aggression studies focussed on instinct. In the 1960s and 1970s, criticism on the social system in general, and on capitalism in particular, was in fashion. So aggression studies focussed on social aspects and on the influence of frustration. In the 1990s, biology was in fashion, and in particular the 'selfish gene'-concept. Aggression studies focussed on Darwinism, but also on cognitive aspects. The relevant literature is vast; we will mention only two or three survey studies on aggression. They are related to road traffic but they are general enough to be used as a guidance. See also Schreuder (2000).

In 1973, Schreuder published a survey of the aggression theories that were available at that time (Schreuder, 1973). Although old and intended for another purpose, the survey may still be useful. A part of the problem was that a generally acceptable definition of aggression was not available at that time.

At that time is was common practice, and it probably still is in certain political circles, to attribute all human aggressive behaviour to one and only one 'cause' (Becker, 1969, Buss, 1961, Carp, 1967, Denker, 1967, Lorenz, 1968, Megargee & Hokanson, eds., 1970, Rattner, 1971, Storr, 1963, 1969). The main 'causes' that were considered were:

(1) The best-known viewpoint is probably the frustration-aggression theories of the 'hard core behaviorism'. According to this viewpoint, frustration always leads to aggression, and all aggression is the result of frustration. "Aggression is always a consequence of frustration" (Dollard et al., 1970, p. 23);
(2) Almost equally well-known is the thesis that aggression is just a normal aspect of animal behaviour (Lorenz, 1968). The thesis was used – by others – to explain

concentration camp atrocities. The transition towards human behaviour never has been made plausible (Denker, 1966, p. 90);

(3) As Darwinism was, and still is, adhered to by many, the evolution theory of aggression was popular. Aggression is needed in the evolution of humans in order to establish an order in society (Kant, 1960, as quoted by Denker, 1967, p. 13). Survival is the prize to be won by the fittest and the fittest is the most aggressive (Darwin, 1890; Dobzhansky, 1965; Van Melsen, 1964). It looks like the idea that aggression is a means to reach a goal (Fris, 1972, p. 19, quoting Buss, 1966);

(4) In the wake of the ideas about ethics, it was stated that aggression is the result of the fact that human beings are "their own worst enemies" (Hobbes, 1651, as quoted by Mulder, 1972).

One might conclude from this that aggression is often, but not always, considered as an inherently 'neutral' agent. This has been succinctly expressed by De Waal (1997). In a section called 'rope walking', De Waal states: "Biologists are not asking anyone to admire or encourage the aggressive behaviour, only to step back enough to see that it is part and parcel of the social dynamics around us. We can dismiss absolute peace as utopian. Only two realistic alternatives exist in our imperfect world of limited resources; (1) unmigitated competition, or (2) a social order partly shaped and upheld by aggression" (De Waal, 1997, p. 183). Although modern ethical ideas would suggest that the psychomoral neutrality of aggression would be generally accepted, it seems that many people and particularly those involved in law-enforcement, consider aggression as outright bad. They may have, however, different opinions as to what is the cause of aggression. These points must be considered carefully in our study.

(d) Stimulus summation and displacement aspects

As is explained earlier in this section, the frustration-aggression theories are very limited and quite oversimplified, particularly in its consequences as expressed by Dollard et al.(1970, p. 23). However, even the most casual observations, e.g. in traffic jams, show that, indeed, frustrations easily do lead to aggression. In other words, aggression is the reply – the 'response' – to a particular frustrating 'stimulus'. This obviously points to the S-R theory that is explained in sec. 10.4.2, where not only the S-R concept but also the limitations of that concept are discussed. The frustration-aggression theory is therefore subject to the same limitations.

A major shortcoming of the frustration-aggression theories is that they are usually presented as simple stimulus-response models. For many animal reactions this might be true and even for some of the more simple aspects of human behaviour. However, in almost all cases, between the stimulus – the frustration – and the response – the aggressive acts – there must be inserted a third aspect. In sec. 10.4.2a, when discussing driving behaviour in road traffic, this intervening variable is termed the decision-making process. When discussing aggression, a similar decision process must be inserted, but here the arguments for the decision are almost always of an emotional nature. This would imply that, in stead of a decision making process, some sort of emotional process should be inserted between the stimulus and the response. Aspects of emotion are discussed in sec. 10.1.7.

The energy to perform the aggressive act seems to stem from the frustration itself. The energy seems to increase when the time between the frustration and the aggressive act increases, because, with increasing time, the frustration increases as well. This is often called the "Reizsummenregel" (the stimulus summation rule) of Seitz (Lorenz, 1954, p. 47). The implication is, that there need not be a direct, proportional relationship between the frustration and the aggressive act: one might expect that under some conditions, a 'small' frustration may cause 'severe' aggression. Often, this is called a trigger effect, the analogy with a gun shot being, that a minute force – to pull the trigger – will unleash the enormous energy of the gun shot itself. When we take the emotional aspects that have been indicated earlier into account, the aggression can be quite out of proportion when compared to the stimulus – the original frustration.

Another factor that needs to be taken into account is the fact that the aggression is often not aimed at the person or persons who have caused the aggression, but into another direction. Lorenz (1968, p. 70) calls this, following Tinbergen: redirected activity or displacement activity (Tinbergen, 1951, cited by Morris, 1968, p. 135). See also Tinbergen (1968, p. 101), Ardrey (1970, p. 94) and Krech et al. (1969, p. 760).

(e) Aggression and crime

In a study related to public lighting, the picture given above was slightly extended (Schreuder, 1998, Chapter 8). When one takes a 'rational decision maker' as a starting point, it is not possible to understand actions that are made intentionally to harm others. The concept of the 'rational decision maker' is discussed in sec. 10.4.2. Therefore, aggression is often considered as an equivalent to violent behaviour as well as to criminal behaviour. The reason seems to be that there is no doubt that violence and crime are bad. Still, there is the need to explain why those vile things do exist. We will come back to this point when the place of conscience is discussed (sec.10.1.9d). Furthermore, it is an oversimplification to consider crime and violence as synonyms. Nevertheless, this is done in the influential publication of Howells & Hollin (1992). They give a survey of more recent aggression theories (Howells & Hollin, 1992, p. 4-8). There is a shift in emphasis, compared to the earlier survey of Schreuder (1973). The politically oriented theories of Laing (1970) are not mentioned. The instinct theories of Freud (1915) and Lorenz (1968) nor the more modern learning theories of Box (1983) are seriously considered, because, according to Howells & Hollin (1992), they have no experimental support. This, in their opinion, is the case with the frustration-aggression theories like those of Dollard et al. (1939, as quoted by Howells & Hollin, 1992, p. 5). Both Schreuder (1973, 1998) and Howells & Hollin (1992, p. 15) suggest that an approach that is founded on psychological rather than on behavioristic considerations might lead to a more comprehensive aggression theory. Such theories exist to a ceratin extent, as is shown by Herkner (1997, p. 621-626).

(f) Affective and instrumental aggression

More recently, another distinction between two types of aggression was proposed by Levelt (1997). This study focusses on aggressive behaviour in road traffic, but the concept is easily applicable on a wider scale. "Socio-psychological literature distinguishes two types of aggression:

(1) Affective aggression, whereby there is an intent to cause damage or whereby a threat to cause damage is made, prompted by a feeling of anger at perceived injustice;
(2) Instrumental aggression, whereby the aggressor attempts to gain psychological or material advantage and thus reckons on causing harm to others. Anger is not at the root of this" (Levelt, 1997, p. 5).

According to this description, anger is an essential constituent of affective aggression, and so are feelings of injustice. This forms a good example of the importance of the emotional intervening variables that have been indicated in an earlier part of this section. One is tempted to call this sort aggression 'hot-blooded', mainly as a contrast to the acts committed in 'cold blood' that are described by the concept of instrumental aggression, prompted by the wish to gain psychological or material advantage.

At the opening of this section, we came back to a suggestion that was given earlier. It is suggested that aggression is related to group activities. We may add group feelings to this. The two group aspects were the establishment of the hierarchy and the establishment and defence of territory. It does not seem to be far-fetched to combine infringements of these actions and feelings with the feeling of anger at perceived injustice that might provoke affective aggression. Indeed, there is an intent to cause damage or at least to a menace of damage. This might explain the vehemence of the aggressive reaction when such things happen. We have given, in an earlier part of this section, several examples of such vehement reactions. It may be noted that the vehement reactions to some sorts of light pollution can be explained as an aggressive reaction to the infringement of the private living space (sec.15.4.3).

Clearly, affective aggression is not enough to explain the manifold appearances of aggression in society, both at a large scale, like wars between nations, or at a small scale, like street violence. For this reason, the concept of instrumental aggression is introduced (Levelt, 1997, p. 5). Anger is, as stated, not at the root of this. So there must be a different psychological complex at work. We will postulate in a further part of this section that conscience – or the absence of conscience – is essential in this. In sec. 10.1.9, the concept of conscience is discussed in more detail.

(g) Conscience and instrumental aggression

Instrumental aggression does not involve anger. It is not, or at least not always, directly related to some sort of frustration. It does not seem to involve many emotional considerations – or none at all. In the foregoing, we suggested that the concept of conscience is instrumental (Levelt, 1997).

When considering the possible role of conscience – or the absence of conscience – may help to clarify aggressive behaviour, we will look first at the small-scale aggression at street level. It is clear that the types of aggressive behaviour seem to be very diverse. Some common examples are given in the following list that is based to a large degree on the most frequent criminal acts that are committed in some industrialized countries (Schreuder, 2000; Terlouw et al., 1999):

- protests and political rallies;
- gang warfare;
- mugging and robbery;
- sexual assault and rape;
- breaking in into cars and homes;
- vandalism and hooliganism.

In the Netherlands, the police reports make a distinction between crimes with and without violence and crimes against persons or against material items (Anon., 1999 a,b). According to the description of the concept of aggression that is given in this section, all of these criminal acts would classify as 'aggressive'. As is mentioned earlier, other descriptions of the concept of aggression to exist that might give a different picture. However, we will use the wider class.

These criminal offenses have one point in common. They are always committed after a conscious decision making process and usually they involve a lot of rational planning. Emotional considerations may or may not be involved, but they are not committed 'hot-blooded' – in the spur of the moment. These acts can be checked against the four characteristics suggested by Kohnstamm that mentioned in sec. 10.1.9b, when discussing intuition and consciousness (ENSIE, 1950, Vol. I, p. 169). In summary. they include:

(1) Involving the whole personality;
(2) Being 'supra-rational';
(3) Absolutely personal;
(4) A gift.

None of them seem to qualify as involuntary errors of conscience where we do wrong unknowingly. However, if we consider the Kohnstamm-characteristics carefully, it becomes clear that the conscience can be 'shut off' as the outcome of a conscious, or maybe also of an unconscious, decision. As an example, some possible reasons will be given that may be used by the aggressor to eliminate the conscience for each of the types of aggressive behaviour that are listed above:

- protests and political rallies: the ends justify the means;
- gang warfare: if we do not kill them, they will kill us;
- mugging and robbery: rich people do not deserve wealth;
- sexual assault and rape; girls like being taken by force;
- breaking in into cars and homes: again, rich people do not deserve wealth;
- vandalism and hooliganism: I like the challenge.

In sec. 10.1.9, the concept of conscience is introduced in the context of the notions of virtue and sin. It is suggested that evil or sin should be characterised as having no wisdom nor spiritual inspiration; being arrogant and disrespectful to others, as being scheming and keen on personal gain and status – in short, as lacking any conscience.

Again, we will take the list of the more common types of street violence and look in how far one of the three characteristics of 'evil' seems to apply – or maybe more than one:

- protests and political rallies: the ends justify the means; arrogance and disrespect to others (only my political ideology matters, the others do not matter);
- gang warfare: if we do not kill them, they will kill us: no wisdom (why should they?);
- mugging and robbery: rich people do not deserve wealth: personal gain (greed, disguised as socially nobel actions – hypocrisy);
- sexual assault and rape; girls like being taken by force (no wisdom – it is not true; arrogance and disrespect – only my lust matters, her feelings do not matter);
- breaking in into cars and homes: again, rich people do not deserve wealth: personal gain (greed, disguised as socially nobel actions – hypocrisy);
- vandalism and hooliganism: I like the challenge: no wisdom (vandalism is not funny at all).

Having eliminated the conscience, results in either callous people or in cowards who perform the criminal – aggressive – acts. This is an important distinction as regards the further consequences of street violence and, more in particular, the degree into which street violence may be prevented by installing proper street lighting. In secs. 11.2.6a and 12.1.2, it is explained in detail that it is one of the major functions of street lighting to act as a crime deterrent. The way it is supposed to work as a deterrent is that criminals – or rather prospective criminals – are easily seen and are afraid of being recognized. If, however, they are not afraid of being recognised, much of the function as a deterrent is lost. The possibility to arrest the criminals and to prosecute them properly is still there, of course. So, the deterrent may work for the yellow-bellied but not very much for the callous.

The description given here is only a brief summary. It is important to note that the fear of being recognised is only one of many aspects of the function of street lighting as a crime countermeasure. As is explained in sec. 11.2.6a, good lighting has an important role to fulfill after the crime is committed. Good visibility allows the police to follow and arrest the criminals and it allows bystanders to give good and trustworthy testimonies. And as is explained in sec. 12.1.4 in detail, probably the most important function of road lighting is to guarantee the feeling of security and reduce the fear for crime of road users, particularly of the pedestrians. Many studies that are discussed in sec. 12.1.4 clearly indicate that particularly the women, the elderly and the young children benefit from this enhanced subjective safety.

It is essential to pay attention to drug related crime when considering the relation between conscience and instrumental aggression. In most countries, the use of drugs and more particulary the dealing in drugs – the drug trade – is considered as a serious crime. It should be noted that much depends on the drug under consideration. In spite of the fact that in many countries a large percentage of the population is outright alcoholic, and of the fact that a sizeable portion of road accidents and road fatalities can be directly attributed to alcohol intoxication, little attention is paid to alcohol usage and trade (Mathijssen et al., 2002). The majority of street violence is directly related to alcohol usage, both of the perpetrators as of the victims, just as – by the way – the majority of indoor violence. Nevertheless, alcohol usage is – apart from some Muslim countries – pushed and pulled very hard as a major high-status social affair. Contrary to this, the use of hard drugs is considered in almost al countries of the world as a very serious crime.

The psychological effects and the social consequences of alcohol and drug addiction are very severe. Both lead on the long run to a serious deterioration of the personality structure. Addiction is discussed in some detail in sec. 4.5.7e. The relation to crime is manifold. First, addicts usually lost most of their conscience functions and are likely to commit all sorts of crimes 'without blinking an eyelid'. Secondly, addicts need a lot of money to buy more alcohol or more drugs. Because of the strict prohibition laws – that seem to be upheld by the drug cartels – hard drugs are much more expensive than alcohol that in many countries is sold by state-owned or at least by state-controlled shops. As most addicts are not capable of holding a job, they have to revert to violent crime to get the money. This is a direct result of the fact that drugs are prohibited. It has been shown in many countries, not only in the USA, that after 'prohibition' – the prohibition to sell or use alcohol – was lifted, violent crime to get alcohol money dwindled to almost zero. It seems that the same holds for pornography and its relation to violent sexual assault.

There is one final point that must be made when discussing street crime and the role of aggression, emotions and conscience. Because, as we have seen, street crime has many forms and each form may have its own cause or sets of causes, there is not one countermeasure to solve all problems. Some sorts of crime that involve cowards, who are afraid of being recognised, may be prevented by good lighting, but some other forms like political violence or hooliganism may be made easier by it. Education might help a lot in crimes where a lack of insight is part of the cause; counselling and psychological or moral support may help those who commit crimes in which emotional factors are predominant. One might go on like this for a while; it is clear that there is no general 'wonder'-cure for the terrible social malady that is violent crime.

This fact is often overlooked in studies about lighting and crime, particularly those made by researchers who seem to have no preceding knowledge about psychology. Often, they make no difference at all between different types of criminals, and simply add up all reported crimes. In sec. 12.1.1a, we discussed in some detail the publications of Clark (2002, 2003), where this mistake is made. See also Marchant (2003).

10.1.7 The second level: the level of emotions

(a) *Emotions as a frame of mind*

The concept of emotion seems to be a very complex and controversial one: "differently described and explained by different psychologists" (Drever, 1968, p. 82). Still, there seem to be some general aspects. In laymen's words, human mental activities are sometimes divided in two: 'rational' and 'emotional' activities. The grounds for this were that: "Emotions have often seen as interfering with rationality, as a remnant of our pre-sapient inheritance – emotions seem to represent unbridled human nature in the raw" (Gregory, ed., 1987, p. 219). Thus, not only may the human mental equipment be divided in just two components, but also the one is far superior to the other. This very broad division is often used by politicians, journalists and natural scientists. See e.g. Dennett, 1993 and Sagan, 1977. There is more to say about it, however. Most psychologists seem to agree "... that it is a complex state of the organism, involving bodily changes and, on the mental side, a state of excitement or perturbation, marked by strong feeling" (Drever, 1986, p. 82). Although defining emotions by feelings may look like circular argument, the description may be used. This, of course, leaves a number of non-rational aspects of human behaviour unaccounted for. In sec. 10.1.5, one of the other aspects, viz. instinct, is dealt with in great detail. In sec. 10.1.9, intuition, as a further non-rational aspect of humanity, is discussed in great detail.

Some models of emotional behaviour are called 'appraisal theories'. The central concepts of these models are the appraisal and the action tendency (Levelt & Rappange, 2000). These models are based on earlier work of Frijda (1989), Lazarus (1991) and Ortony et al. (1988). The two elements are described as follows: "Appraisal is the evaluation of an event, action, or object as favourable or unfavourable for an interest or concern. Concerns are goals such as standards, norms, wishes and attitudes. The affective reactions are pleasure or displeasure at the consequences of an event; approval or disapproval of an action; or like or dislike of an object. These feelings prime the action tendency" (Levelt & Rappange, 2000, p. 1). Further-on they define moods: "Moods are states of mind in which the object or the cause is much more sweeping and relates to life as a whole" (Levelt & Rappange, 2000, p. 2). When we compare these models with earlier sections of this book, we may say that affective reactions look like what we think is the essence of emotions; concerns look more like contents of conscience; the action tendency seems to have little to do with emotions, and moods suggest an idea not unlike the level of intuition. The model has been applied successfully to road safety studies (Levelt, 2001). Because it does not take into account that emotions are not like instincts nor like intuition at all, it does not help us here to find a more general description of emotions.

When looking in a more general way, it seems that there are many different emotions. As an example, we will quote a list given by Krech et al. (1969, p. 521-522) where six main classes of emotions are listed:

(1) Primary emotions, like e.g. joy, fear, anger, grief;
(2) Emotions pertaining to sensory stimulation, like e.g. pain, disgust, horror, delight;

(3) Emotions pertaining to self-appraisal, like e.g. shame, pride, guilt;
(4) Emotions pertaining to other people, like e.g. love, hate, pity;
(5) Appreciative emotions, like e.g. humour, beauty, wonder;
(6) Moods like e.g. sadness, anxiety, elation.

A closer inspection of this list shows a few clusters of what we will, for short, call 'frames of mind'. A first cluster contains some aspects that look more like instincts than like emotions. To this cluster belong the frames of mind pertaining to self-appraisal, like e.g. shame, pride, guilt (item 3 of the list given above). A second cluster contains some aspects that look like 'real' emotions – we will have to come back to what this word exactly means. To this cluster belong the frames of mind pertaining to primary frames of mind like e.g. joy, fear, anger, grief and the frames of mind pertaining to sensory stimulation, like e.g. pain, disgust, horror, delight (items 1 and 2 of the list given above). A third cluster contains some aspects that may look a little like emotions but they are clearly on a higher level – the level we have indicated as the 'intuitive level'. To this cluster belong the frames of mind pertaining to other people, like e.g. love, hate, pity, as well as appreciative frames of mind, like e.g. humour, beauty, wonder (items 4 and 5 of the list given above). A fourth and final cluster contains some aspects that do not seem to be emotional but rather describe a general attitude. To this cluster belong the moods like e.g. sadness, anxiety, elation (item 6 of the list given above).

(b) Feelings and emotions

Drever (1968) did describe emotions in terms of feelings. This might look like a circular definition, but it is not. Feelings are primarily anchored in the biological context of the human mind; many animals show therefore feelings as well. Even the most casual observations of the behaviour of domestic animals like dogs, cats, horses, elephants, show that they have feelings, just as human beings. It is sometimes stated that one should not attribute human characteristics like feelings to animals. In the way we introduce the concept of feelings, this criticism is not applicable. We have defined feelings as an aspect of consciousness that is shared with animals, at least with many 'higher' animals. In fact, having feelings of a sort is often used as a characteristic of higher animals to begin with. It is the same reasoning as stating that animals and humans have many instincts in common, as is explained in detail in sec. 10.1.5.

This ties in with the results of neuro-physiological research. It has been found that the activity of specific brain regions does increase markedly when the test persons are subjected to test that involve feelings. This part is the limbic system (Greenfield, 2001, p. 111). The vertebrate brain can be divided in three parts; the brain stem, the limbic system and the cortex (Greenfield, 2000, p. 10, referring to MacLean, 1970). As is explained in sec. 10.1.5, the brain stem – the 'reptile-brain' – is thought to be directly involved in primitive drives and instincts. The limbic system is more particularly involved in emotional affairs of the type we have called 'feelings'. It is pointed out that some emotional aspects are related to cortical activities, particularly of the frontal lobes (Greenfield, 2001, p. 111,112). As is explained in sec. 10.1.9, these aspects are precisely those we have indicated as belonging to the level of intuition and not to the emotional level.

Although a precise definition is difficult to give, it seems plausible to consider feelings as the contents of what we have called earlier the emotional level of consciousness – the second of the four. When deciding what aspects do belong to this level of consciousness and what aspects do not, we will follow the course we have suggested earlier: feelings that are shared with higher animals will be classified as belonging to the emotional level. In a case of doubt, the results of neuro-physiological studies on brain activities may give additional information. If a specific 'frame of mind' is related to outspoken activities in the limbic system, feelings are likely to be involved. As has been stressed earlier, this criterion it not conclusive as deviations may occur. A third important characteristic of feelings is that they are shared with others. And a final criterion is the occurrences of bodily changes and a state of excitement (Drever, 1986, p. 82).

(c) Classification of emotions and feelings

When looking at what sort of feelings one should expect to find on the emotional level, we turn back to the clusters that were derived from the list of Krech et al. (1969, p. 521-522). The second cluster we discerned, included primary frames of mind like e.g. joy, fear, anger, grief and the frames of mind pertaining to sensory stimulation, like e.g. pain, disgust, horror, delight. Indeed, these feelings are easily shared with others and they are often accompanied by bodily effects. In fact, some are even used to describe bodily effects, like e.g. pain or disgust. One might add the feeling of solidarity to the group members (Schreuder, 1996). We will come back to this point furtheron.

There are a few emotions or feelings in the lists that we have quoted, that deserve some more detailed attention. In a way, they seem to form 'families' of feelings. We will discuss three of those families: Fear, Happiness and Fellowship. Fear seems to occupy a somewhat special place in these lists. Fear has a number of components. One is anxiety, a diffuse feeling of uneasiness without a specific cause. It might classify as a 'mood' such as we have described earlier. It pervades the whole consciousness without any specific action or reaction. When the feeling becomes more specific, it is better to speak of fright; the term fear is usually reserved for the case of a specific source or cause. In sec. 12.1.4 it is explained in some detail what is the role of fear in feelings of subjective safety. It is often expressed that one of the major benefits of good road lighting is the prevention of subjective feelings of not being safe. This is usually expressed in the term of 'fear for crime' (Painter 1991, 1993, 1999; Painter & Farrington, 1999; Schreuder 1994, 1998, 2000, 2001).

The second 'family' we want to discuss is Happiness. In the lists one will find joy and delight. They are related to the more general concept of happiness. Happiness is sometimes defined as the 'absence of grief', in the same way as 'safety' is often defined as the 'absence of accidents' and 'health' as the 'absence of maladies'. Such, or similar definitions are sometimes used – often implicitly – in statistically oriented accident studies, like e.g. Noordzij et al. (1993); Harris (1989, 1989a); Koornstra et al., eds. (1992); Elvik (1995).

In some studies, other approaches are used, e.g. in studies on social safety (Anon., 1991, 1994). For many, it is more convincing to treat 'happiness' and 'grief' as separate feelings. We will explain the way these separate feelings, that seem to be conflicting, can be considered for the case of 'health'.

In many non-western civilizations, humoral medicine is applied as a standard (Helman, 1990, p. 17-21). Humoral medicine "pertains to the four humors, or four liquids, at one time supposed to control the health" (Smith & O'Loughlin, eds., 1948, p. 541). Humoral medicine is based on reaching or maintaining harmony between different bodily parts and bodily functions. In contrast, the body is sometimes regarded as a machine, or even as a computer. This model is prevalent in Western 'scientific' medicine. In normal conditions, the machine works – is healthy –, but sometimes one or more parts break down – the body is sick. The broken parts need to be repaired or replaced to bring back the machine in healthy working order (Helman, 1990, p. 21-23). The machine approach is considered as "simplified" (Helman, 1990, p. 23). "Health is seen as more than just an absence of unpleasant symptoms" (Helman, 1990, p. 91-92). The World Health Organization has defined health as follows: "Health is defined as a state of complete physical, mental and social well-being and not merely as the absence of disease or infirmity" (WHO, 1946). This seems to be more in line with humoral medicine than with machine or computer medicine.

It is simple to draft similar definitions for 'happiness' and for 'safety'. As a matter of fact, the definitions for health, for happiness and for safety overlap to such a large extent that it is almost possible to apply the WHO-definition for all three!

It should be noted that, just as with other feelings, happiness has a counterpart in dignity, which is more in line with the intuitive level of consciousness. See e.g. Schreuder (1999).

The third 'family' of emotions or feelings we want to discuss is love. Love is a complex concept. In a very general description it is characterised as follows: "to conquer one's own solitude without loosing one's own individuality" (Quitmann, 1991, p. 261 as quoted by Groeben & Erb, 1997, p. 32). In psychology, love is often understood as an element of communication and interaction; it is often considered as a synonym to sympathy. It is usually restricted to the sexual love between partners of different sex (Herkner, 1997, p. 615-616). In this respect, society is more advanced – or more degenerate, as many will prefer to say – than psychology. Intimacy plays a dominant role (Sternberg, 1986). This seems to imply that it involves at the one hand the instinct of procreation and partner selection that is discussed in sec. 10.1.5e. At the other hand, it involves the feelings of joy and delight that were classified earlier as 'real' emotions belonging to the emotional level of consciousness.

We have suggested earlier that solidarity is a genuine feeling. One might classify it as fellowship. As we have mentioned earlier, this concept is not in the list proposed by Krech et al. (1969, p. 521-522). Love and pity are, however, included. All form part of the 'family' that describes love. When the group is one of family ties, one might prefer the terms of brotherhood or sisterhood. When fellowship is threatened, it can easily lead to aggression and thus to street violence. One of the more violent forms of fellowship is organized crime. Apart from drug dealing and other criminal acts that are discussed in sec. 12.1.2, maffia-like practices may arise. An extreme form is the vendetta or blood revenge. "The vendetta is a respected entity and banditism is something normal, because as there is no war around, the men have to show in another way that they are capable, fast and strong" (Deledda, 1903, quoted by Roodnat, 2001). A similar explanation is given for ex-partisans who became political terrorists: "Some had ideological motives. others were just intoxicated by the thrills and glamour of making history" (Dibdin, 1991, p. 55). Another extreme case is hooliganism. Many consider this as a pervert extremism of loyalty to football clubs. Others have different opinions: "Football vandalism in England is organized crime. It has relations to drug trafficking, counterfeit money, money whitewashing. There is a strict organization that results in co-operation in different areas of crime. The brains behind it have no relation to soccer football" (Anon., 2001). The relation between political terrorism and hooliganism at the one hand and aggression and street violence at the other hand is clear.

Anthropologists may probably devote their attention to a completely different aspect of love: the maternal love. This frame of mind belongs more to the level of instincts than to the emotional level of consciousness. As is explained in sec. 10.1.6, when discussing of aggression, instincts like maternal love are likely to trigger vehement aggressive reactions from the part of the mother when the child is threatened. It is a very serious matter to contemplate, not only when meeting black bears in the wild, but also when considering street violence.

Finally, in the Judo-Christian religious tradition, love has again a completely different connotion. Love has two distinct aspects: first there is the Love of God towards all creatures ('agapè'), and then there is the love between human beings, more particularly between the members of the congregation ('eros'). These two aspects of love are regarded by many as the two cornerstones of any civilised and ethically viable society. It is quite clear that these aspects of love do not represent feelings that need to be discussed at the emotional level of consciousness. As far as these aspects are relevant for our study, they will be dealt with when discussing the intuitive level of consciousness.

(d) Feelings and affective aggression

In sec. 10.1.6 it has been explained that aggression is related to group feelings: the establishment of the hierarchy, and the establishment and defence of territory. Infringements of these feelings may easily lead to the feeling of anger, which is at the root of affective aggression (Levelt, 1997). As is explained in sec. 10.1.6f, affective aggression is an important component of street violence.

10.1.8 The third level: the level of the ratio

(a) The ratio as the ultimate mental capacity

Many believe that the ratio represents the ultimate state of human development. In the mean time they do not seem to note the contradiction in this statement: they 'believe' – and believing is in no conceivable definition of the ratio, a part of it. This sort of lapses in clear – clean – thinking is abundant in the literature of the rationalists. As an example: the ratio can be described as "serial reasoning" (Dennett, 1993a, p. 252). Dennett states in another context: "I think there is no real difference between knowledge and insight. If you know something, if you possess the knowledge, you do understand it" (Dennett, 1993, p. 106). We may safely assume that for almost anybody it is immediately clear that understanding and knowledge are two completely different things.

Another aspect that causes a lot of misunderstanding is that many believe that, as said earlier, the ratio represents the ultimate state of human development. In fact, there are two groups of believers in this matter. Many believe that, for the present al least, the ratio is the one characteristic that distinguishes human beings from animals: human beings are rational, beasts are not. The future may be different. "We are just the most recent entities that have rationality at our disposal" (Dennett, 1993a, p. 74). The second group goes much further. In the Judo-Christian tradition, God created Man along His image; therefore, there never can be a creature that is 'better' than human beings; as a matter of fact, when taken literally, this belief precludes all ideas about evolution – Darwinist or otherwise. Without any doubt, these points are of the utmost importance for most people; nevertheless, we will not discuss them any further because they fall outside the framework of this book. The reason we did mention the points is, however, well within this framework: it is the opinion that the ratio is the highest possible capacity of human beings. In terms of levels of consciousness, there is no higher level possible than the rational level. This opinion is supported by many, probably by far out the majority of people in the Western world, more in particular by philosophers, psychologists and natural scientists. However, this opinion seems to be completely alien to almost all philosophers and teachers in the East, particularly those of the Hindu world. They seem to be absolutely convinced that, above the rational level of consciousness, there is at least one more level, the intuitive level. Many believe that there are many more levels. This insight is shared by many Christian and non-Christian mystics (Happold, 1975). For this reason, we may call the intuitive level just as well the 'spiritual level' or the 'mystic level'. (Schreuder, 1996). In sec. 10.1.2 we have quoted Heisenberg: "The cosmic insight of the natural sciences is not any longer a part of the natural sciences. It is a view on the relation between human beings and nature and not a view on nature" (Heisenberg, 1955, p. 21). It goes without saying that the term mystic has nothing to do with sorcery or magic. In sec. 10.1.9, the intuitive level will be discussed.

The typical short-sighted Western considerations about the superiority of the ratio are clear in the following quotation: "The knowledge and rational thought processes of Western man are expected to become universal and any barrier to the diffusion of Western knowledge are expected to be questions of time and attitude rather than questions of basic differences in perception, thinking and learning. The opposite view, that non-Western men think in modes qualitatively different from our own has also its protagonists, like Lévi-Bruhl, 1922" (Lloyd, 1972. p. 15). It is interesting to note that even the people who propagate an cross-cultural approach do not always get any further than comparing the Western attitude to that of 'primitives', as is clear from the title of the well-known work of Lévi-Bruhl, 1922, that is quoted by Lloyd, 1972. p. 15.

(b) The characteristics of the ratio

Whatever one may think about the other levels of human consciousness, it is certain that the development of the ratio has been crucial to the origin of modern human beings. We will not go in detail about the history – or pre-history – of the development that probably took a very long time to come to fruition. It is certain that the dominance of the ratio did not occur long ago. Most people will point to the classical Greek period of what is usually called the 'Golden Age of Pericles' and in particular to ancient Athens about 600 to 500 before the beginning of the Christian era. Those who did not fully comply were gradually banned from the mainstream of natural sciences towards the outskirts of the human mental empire, where metaphysics, esoteric knowledge and mystic experiences still existed. It is interesting to note that the natural sciences were, since about the 17th century, dominated by the Protestant North-Western Europe.

Being rational seems to be concentrated in two distinct but interrelated mental capacities:
(1) To be able to generalize;
(2) To be able to apply abstract reasoning.
Both aspects could be characterized as 'serial reasoning' (Dennett, 1993, p. 252). This means that first comes one thing and after that the next. It resembles the serial calculation of a digital computer, contrary to the parallel processing of information of the human intuitive frame of mind, that is explained in sec. 10.1.9.

We will give one simple example of these two capacities. Assume a creature sees an apple falling form a tree. A creature who cannot use the ratio, let us take a worm, might think, if we may use the word thinking: "Great. An apple, I like apples, so I will eat it". This reaction is just a conditioned reflex: the worm has learned that apples are good to eat. A chimpanzee might think: "Great. An apple, I like apple. I will shake the tree so maybe more apples will fall, so I can eat them". The chimpanzee has gained the experience that shaking trees might cause apples to fall. This is the dawn of using ratio; it is the first step in using the abstract rule of cause and effect. Now come creatures who have a full capacity of using the ratio. These creatures can do one or more of many different things – by the way, they are flexible enough in their evaluation of the situation to make the best possible choice. To name a few:

- they can be aware that not only this apple does fall but that eventually all apples will fall – a mater of generalization;
- they can be aware that not only apples but all other objects heavier than air will fall, also objects they have never seen or heard of – a mater of generalization;

- they can realise that gravity causes the apple to fall; eventually they may realise that all possible objects heavier than air, even objects they have never seen or heard of like planets or moons will fall if they are subjected to the pull of any type of gravity, even gravity fields they have never observed or heard of: a matter of abstraction.

At this stage, of course, they not only are capable of using the ratio, but it will also be likely that they will be appointed to Professor in Mathematics and Physics at the University of Cambridge in England – as befell to Isaac Newton.

(c) Language and ratio

Probably the most important aspect of rationality is language. Language is the means to convey information from one individual to the other. An often used description of the concept of language is "The means of verbal communication and its graphical representation". Language, however, has many other forms (Smith & O'Loughlin, eds., 1948, p. 621). The crucial concept is 'words'. We will restrict ourselves here to the meaning of language as 'word-language' or 'verbal language'. These are other forms of language but they lack the rationalistic characteristics of verbal language. A word is "A unit of language, by itself denoting an entity" (adapted from Smith & O'Loughlin, eds., 1948, p. 1196). Each word thus represents an entity, whether object, quality or relation.

Words imply generalization – all apples are called apple – and abstraction – all apple-like things are called apple – thus requiring the two basic characteristics of rationality. So, both generalization and abstraction are needed in allotting meanings to words. As such, verbal language not only is a typical product of the rational level of consciousness, but also, verbal language is the only means in which new concepts, new thoughts, or any new content of the consciousness can be transferred from the one who 'knows' to the one who 'does not know'. This in stark contrast to the other types of information transfer, e.g. by non-verbal communication. Here, new concepts cannot be conveyed. The message can contain only aspects that are known to both sender and receiver. We will not discuss here the theories of language that abound in psychology and philosophy. The fact that it is an expression of the rational level of consciousness is sufficient here.

Sometimes, non-verbal communication is also classified as 'language'. Non-verbal communication may use any sensory channel. A very large amount of literature exists on non-verbal communication both in humans and in animals. We will not discuss that, because it is not relevant here. What is relevant, has been pointed out in sec. 10.1.5, when discussing instincts.

Verbal communication is almost exclusively restricted to human beings, whereas non-verbal communication is very widely spread over almost all areas of life – not only animals but also plants.

Verbal language is constructed from words by means of rules of syntax. We do not discuss here where these rules stem from, whether they are innate or acquired. The rules of syntax are functional rules. They allow any specific word to be used. That means that a verbal language is fixed as regards its syntax ('grammar') but it is completely free as regards the actual contents or meaning of the message (the semantics).

The first point to consider may seem trivial, but it is worth-while to mention. Using any language involves the transport of information. The concept of information transport is usually imbedded in the principles of information theory and of communication theory. These theories have been conceived by Shannon & Weaver (1949) and elaborated by Wiener, (1950, 1954). See also Bok (1948), Cherry (1966, p. 41 ff) and Van Soest (1956). Here, it is sufficient to recall that the amount of information that is to be transported by a channel never can be larger that the capacity of that channel:

$$C > T \quad [10.1.1]$$

with:
C: the capacity of the communication channel;
T: the information content of the message.

This relation has been called "The fundamental theorem of a communication channel without noise" (Shannon & Weaver, 1949, p. 28). See Schreuder (1998, equation [8.1.1], sec. 8.1.3).

Information can be classified as follows (Roszbach, 1972):
(1) Coded information, coded according a pre-arranged language – usually words in 'common language';
(2) Structured information, according pre-arranged codes, like signals in traffic signs;
(3) Unstructured information, acquired by an actively searching observer using heuristics, like e.g the visual guidance by means of tree lines in road traffic. Also 'body language', or the collection of radio signals from celestial bodies belong here.

When noise N is included, the relation becomes:

$$C > T + N \quad [10.1.1a]$$

This relation has been called "The fundamental theorem of a communication channel with noise" (Shannon & Weaver, 1949, p. 39). The concept of noise is explained in sec. 14.2.3b, where the use of electronic measuring equipment is discussed.

Messages and noise can be expressed in one-dimensional time series (Shannon & Weaver, 1949, p. 4; Wiener, 1948, p. 74).

Much more important is the fact that language, being the transfer of information, presupposes a sender and a receiver. The transfer is always in essence a transfer of energy, so there must always be a sort of coding of the information into the energy at the side of the sender and a sort of decoding at the side of the receiver (Anand & Zmood, 1995; Schreuder, 1972; 1984; 1987; 1991; 1998; Van Soest, 1956).

Words are the units of verbal language. Earlier we pointed out that each word represents an entity. Many assume that this representation is nothing more – and also nothing less – than a one-to-one relationship. The opinion of Murdoch seems to be more relevant, where two important points are indicated: "The first is that if we want to stick naively to a description of 'what occurs' we shall be unwise to divide words and other imagery sharply from each other. Word experience in thinking may have various kinds of image character. This indicates the crystallising role which the occurrence of words, and the determining role which the availability of names, may play in thought. The second point is the serious empirical unsuitability of anything like a mathematical model for language. Mathematical symbols are correctly considered as not occurring as contents of consciousness" (Murdoch, 1999, p. 34-35). One might add to this the opinion of Murdoch about language and about thinking more in general: "I shall assume, as we all do when we are not philosophing, that thinking is a private activity which goes on in our heads, that it is a 'content of consciousness'. I shall be assuming (as, again, we all do) that within limits we all have similar 'mental' experiences. I want to consider language as a kind of thinking" (Murdoch, 1999, p. 33).

These opinions allow to include non-verbal aspects of thinking into language, although that might seem to be a contradiction in terms. It is an aspect that is very easy to observe. Take, for instance, the term 'cow'. In general language, it means a large mammal that says 'Moo', occasionally gives milk and tastes good when it is dead – at least for those people who eat meat. However, the word can be, and often is, used as a term of abuse which is used for human females that are either ugly, old or just plain unpleasant. This aspect of the concept 'word' is related to the feelings that are discussed in sec. 10.1.7b on the emotional level of consciousness; words of this type may trigger aggressive behaviour. Also, words can have a meaning that surmount the rationalistic meaning, such as the sacred words that may be pronounced only at special religious occasions like e.g. the word 'Aum' for Hindus or 'JHWH' for Jews. Using the description of Murdoch that has been quoted here has a more mundane advantage: it makes the discussion as to whether the language preceded the tool-making in early humanoids, or the other way around, not relevant. Quotations like that from Dennett, simply are worthless: "It seems that our ancestors could subdue the fire and could control it, a million years or so before they had language at their disposal" (Dennett, 1993a, p. 75). It also reduces the following quotation to not much more than a figment of phantasy. When considering deaf-mute children, it is stated that they have normal brains but a sub-normal consciousness, because they cannot hear the words: "According to my theory, the consciousness of such children would be enormously inferior compared to ours. It would differ just as much from our consciousness as ours differs from that of another species of animals" (Dennett, 1993a, p. 89-90).

The reason to pay attention to the language-aspects of the rational level of the consciousness is that reasoning, and reasoning by means of verbal language more in particular, allows to get rid of the conscience. As is explained in sec. 10.1.9b, the conscience serves as a gauge to find out whether a specific action is 'good' or 'bad' – whether it should be pursued or refused. In particular, this is relevant for what has been called the instrumental aggression (Levelt, 1997). Language provides a means to 'rationalize away' the conscience.

(d) Causality, determinism and ratio

Another important aspect of the rational level of consciousness is causality. Again here, a lot has been written about causality, in theology, in philosophy and in psychology. We will not go into the details, but we will restrict ourselves to those aspects that are relevant for the theme of this book. In this respect, causality may be referred to as the rules of cause and effect. These rules can be described as follows:
(1) Everything in the Universe has a cause;
(2) There are no causes without effect;
(3) The same causes will always lead to the same effects.
Again here, the two main characteristics of rationality are accounted for: generalization and abstraction.

Two consequences are immediately clear:
(1) It is not possible that there is anything at all in the Universe, unless there is a First Cause. This is, of course, one of the traditional problems of philosophy: where does the First Cause come from? In the Middle Ages, Western philosophers chose the easiest way out. They simply postulated that the First Cause is God the Creator. The benefits were two-fold: normal human beings need not have the scientific task to find out more about it, as God is above science, and philosophers could avoid a clash with the Church. It is interesting to note that the same attitude was in 1981 still adhered to by the Roman Catholic Church. "The Pope told us that it was all right to study the evolution of the universe after the big bang, but we would not inquire into the big bang itself because that was the moment of Creation and therefore the work of God" (Hawking, 1988, p. 122).
(2) The laws of the Universe must be completely deterministic. Because, as stated earlier, it is assumed that one of the characteristics of causality is that 'the same causes will always lead to the same effects', there is no room for any flexibility. If it seems to be otherwise, many postulate that: "If determinism is true and you are able to change yourself, then you were predetermined to changing yourself" (Dennett, 1993a, p. 95). This sort of statement may be encountered quite often. There is nothing to be brought in against it. It is simply an 'act of faith', a thing you may believe or not. Acts of faith are considered in sec. 10.1.9, where the intuitive level of consciousness is discussed.

Descartes, in his famous rebuttal, gives an excellent, be it rather long winded, explanation as to how such an act of faith works: "But how do I know that God has not brought it to pass that there is no earth, no heaven, no extended body, no magnitude, no place, and that nevertheless they seem to me to exist just exactly as I now see them? Possibly God has not desired that I should be thus deceived, for He is said to be supremely good. If, however, it is contrary to His goodness to have made me such that I constantly deceive myself, it would also appear to be contrary to His goodness to permit me to be sometimes deceived, and nevertheless I cannot doubt that He does permit that" (Chavez-Arvizo, ed., 1997, p. 137). The key word is, of course: 'I cannot doubt'. That is the pure act of faith.

So we meet here one of the apparent contradictions in human consciousness. At the one hand, rationalism by its nature itself forces us to accept determinism and refutes the existence of the free will; at the other hand, religious and spiritual experiences dictate the existence of the free will and the direct consequence of it, the responsibility of human beings for their own actions. The reason for this contradiction, and the reason for the fact that the contradiction is only apparent, is that here the contents of two different levels of consciousness have come into view at the same time. As is explained in sec. 10.1.10, when introducing the four-level model of consciousness, the levels are to a large degree independent of each other. It should not surprise us that a conclusion made on one level seems to contradict a conclusion made, regarding the same matter, at another level. Probably the most common, and maybe also the clearest, example is the selection of a bride: for one and the same man, on the instinct level miss A is the most appropriate one because of her bodily dimensions; miss B, on the emotional level, because she is such a good sport and so much fun to be with; miss C, on the rational level, because she is of an aristocratic and wealthy family, and still he will ask miss D to marry him because he loves her – the final decision being made on the intuitive level. This complex decision making process is probably the reason why it is so difficult to explain to others the choice of miss D as the future bride!

(e) Cognition

In classical functional psychology, four basic functions of the human mind are discerned:
(1) Perception;
(2) Feeling;
(3) Cognition;
(4) Volition.

Crudely speaking, cognition is thought to involve thinking. "Thinking, or, as neuroscientists prefer, cognitive processes" (Greenfield, 1997, p. 20). A more precise definition is hard to give: "Cognition has no obvious counterpart in everyday language. It is an umbrella term for brain functions that are not directly related to brain inputs. In addition the term is often implicitly contrasted with the emotions and generally is reserved for activities such as learning, memory and language. However, because the term is so vague, any dichotomies where cognition is contrasted with other functions should be approached with caution" (Greenfield, 2000, p. 204). This would mean that cognitive processes cover only a part of the processes that are discussed here as being part of the rational level of consciousness.

It is generally assumed that the parietal cortex is involved in the function of thinking (Greenfield, 1997, p. 20). The parietal cortex is a region towards the back of the head at the top (Greenfield, 1997, p. 19). As far as rational activities are related to brain activities, it is often assumed that the relevant brain parts that are involved lay within the cortex. Not the whole cortex, because the frontal lobes, that lay directly behind the forehead, seem to be involved in other levels of consciousness.

(f) Cognitive aspects of vision

Visual perception has to do in the last instance with transfer of information. This aspect of human activities is the subject of cognitive psychology. After many years where psychology was dominated by behaviorists, gradually the cognitive psychology became a subject worth-while to study. The reason was that practice required data about cognition, more in particular the practice of the advertising business. It became clear that the theories of the behaviorists could not explain why people bought one product and disregarded another. This is similar to the aspects of 'Gestalt' that are discussed in sec. 10.2.1. Furthermore, the information technology required data on how patterns were recognized, mainly for computers that could recognize handwriting, like e.g. the signatures on bank cheques, or for computers that could recognize spoken words and convert them into data files.

10.1.9 The fourth level: the level of intuition

(a) The characteristics of intuition

Intuition is sometimes described as: "The immediate awareness, either of the truth of some proposition, or of an object of apprehension such as a concept" (Blackburn, 1996, p. 197). Descartes proposed a similar description: "By intuition I understand, not the fluctuating testimony of the senses, but the conception which an unclouded and attentive mind gives us so readily and distinctly that we are wholly freed from any doubt about that which we understand" (Chavez-Arvizo, ed., 1997).

These two quotes have one important aspect in common:
(1) The immediate awareness;
(2) Free from any doubt.
It seems that the cognitive aspects that have been discussed in sec. 10.1.8e, are not involved; cognitive effect are not 'immediate', because they involve rationality or reasoning or 'thinking'. The quotes suggest rather some sort of relevation. Thus, the intuitive level is also called the spiritual level. When we take into account that many relevations involve mystic experiences, the term mystical level also may be used.

Many relevations are considered as being divine of nature. It is well-known that according to the Jewish religion, the whole of the Torah (the Pentateuch) is divine relevation to Moses. This is the eighth of the 'Thirteen Fundaments of Jewish Belief' as defined by Maimonodes (Unterman, 1991, p. 30). Not all relevations, however, are of a divine nature. Earlier, we have quoted Weinberg: "Every once in a while mathematical abstractions, experimental data, and physical intuition come together in a definitive theory" (Weinberg, 1993, p. 3). Einstein seems to suggest something similar, when discussing the axioms of geometry: "We are inclined to accept axioms as 'true'. A proposition is only true if it is deduced in the right way from the axioms. The question about the axioms themselves being 'true' has in its own not any significance" (Einstein, 1956).

As said earlier, the most striking aspect of intuition seems to be that there is no earlier experience or cognition involved. It seems to be in direct contradiction to causality, that has is explained in sec. 10.1.8d. On these grounds, the distinction we have made between the rational and the intuitive levels of consciousness seems to be justified.

The characteristic of being 'immediate' is supported by a number of quotes that are related more to the practice than to the philosophical theory. The first is from Mithen: "Young children seem to have intuitive knowledge about the world in at least four domains of behaviour: about language, psychology, physics and biology. The intuitive knowledge within each of these appears to be directly related to a hunting and gathering lifestyle long, long ago in prehistory" (Mithen, 1996, p. 52, referring to Cosmides & Tooby, 1987, 1992, 1994). The second quote refers to what is called the 'intuitive method': "Husserl does not refer to the description of entities that can be observed by the senses, but to the description of entities about being and forms of being that we experience through another type of observation, the eidetic comprehension and insight" (Diemer & Frenzel, eds., 1970, p. 268, referring to Husserl, 1928).

(b) Intuition and conscience

In sec. 10.1.6f, when discussing instrumental aggression, the role of conscience is mentioned. In psychological terms, conscience is defined as follows: "An individual's system of accepted moral principles, or principles of conduct" (Drever, 1968, p. 49). In philosophy, it is sometimes stated that "Humans are aware that an action is morally required or forbidden" (Blackburn, 1996, p. 76). Neither author gives any suggestions where these principles come from.

Some believe that a strict definition of conscience cannot be given; a description "would tell more about the theories of philosophers than that they have any appeal to ordinary people" (ENSIE, 1950, Vol. I, p. 169). Nevertheless, the same article quotes Kohnstamm (without any further reference) for a description, that might be useful for our considerations, of a conscious decision as an act with four characteristics (ENSIE, 1950, Vol. I, p. 169):

(1) It involves the whole personality (ratio, feelings etc.) and it is clearly considered and motivated;
(2) It is higher that ratio ('supra-rational');
(3) It is concrete and valid only on an absolutely personal basis;
(4) It is considered by human beings as a gift.

As indicated above, it seems impossible to give a generally acceptable definition of conscience. Over the centuries, this was one of the major areas of interest of philosophy, more specifically of ethics. We will refrain from that; we will make use of the lists given by Kohnstamm that is given here and that of De Wit, that will be discussed later, for a suggested description of the concept of conscience.

In Christian Roman Catholic philosophy, the guardian of conscience is the Church; in the Protestant philosophy, it is an autonomous authority (Blackburn, 1996, p. 76). This leads to two errors of conscience: "Some that are voluntary or blameworthy and others that are involuntary; in the former case we are responsible, in the latter we do wrong unknowingly" (Blackburn, 1996, p. 76).

(c) *Intuition and ethical behaviour*

In an sec. 10.1.6a, when discussing the roots of aggressive behaviour, the concepts of good and bad, or virtue and evil – or sin – were mentioned. Contrary to the idea that aggression is neutral in a psychomoral sense, is the conviction that aggression is 'bad'. This notion ties in with the concepts of good and bad, of virtue and evil. As has been mentioned earlier, these notions are often used as a starting point for considering law-enforcement measures regarding aggression and street violence.

It must be realised that these two concepts lay at the root of religion and of philosophy. This is not the place to discuss these religious or philosophical issues. We will restrict ourselves here to a general description of a number of aspects of these two, where 'good' and 'bad' will be regarded as almost synonyms to 'virtue' and 'evil'.

In the Christian sense, one of the major characteristics of virtue, seems to be the "general benevolence" (Blackburn, 1996, p. 394). In an unpublished lecture, this notion has been worked out in more general terms that might also be relevant for non-Christians (De Wit, 2000). The central ideas are that people want to do good and that for this they look for a role-model. The role-model has the following characteristics, that conversely can be attributed to the idea 'good' itself:

- they show wisdom; they are spiritually inspired;
- they are meek; they respect others and they do not bulldoze through their own ideas;
- they are compassionate; they act without reserve without the wish to get back something in return.

The role-model idea is found in many places. An intriguing quote is from Confucius: "A virtuous ruler is like the Pole star, which keeps its place while all the other stars do homage to it" (Giles, ed., 1998, p. 39).

The ability to discriminate between good and bad, between virtue and sin, is often regarded as an act of Divine Grace: "In our various degrees, we are all sinners. To acknowledge and accept that load is good. Perhaps even to acknowledge and accept it and not entertain either shame or regret may also be required of us. If we find we must say: Yes, I would do the same again, we are making a judgement others may condemn. But how do we know that God will condemn it? His judgments are inscrutable." (Peters, 1994, p. 314). Because of that, and in spite of all the troubles in the world, there is still hope: "Thanks to God, there are still, as there always have been and always will be, more good men that evil in this world, and their cause will prevail" (Peters, 1994, p. 305). The same idea is expressed as: "Goodness is part of our form of life; goodness is natural" (Foots, 2000, as quoted by Lievers, 2001). See also Goodal, 1999.

By implication, evil should be characterized as having no wisdom nor spiritual inspiration; being arrogant and disrespectful to others, as being scheming and keen on personal gain and status – in short, as lacking any conscience.

There is, of course, a close relation between ethical behaviour and behaviour according to the conscience. As we have mentioned earlier, both ethics and conscience are difficult to define. Some general characteristics can, however, be given. "Ethics are 'fit and proper' in which way they are different from all other considerations. Ethics are defined as the teachings of the fundamental issues. These fundamental issues form together the 'a priori'-aspects of the moral rationality. The individual human being finds the fundaments within himself, even if they are of general human validity" (Bierens de Haan, 1942, p. 5,6). The key words are 'fit and proper' which are understood by Bierens de Haan as being self-explanatory. This is more than just a trick to avoid a circular definition; it is accepted by many that conscience may be regarded as something a human being does not need to learn because it is known 'of its own accord'.

Regarding the conscience, the following characteristics are mentioned: "What characterizes conscience is its unconditionality: conscience does not allow contradiction; it does not accept excuses" (Bierens de Haan, 1942, p. 32-33).

(d) Origin and development of conscience

In the four-level model of consciousness that is explained in sec. 10.1.10, it is assumed that the different levels did show themselves one after the other during the development of life. The idea of the evolution of life is nowadays accepted by most people – at least in the Western world. It should be noted that this does not automatically imply that each species did actually grow out an earlier species; an alternative idea is that each species did originate anew – 'from scratch' – and that the end results can be grouped nicely in a series of increasing complexity. As an example, it is easy to line up a number of people in a row of increasing height; this is not the same as stating that the taller ones did 'grew out' of the shorter ones. The mechanism of the evolution itself is far from clear as will be explained furtheron in this section.

Something similar may be stated for the consciousness. The rational level did not evolve from the emotional level, simply because they both exist to this day. It is better to state that the first level – the instincts – did show itself; later, the emotional level followed; still later the rational level and so forth. This is therefore not a 'true' evolution. The word 'development' seems to be preferable. Apparently, the functions of the consciousness did develop in a parallel fashion to the development of the brain functions. As is explained in sec. 10.1.4c, it is possible to allot functions of the consciousness to brain areas. One might try to explain this in the following way: the contents of the consciousness are located in the consciousness, wherever that may be; they can only manifest themselves into acts (into 'behaviour') by means of specific brain activities. These brain activities can be recorded as is explained in sec. 8.1.5c. The fact that the activities can be recorded does not imply, of course, that the acts of consciousness are the same as the brain activities, and even less that consciousness is identical to brain activities. "One cannot help feeling that the study of mysticism through EEG, EEC and similar methods, is like studying art through films of the eye movements of art viewers" (Staal, 1975, p. 107-108). This statement is often made with a great but baseless flurry of facts that are supposed to serve as 'proof'. See e.g. Crick (1989, 1994); Dennett (1993; 1993a) and others. What it does imply, however, is that, because crocodiles have a rudimentary cortex, they will have a rudimentary ratio, and most probably a rudimental conscience as well.

It seems justified to assume that the intuitive functions did develop gradually along with brain functions until it did reach the level we may find in human beings to-day. If we follow this idea, the logical next step is to assume that a further development will manifest itself in the future in a further extension of some brain elements together with a further extension of consciousness. Incidently, the frontal lobes of the brain allow for quite a lot of further development. This thought may be alien to the Western world, but it seems to be commonplace in many circles in the East. Already in the Upanishads 'the fourth' i.e. the mystical state of samadhi is introduced (Staal, 1975, p. 146).

It should be stressed that this development that is suggested here, is supposed to take place in the whole species, e.g. in the whole species of Homo Sapiens. It does not say anything at all about how individual persons or groups of persons may acquire their conscience. As will be explained in a further part of in this section, we will assume that the conscience, just as the ideas of 'fit and proper' as well as the ideas of 'good' and 'bad' are – in one way or another – innate in human beings.

Many consider conscience, and more in general all ethical considerations, as nothing more than acquired patterns of behaviour that have evolved during the ascent of humans from proto-humans just because it makes them more fit for survival. For many, evolution is a generally accepted fact, even a 'scientific' fact. For Gould, this fact follows directly from the large number of new species that could be found after a mass extinction in the late pre-Cambrian period, about 570 million years ago: the "Cambriam Explosion" (Gould, 1989, p. 24). Gould postulates the concept of contingency in evolution: all sorts of things happen at random, and only those that are more 'fit' than the others, survive (Gould, 1989, p. 51-52; 301-304). According to Gould, the proof of this is to be found in the Burgess Shale in the Canadian Rocky Mountains, that records the fossilised witness of a small catastrophe of a few seconds, in an area of 100 m long and 2 m wide. "Little taller than a man, and not so long as a city block." (Gould, 1989, p. 69). Gould describes the thoughts of evolution as the 'Darwinistic doctrine' (Gould, 1993).

About the origins of life, many scientists seem to be equally sure. "Life came into being almost as soon as the conditions became favorable" (Gamov, 1948, p. 155). The time for this might seem long enough for natural causes. This idea stems from statements like: "In due time, the impossible becomes the improbable and the improbable becomes the almost certain' (Gould, 1999, p. 92, quoting without further reference George Wald). However, according to the results of more recent investigations, life on Earth started almost immediately when it was physically possible. "If life originates as soon as it is possible, one might conclude that this origin is rather predictable, that it follows logically from the way, the organic chemistry and the physics of self-regulating systems function" (Gould, 1999, p. 92).

It should be pointed out that the thesis of Darwin was not evolution as such but its process, as is evidently clear form the title of his most famous book: "The origin of species by means of natural selection, or the preservation of favoured races in the struggle for life" (Darwin, 1890). There are problems, however. There is no hint of experimental or empirical support for the origin of 'new' species along these lines. Selective breeding is, of course, well-known, but only within one species. "Darwin scarcely addressed the problem of how new species arise. His mechanism, natural selection, concerns changes of species through time, but this alone will not produce new species; it will merely modify and preserve old ones" (Gregory, ed., p. 239). Furthermore, it seems to many that the 4 000 million years of life, such as is suggested by Gould (1989), is by no means long enough for the evolution process on the basis of random variations. Some remarks about the theory of time are made in sec. 10.1.5a. Finally, according to many biologists, it is even not possible to define a 'species' in biological terms: "The rift between biological species and varieties is a fiction" (Goldschmidt, 2002, p. 150. See also Goldschmidt, 1997).

Taking all the different viewpoints and opinions that have been touched upon in the foregoing part of this section into account, it seems justified to regard ethical behaviour and consciences innate so far as the individual people are considered. We have seen that what is 'fit and proper' need to be learned because it is known 'of its own accord'.

This follows another thought that is often expressed, although we will not pursue it here. This thought is that consciousness develops, not because of some random variation that seems to be favourable for the survival and for the promotion of certain gene patterns, but because of an autonomous drive to do so. This is aptly expressed as follows: "Human consciousness demands explanations about the world" (Leaky & Lewin, 1992, quoted by Miley, 1998, p. 10).

(e) The elements of ethical behaviour

For practical purposes, it is important to know which types of human behaviour would classify as innate and which as acquired; what elements one may expect to be regarded universally as 'fit and proper' and what elements depend on culture and customs. Strangely enough, the literature does not offer much help, so we will look at the Ten Commandments of the Bible as they reflect the feelings of a considerable part of humanity. Sure enough, the Koran offers also a number of viewpoints, many of which are very similar. The Bible sees to be a good starting point. In an extremely brief and over-simplified fashion, based on the rendition given in ENSIE (1950, Vol. X, p. 1168), the Ten Commandments are:

I Worship no other gods;
II Be merciful;
III Do not use God's name in vain;
IV Honour the Sabbath;
V Honour thy Father and Mother;
VI Do not murder;
VII Do not commit adultery;
VIII Do not steal;
IX Do not lie;
X Do not desire the properties of others.

Evidently, there are three groups of Commandments:
(1) Those related to the Worship of God (Nrs. I, III, IV);
(2) Those related to the stability of the structure of society (Nrs. II, V, VII, X);
(3) Those that may be regarded as elements of ethical behaviour (Nrs. VI; VIII, IX).

According to this viewpoint, the elements of ethical behaviour all relate to the immediate relationships between people. For lack of a better alterative, we will assume that these elements are both innate and universally human. It is important to know that, because one may expect that these elements, or the lack of them, are crucial aspects of aggressive behaviour.

(f) Deficient conscience

The fact that we assume that ethical behaviour and conscience are innate, and thus present in all people, does not imply that all human behaviour is in agreement with these two principles. In sec. 10.1.6f, when discussing instrumental aggression and when considering the possible role of conscience, a list of acts of so-called 'small-scale' aggression at street level is given (Schreuder, 2000; Terlouw et al., 1999). This list can be compared with the four major causes may be defined that would result in deviant behaviour, the first three being more or less permanent, and the fourth more temporary and thus more transient:

(1) The conscience can be overruled. It has been explained earlier that conscience does not allow contradiction; it does not accept excuses. However, there are many cases where the situation requires that the arguments are overridden. The conscience is still operating but it is not allowed to be the source of actions. On the collective level, it is almost universally, fortunately not totally, accepted that war not only allows but even requires to kill; on the individual level, is it often assumed that the victim being rich and the perpetrator being poor not only allows but even stimulates to steal.
(2) The conscience can be weak and even absent; it can be weakened further when the conditions of living are extremely threatening. In a harrowing report on life in the Gulag, it is stated that "extreme misery kills human emotions; when the situation improves only in the slightest, the emotions come back. First indifference, then fear, then jealousy, then care for animals, then care for humans. Love comes back as the last – if at all. But still, the sufferers are human. However, at the moment someone

steals from weaker fellow sufferers or terrorizes them, humanity is lost. These are the characteristics of the mafiosi criminals" (Steinz, 2001, quoting Slalamov, 2001). This seems to be the moment that conscience is killed. Although it is not stated explicitly, is seems safe to assume that this refers to all mafiosi criminals all over the world at all times, not only in the Gulag. More in particular, it is often assumed that drug dealers and Secret Police torturers really do not have any conscience. Maybe they have had some of it at some time, maybe never. Maybe Sarasto's words refer to those: "Der verdienet nicht, ein Mensch zu sein (He does not deserve to be a human being)" (Mozart, 1791, Act 2, Scene 15). However, conscience can be weakened by degerenative brain malfunctions such as Alzheimer Disease (Greenfield, 2000, p. 157-158; 2001, p. 15-18). See also Alexander & Selesnick (1966). It has been suggested that the brain malfunctions that are correlated with dyslexia, also may influence the operation of the conscience, although usually dyslexia is regarded as just a difficulty in learning to read (Gregory, ed., 1987, p. 205-206). Something similar is suggested for epilepsy with equally limited support (Gregory, ed., 1987, p. 223-225; Sagan, 1997, p. 167-168).

(3) The conscience can be blocked by malfunctions in the brain. The conscience is still present and is still within the consciousness, but the implementation into ethical behaviour is blocked. This can be the result of tumors or injuries, such as are described in detail by Damasio (1994). This also can be the result of the latter degenerative phases of alcohol or drug abuse (Leuw, 2002);

(4) It is, of course, also possible that conscience is put out of order (put 'to sleep') on a temporary base. This can be the result of intoxication by alcohol or drugs or by the flush of powerful emotions like orgiastic joy, rage etc. In court, people who did commit crimes 'while intoxicated or incapable' often got a reduction in penalty because of 'diminished responsibility'. This is often the case for aggression and street violence. It should be noted, however, that in cases concerning traffic accidents, the opposite is true. 'Drunken driving' results in more severe punishments. Not just for road traffic accidents, but also for shipping, rail and air accidents (Van Ooijen, 1969; Steffen, 1962). In this respect, some information concerning the relative accident involvement, expressed in the relative probability to get injured as a car driver in an accident, is given in Table 10.1.2.

Condition	**Relative accident involvement**
Sober	1
Alcohol 0,2-0,5 g/l	0,9
Alcohol 0,5-1,3 g/l	5,2
Alcohol over 1,3 g/l	48
Sedatives	4,4
Combined drugs	8,8
Alcohol and drugs	458

Table 10.1.2: *Relative probability for car driver injuries (Based on data from Mathijssen et al., 2002, table 3).*

(g) Intuition and mysticism

A definition of mysticism can, in essence, not be given, because definitions belong to the realm of rationalism whereas mysticism belongs to the realm of intuition. Still, a description can be given. "It came to mean a particular sort of approach to the whole problem of reality, in which the intellectual, and more especially the intuitive, faculties came onto play. It is a consciousness of a *beyond*, of an *unseen* over and above the seen, of something which is not of the external world of material phenomena, though it is interwoven with it" (Happold, 1975, p. 18-19; italics from Happold). It musty be noted that "The case for the validity of mystical experience is not a self-evident one" (Happold, 1975, p. 16). Some restrict mysticism to the realm of religion: "Any worth-while study of mysticism must, of its nature, be a study of comparative religion, for mysticism is a manifestation of something which is at the root of all religions" (Happold, 1975, p. 16).

According to some, a definition of mysticism cannot be given for logical reasons: "Since we do not have a theory of mysticism, we do not precisely know what mysticism is and we are not in a position to provide a definition" (Staal, 1975, p. 18). This seems to be logical but as mystical experiences are not logical, the matter of not defining mysticism is meaningless. Staal seems to understand that: "Underlying my approach to the study of mysticism is some intuitive notions of what mysticism is like" (Staal, 1975, p. 18). This is, of course, the point: as mysticism belongs to the intuitive level of consciousness, intuitive knowledge is exactly what you may expect to get.

Nevertheless, many have problems with the supra-rational aspects of religion and mysticism. "Religions, eastern and western, have in common a conflicting desire to avoid logic in the attempt to express the mystical and at the same time to justify its claims by means of reason" (Feibleman, 1976, p. 44). This quotation is typical for "A popular account for the Western world" – the sub-title of this book.

In an old and difficult to grasp treatise, an excellent overview of Roman Catholic Mysticism is given, a survey that is still perfectly to the point at present (Butler, 1960). It appears that the viewpoints given in that book cover in essence all mystical experiences, Christian or non-Christian alike. In the Roman Catholic tradition, the mystical experience is defined: "Direct contact with Transcendental Reality" (Butler, 1960, p. 66). The Ultimate Reality which seems to be identical to the Transcendental Reality is to understood as being God (Butler, 1960, p. 95). At another place it is stated that "The mystical experiences are the vision of the divine Essence. They are the rarest of all mystical favours and, if ever granted, they are truly miraculous." (Butler, 1960, p. 54).

While arguing that mysticism is just a delusion, Russell gives an excellent description of what mysticism is all about: "Metaphysics has been developed from the union and conflict of two very different human impulses, the one urging men towards mysticism, the other urging them towards science. We need both science and mysticism. The attempt to harmonize the two makes philosophy, to some minds, a greater thing than either science or religion" (Russell, 1953, p. 9).

Russell (1953, p. 15-17) lists a number or characteristics – or 'doctrines' – of mystical philosophy:

(1) The belief in insight as against discursive analytic knowledge – a hidden wisdom now suddenly certain beyond the possibility of a doubt;
(2) The belief in unity, refusing to admit opposition and division. We will come back to that when discussing Brahmah and Maya;
(3) The denial of the reality of time. We will come back to that as well;
(4) All evil is mere appearance. We will come back to that as well when discussing Brahmah and Maya.

The reasons for Russell to reject mystical philosophy seem to be rather weak: "Mysticism seems to me to be mistaken. The scientific attitude is imperative, maintaining that insight, untested and unsupported is an insufficient guarantee of truth. Intuition, in fact, is an aspect and development of instinct" (Russell, 1953, p. 18; 23). In view of what we have explained earlier, we will disregard the criticism of Russell as not relevant.

Three points in the list of Russell deserve some further attention. First, the belief of insight as a hidden wisdom that suddenly becomes certain beyond any doubt. This aspect seems to be crucial in all mystical experiences.

Secondly, the belief in unity. This is closely related to the fourth point, that all evil is mere appearance. It would have been better if Russell had stated: "Both good and evil are mere appearances". The following quotation is from an unknown source: "All and Nothing, Empty and Full, Infinite and Dimensioneless, that is Bramah, the Great Unknown, that is God. For reasons that are unknown and unknowable for humans – we may just guess – Bramah is split in countless polar twins like good and bad, body and soul, up and down, waves and particles, matter and spirit. The twins are separate and opposite, they may be compared but not almalgated. They are Maya. Maya is the world of delusion, the world known and knowable to humans. Maya is real. It is not a hallucination. In the rare moments of mystical experience when the individual and God become One, some may know the unity, the reality of Bramah indivisible. Such mystic experiences may not be forced but it seems possible to prepare body and spirit for them by contemplation, by breathing exercises, by posture and even by drugs". Another quotation: "The eye with which I see God is the same eye as the eye with which God sees me. My eye and God's eye are one and the same" (Master Eckhart, after Novak, 2002, p. 316, quoted from Blackney, 1941, p. 206). The point is that in Bramah, good and evil are not separate, they are in Maya. And it is in Maya where we might find our conscience.

The third point is about the denial of the reality of time. See also sec. 10.1.5a. Time is a concept that is not self-evident. In a way, it is just a mathematical construction without any reality. It is nothing but a coordinate. Hawking has given a comprehensive survey of the different theories of time that were used in physics over the centuries (Hawking, 1988). According to traditional wisdom as well as according classical – Newtonian – mechanics, time is a linear phenomenon that marches on, without interruption or without yielding to any external influence. Time can be graphically depicted as a point which represents 'now' that shifts at a constant speed over a line of infinite length. The most striking aspect of the picture is that all physical laws are invariant as regards the direction in which the 'now-point' moves: future and past are interchangeable. It is just a picture, not a definition. It is clear that 'speed' presupposes a time concept. In the space-time continuum introduced by Einstein, this simple picture is not relevant any more. See Feynman et al. (1977, Vol. I, Ch. 15, p. 1; 15-21). The space-time continuum is actually a four-dimensional block that represents, according many physicists the Universe. In that model, time as such is non-existent; future and past are all included in the block. This would mean that the Universe is completely predetermined and that there is no place for chance occurrences. Also, the concept of entropy that is crucial in thermodynamics, requires another concept of time where the invariance of direction is not valid any more. But still, time is one-dimensional. This in contrast to the time concepts of Hinduism, where it is cyclic. The cycle is formed by Bramah, the creator – Vishnu, the maintainer and Shiva, the destroyer. The cyclic aspect is that the destroyer and the creator really are one – another form of Maya. Several of these considerations are discussed in sec. 10.1.5a.

10.1.10 The four-level model of consciousness reconsidered

In the preceding sections, we have discussed in considerable detail the structure and the function of human consciousness. The reason for that discussion is that in almost all human activities, the reflexes excluded, there is always a moment of consciousness; human activities are the outcome of a decision making process. Whereas reflexes can be described by the simple stimulus-response model (or S-R model) of behavioristic psychology, actions can better be described by the stimulus-decision-response model (or S-D-R model) that is explained in sec. 10.4.2a.

Out of the discussion it became clear that human consciousness is a very complex system. First, from experiment but also from day-to-day experience, it is obvious that the actual or working consciousness is extremely small: the number of items that can be worked at simultaneously is restricted to some 10 bits of information per second. This is sometimes called the 'working memory'. At the same time, the 'random access memory' is extremely large. No-one did ever find a limit to what people might remember and reproduce at will. The memory that contains items that cannot be reproduced at will is still larger. Part of this is the subconsciousness that was known already a long time, but that got a sound foundation by the psycho-analytic work of Freud. Furthermore, there seems to be all sorts of 'side-consciousness' that are triggered by psycho-active substances. For all practical purposes, this aspect of human consciousness, that seems to be the same as memory, can be regarded as unlimited.

But there is more. Even the most casual observations make it clear that there are also qualitative distinctions to be made within the concept of consciousness. The most obvious one, the one that is made everyday by almost everyone is the distinction between emotions and reason. A closer look did suggest that there are five ways of life. There seem to be

several levels of consciousness that have little in common and that can operate almost independent of each other. It is tempting to list the five ways of life in an hierarchy that goes from low (or primitive) to high (or sophisticated). The first level is the vegetative level. As it seems to involve processes that are almost completely unconscious. Thus, the vegetative level will have to be disregarded when considering the stimulus-decision-response model. The higher levels are included in a 'four-level model of consciousness' that is introduced here. As was explained in earlier sections of this chapter, the four levels of the model are:
(1) The level of instincts;
(2) The level of emotions;
(3) The level of the ratio;
(4) The level of intuition.

All four may provide material on which the 'decision' in the S-D-R model can be based. What should be discussed now is the relation between the four levels. There must be a relation, simply because the four levels are all part of the total of human consciousness. A first approach might be to consider the different levels as 'sets' where each lower level is a sub-set of the higher level.

When we consider the actual interactions between the levels, this suggestion seems to need some more elaboration. As has been explained in the foregoing sections of this chapter, the decisions made on considerations of instincts, of emotions, and of the intuition are quite different in nature. More specially, they seem to lead to quite different types of criminal acts, and of different related acts of aggression and street violence. There seem to be grounds, therefore, to consider these three levels, or at least the actions that follow from decisions on these levels, as independent of each other. Two remarks must be added, however. The first is that in all cases, the conscience acts as an overall touchstone, where the ethical acceptability of the acts are judged. In case that the act is judged as ethically unacceptable, the conscience must be overruled in one of the ways that have been explained earlier.

The second refers to the role of the ratio. Many decisions, also decisions that may lead to criminal acts, are based exclusively on rational considerations. In this respect, the level of the ratio can be grouped together with the three others, and be considered as independent. However, just as with the conscience, decisions on other levels can be promoted, altered or withheld on the basis of rational decisions. It is customary to include such considerations into the motivation that is discussed in sec. 10.4.1. One peculiarity of the rational aspects of motivation is, that is it customary to justify any decision on rational arguments. On may surely say that it is a characteristic of the society, at least of the Western society of the last few centuries, to do so. Decisions made on rational grounds have a much higher 'status' than decisions that are 'only' made on emotional – or other – grounds. One peculiarity of the ratio is that it may work extremely rapid, notably if the person is trained in this. This speed is often used in the following way. After a decision has been made, say on emotional grounds, it is almost always possible to think of justifications for an act after the decision has been made, and still have plenty of time to present the rational arguments before the action takes place. Thus, it seems that the decision has been made on the basis of these rational arguments.

Probably following considerations like these, it is sometimes suggested that the ratio is nothing but a trick of recent times to make a few things more convenient, and that it is not, like other mental functions, a result of a long evolutionary process. This idea seems to be too short-sighted. "Language, reasoning, decision making are examples of what one might call 'higher cognitive functions'. Human beings have much more of these functions at their disposal than our direct ancestors" (Van Lambalgen, 2003, p. 21). The domain-specific aspects of mental functions that are advocated by the evolutionary psychology, are not sufficient to explain the complexity of reasoning (Van Lambalgen, 2003, p. 27).

10.2 Perception of complex visual stimuli

10.2.1 Gestalt aspects

In sec. 10.1.2, it is mentioned that the ground rule of reductionism, which states that 'the total equals the sum of the parts', is not generally applicable. It has been suggested that this rule is valid only for a small part of human experiences, such as the algebra – and probably not even for all of the algebra. One area where this ground rule of reductionism leads to completely wrong conclusions is the simultaneous perception of a number of separate stimuli. See e.g. Glaser (1997, p. 244). The individual stimuli work together, in ways that are explained in the following part of this section. The figure-and-ground effects were a central issue. This did imply that most emphasis was placed on visual perception, relative to perception with other sense channels (Hofstätter, 1957, p. 143, Drever, 1952, p. 108)

The word 'Gestalt', that originally stems from German, has been adopted universally for the description of these phenomena. It has been stated that the Gestalt psychology has been founded by Von Ehrenfels (1890, as indicated by Glaser, 1997, p. 240). As is customary in psychology, a 'school' was established in 1910 by Wertheimer, Koffka, and Köhler (Blackburn, 1996, p. 157). In the early part of the 20th century, it became one of the major streams in psychology, particularly through the studies of Koffka (1963) and Köhler (1929). See Van Essen (1965, p. 153). Emphasis was placed on the background (Koffka, 1963, Chapters 3, 5, 6). The Gestalt psychology was "equally hostile to behaviorism and to introspection" (Drever, 1968, p. 108). These are the two other major streams in 20th century psychology, apart, of course, from psycho-analysis, that seems to belong more to psychiatry than to psychology. A more modern school of psychology is the cognitive psychology, the most recent being the evolutionary psychology. For physicists it seems to be strange that science is subjected to schools. It seems therefore to be better to judge the Gestalt psychology on its merits, rather than on the school it might belong to. In a way, the Gestalt psychology has some likeliness towards the phenomenological school of philosophy. "According to Kant, phenomenology denotes the description of experience in abstraction from its internal content" (Blackburn, 1996, p. 284).

It has been suggested that the Gestalt psychology floundered because "there never was established a real bridge towards the understandings of neurobiology" (Glaser, 1997, p. 244). One might wonder whether this is a justified objection. It has been assumed that "the site if not the actual substance of consciousness – the precise point where quantum activity interacts with classical physical activity of the brain is not known" (Penrose, 1994).

As has been indicated already, the Gestalt quality is something over and above anything in the array of individual sensations. Gestalt is commonly understood as "the theory of perception developed in opposition to the classical model of J.S. Mill and H.L.F. von Helmholz. Phenomena like the 'figure-ground' switch make vivid that to take a scene one way or another goes far beyond having the same blank experience – the interpretation changes the experience itself" (Blackburn, 1996, p. 157).

We will explain in some detail how one may understand the way the Gestalt approach leads to a specific understanding of the processes of visual perception. For this, we will make use of a number quotations from Gregory (1965).

"The eye has been compared with a camera, but the most interesting aspects of observation have nothing to do with a camera. It is tempting, but incorrect, to say that the eye produces an image in the brain. An image in the brain presupposed some sort of internal eye to see with, and this eye requires another eye to see the image produced by that eye, etc." (Gregory, 1965, p. 7). "Gestalt psychologists have pointed out the problem as to how a mosaic of stimuli on the retina can give rise to the observation of objects. They emphasized the characteristic of the perception system to assemble individual items into groups. We try to organize the immediate sensory impressions into objects. Observing objects involves many more sources of information that just the data that are provided by the eye while looking. Usually, being familiar with the object is crucial, and this may involve other sensory channels as well, not just visual observation, like taste, smell, hearing but also touch and pain. Objects are much more than just patterns of stimuli: they have a past and a future. When we know their past or when we can predict their future, objects become more than experience. They become a part of knowledge as well as a part of expectation" (Gregory, 1965, p. 8).

"Observation is not only determined by patterns of stimuli; it is a dynamic search for the best interpretation of the data that are available. These data consist of visual experiences and of knowledge from other characteristics of the objects. An object that is perceived is a hypothesis, suggested as well as checked by sensory input data. Once in a while, the eye and the brain reach a faulty conclusion. Then, we are a victim of a hallucination or of an illusions. If a hypothesis about the observed item – an observation – is wrong, we are misled in the same way as scientist who are misled by faulty theories that misinform about the world" (Gregory, 1965, p. 13-14).

A number of 'Gestalt Laws' have been defined. As suggested earlier, in most cases they are related to the way an object is seem against it background. These aspects are summarized in two descriptions that are similar, although not identical: the 'foreground-background' aspects and the 'figure-to-ground' aspects. A number of these 'Laws' have been depicted in Figure 10.2.1. This figure is based on Glaser (1997, p. 242). See also Graham, ed. (1965) and Metzger (1953) and CIE (2000).

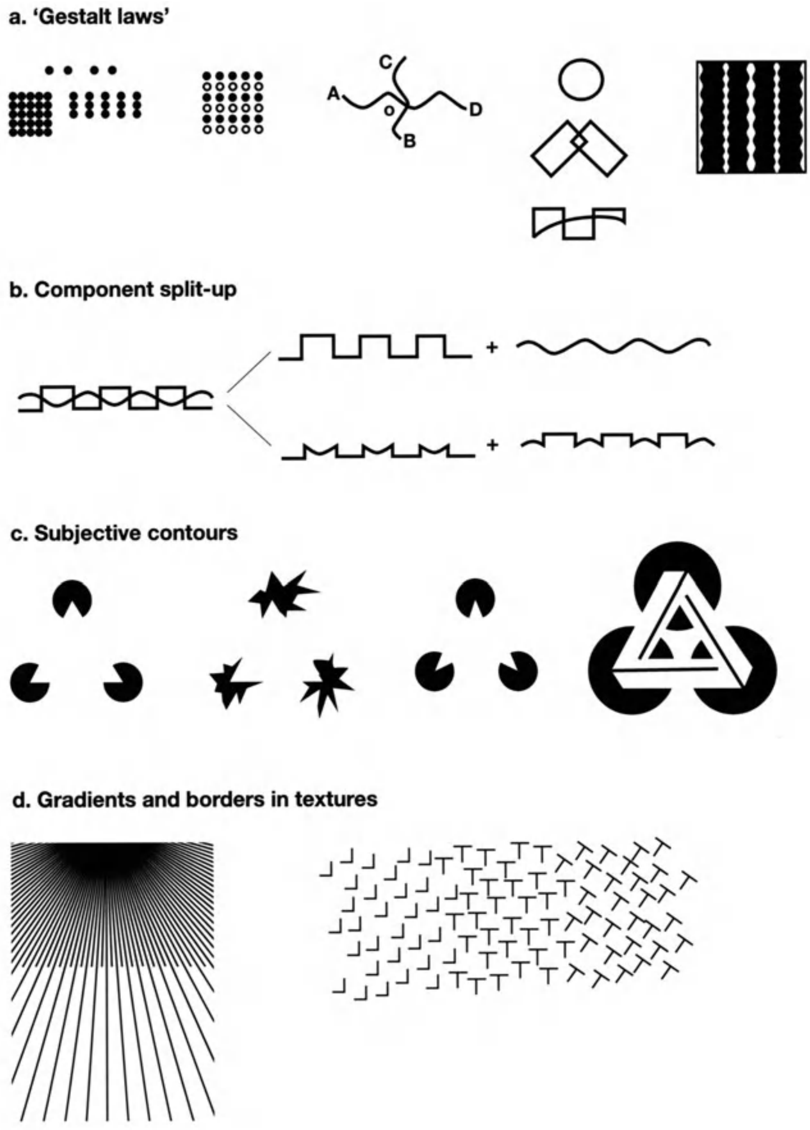

Figure 10.2.1: *A number of principles and phenomena of visual perception (After Glaser, 1997, Figure 4, p. 242. Based on data from Gibson, 1973 and Haber & Hershenson, 1980).*

10.2.2 Visual illusions

In sec. 10.1.2 it is explained that, according to the empirists, all knowledge is the result of sensory perception (Kohnstamm & Cassee, eds., 2002, p. 177; 182). It was mentioned that already Leonardo da Vinci has such notions: "All our knowledge has its origin in our perceptions" (Richter, ed., 1952, p. 4). However, it has also been pointed out that, although sensory perception may provide useful information about the world 'out there', one never can rely on it in order to come to hard conclusions about the outer world. Sensory perception is not a really good help to acquire true knowledge.

In sec. 10.3.1c, it is explained that what we see is influenced to a considerable degree by what we expect to see: the patterns of expectation play an important role in the acquisition of information. In this section, we will discuss these phenomena more in detail, concentrating on visual illusions.

In sec. 10.1 it is mentioned that an object that is perceived can be regarded as a hypothesis, and that once in a while, something can go wrong (Gregory, 1965, p. 14). In the extreme case, a whole world can be created that will be taken for reality. This may occur under the influence of psycho-active drugs or as a result of certain mental illnesses. The result may be a hallucination where the experiences are completely detached from reality (Gregory, 1965, p. 131). Hallucinations are similar to dreams in so far that the person who is confronted with them, is under the impression that it is reality that is perceived. Neither hallucinations nor dreams are experienced as such. It is often assumed that hallucinations and dreams represent the spontaneous activities of the nervous system when it is not occupied by the processing of sensory information. When the spontaneous activities proceed unbridled, full-fledged hallucinations may occur (Gregory, 1965, p. 132).

Contrary to hallucinations, every healthy, normal person can experience visual illusions, where the visual world is distorted. As has been explained in the preceding section, there is a close link between 'Gestalt-seeing' and visual illusions. Therefore, it does not come as a surprise that in many places, visual illusions are also classified as hallucinations.

Visual illusions are very easy to evoke. Many are standard drawing-room pleasantries. No-one is immune from them, even if one fully aware of the fact that it is an illusion and not reality that is perceived. Some of the best-known examples are given in Figure 10.2.2. The figure is based on a number of illustrations from Gregory (1965).

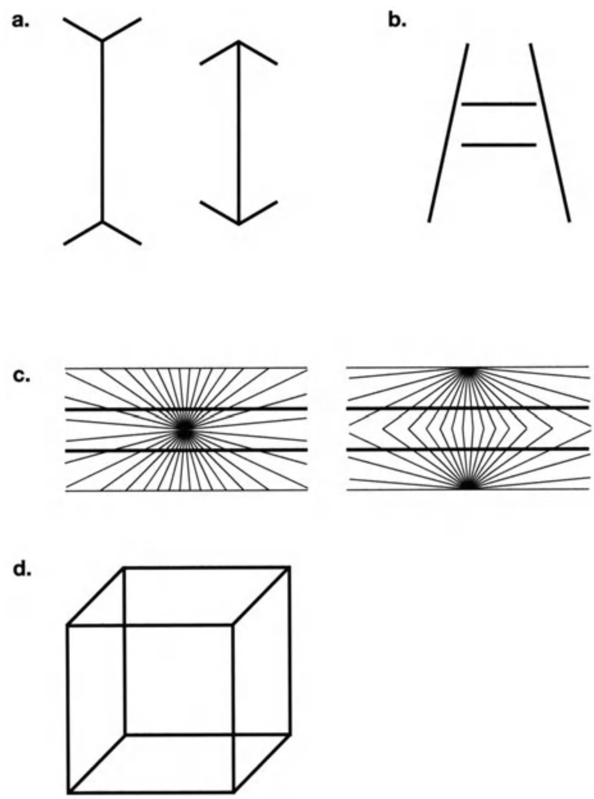

Figure 10.2.2: *A number of well-known visual illusions*

(a) Muller-Lyer
(b) Ponzo
(c) Hering
(d) the Necker-cube

The reason to pay attention to visual illusions is that they once more make very clear that visual information – or any sort of sensory information for that matter – can give only a very rudimentary picture of reality. True knowledge requires a fundamentally different source of information.

10.2.3 Vigilance and attention

(a) Vigilance

The fact whether an object will be consciously observed in the correct way, does not only depend on the visibility of the object, but also on the physiological and psychological state of the observer. Aspects of motivation and of vigilance play a role

(Schreuder, 1998, sec. 8.1.2, p. 134-135). Motivation is, in general terms, discussed in sec. 10.4.1. Vigilance is discussed in this section.

It is customary to subdivide vigilance in 'attention' and 'awareness'. Vigilance is understood as a general, qualitative way to cope with incoming information. This is the sum of all stimuli from the surroundings. A state of high vigilance is called a state of 'arousal'. This has to do with the fact that the observer is prepared to perform the task under consideration. Hence the link with motivation. It has to do with the general physiological condition of the observer in which certain hormones like adrenaline play a role. Attention means the direction of the vigilance. Motivation is the degree in which the observer is prepared to participate in the observation process.

Both arousal and attention depend on the mental and perceptual load. When the load increases, the arousal, in general, will increase as well, but the attention may decrease. In extreme cases, other factors may play a role, but usually they are have little importance for visual perception.

(b) Arousal

Usually, arousal is considered as a physiological aspect. Arousal can be reinforced by certain psycho-active substances like e.g. cocaine or benzedrine. A minimum level of arousal is needed for an adequate task performance. Very few tasks can be adequately performed when a person is in a state of drowsiness, even task that seem to be automatic. An inadequate level of arousal is often considered as an important contributing factor in road accidents (Schreuder, 1985).

(c) Attention

In an important, but rather old, textbook of psychology, attention is described as: "The focussing of perception involving a heightened awareness of a limited part of the perceptual field" (Krech et al., 1969, p. 186). Awareness is described as: "An emotional feeling" (Krech et al., 1969, p. 606). And finally, about emotions, the following is stated: "The hormones of the adrenal gland, the thyroid gland and the pituitary gland are of special importance for emotional response" (Krech et al., 1969, p. 591). In spite of the fact that these descriptions are rather vague, it will be clear that attention has an hormonal as well as an emotional side. Other descriptions may be found in the literature, but usually they are less encompassing. Attention is understood by some as nothing more than a set of passive filters (Gleitman, 1995, p. 227-228). In a comprehensive study on most aspects of psychology, attention, vigilance and arousal are not mentioned at all (Straub et al., eds, 1997).

(d) Perceptual load

Both attention and arousal depend on the perceptual load, but in different ways. When the load is very low, attention is high; there is no competition between different stimuli. When the load increases, attention may stay high, but is will be distributed over different stimuli. In visual perception tasks, many problems can be attributed to a suboptimal choice of the priorities of observation. This will be explained in a further part of this section. An in increase of the load usually leads to an increase in the level of arousal. When the two effects – the decrease of attention and the increase of arousal – are combined, the well-known 'U-shape curve' will result (Brunia, 1979). This is depicted in Figure 10.2.3.

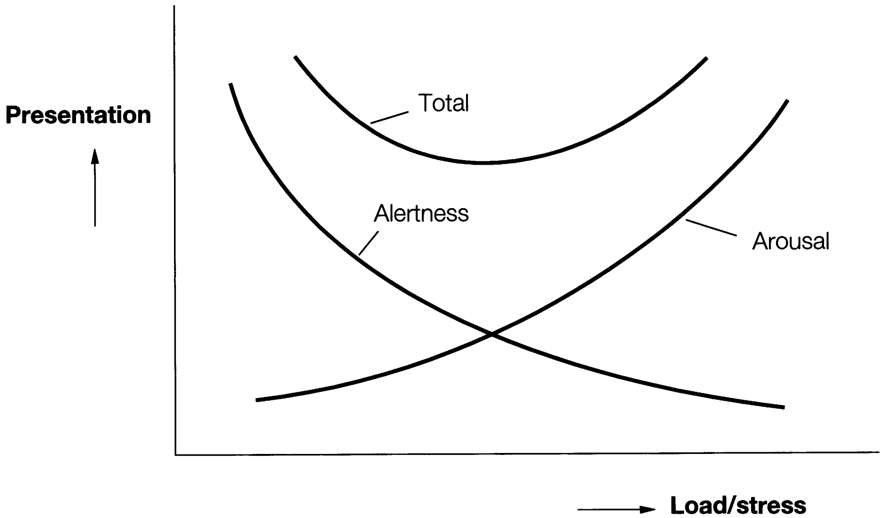

Figure 10.2.3: The U-shape curve: the effectiveness as a function of the load. After Schreuder, 1998, figure 8.1.1

(e) *Priorities of objects*

Not all visual objects are equally important. In car driving, the majority of stimuli has no relevance for the driving task. They only increase the 'noise' (see sec. 14.2.3b). Other objects, however, may carry information or risk. They are called 'visually critical elements' (Padmos, 1984; Schreuder, 1984, 1991). It is a matter of selecting the right priorities for observation to ensure that the visually critical elements are indeed seen properly and in time, and that the irrelevant stimuli are filtered out. Obviously, this is, at least in part, a cognitive task, because it depends on the conditions whether a specific objects is a visually critical element, or just 'noise'.

(f) *Distribution of attention*

Attention is not a constant quantity that can be subdivided at will. For this reason, the method of the supplementary task is questionable in task analysis research (Michon, 1964; Brown & Poulton, 1961; Schouten et al. (1962); Schreuder, 1998, sec. 8.1.3). The matter is questionable, because it is clear that under certain circumstances, the communication channel, that is discussed in sec.10.1.8c, can be 'overloaded', which is of course impossible if it were constant (Roszbach, 1972; McKnight, 1972; Mackie, 1972; Van Soest, 1956, p. 57).

More recently, it is made clear that the direction of the attention is governed by top down and bottom up processes. In road traffic, most decisions are the result of top-down attention processes (Theeuwes, 1992). This means that a car driver makes a decision where to direct the attention. This decision is made on cognitive grounds, and is not much influences by the accidental characteristics of the outer world (Schreuder, 1998, p. 135). As a consequence, objects that are installed with the express intention to attract the attention of drivers, usually are not very effective. In road traffic, traffic signs and general warning signs do not attract much attention (Gundy, 1989).

(g) *The functional field of view*

In sec. 8.2.3c, it is explained that visual observation in the direction of the optical axis of the eye – the foveal region – is different from that in the periphery. This distinction has to do with the anatomy of the eye, viz. the distribution of cones and rods over the retina. There is, however, also a functional distinction. This distinction is sometimes linked to evolutionary processes, leading to a slight gender difference (sec. 8.4).

It has been found that the field of view can be subdivided, in a functional fashion, as follows:
- from the axis to about 2 degrees eccentricity: the foveal observation;
- between 2 and 25 degrees, the near periphery. Observations can be made without turning the eye – the static field of view;
- between 25 and 85 degrees, the periphery. Observations can be made by turning the eye, but not the head – the eye field;
- over 85 degrees, the far periphery. Observations can be made only by turning the head – the head field (Bunt & Sanders, 1973, p. 1a).

These angles represent the maximum for the fields. It can be easily noticed that in practice, most people will turn their eyes or their head at much smaller angles, because that is usually easier to do.

10.3 The visual task in road traffic

10.3.1 Scenes, sequences and objects

(a) *The visual animal*

It is commonplace to remark that 'the human being is a visual animal'. This should mean that life depends on the visual system. Now, life is often characterised as the ability of individuals to adapt to the environment. A variation of this description is that life is the ability of species to adapt to the changes in the environment. Because this Darwinistic idea does not seem to apply to actual species of animals or plants, but rather to variations within species, it seems better to restrict to the first characterization. Adaptation to the environment implies gathering information about the environment. A visual animal is supposed to get this information by means of the visual information transfer system, or, in other words, the visual system. Casual observations suggest that indeed the visual information plays the predominant role in human activities. One may find in the literature remarks like: "in car driving, over 90% of information is visual in nature", but it is difficult to quantify such statements. One reason may be that most human activities are the outcome of decision making processes. The success of these processes depends on a reliable input of information, but they depend more on the quality of the decision making process itself (Schreuder, 1998, sec. 4.1). Before we will discuss the role of visual information, we will deal briefly with the input and output of systems, more in particular of the human visual system. In cases where the systems are not readily available for direct experiments, models are often used.

As is explained in sec. 10.1.4a, a model is a tool that is used to study certain aspects of reality (Schreuder, 1998, p. 95). There are many types of models. The first distinction is between colloquial models and formal models. Colloquial models are just what it says: a model. In formal models, not only the model itself but also the language and the axioms need to be formalized. Then there is the distinction between descriptive models and prospective or predictive models. Descriptive models just give a description of reality. Predictive models allow to make a prediction of reality. Basically, they allow to manipulate the model, observe the outcome and to predict that the 'real' manipulation will result in the corresponding outcome. The advantage is obvious: one may study reality without touching it. Most computer simulation models are of this type. These models are described in some detail in Schreuder (1998, p. 95-96).

(b) The supply-and-demand model

Sanders (1967, p. 15) discerns three classes of models, which he calls 'technological models': the communication model, the feed-back model and the adaptive model. The names indicate nicely what they mean. In fact, these are refinements of the predictive model indicated above.

Schreuder (1970, 1974) introduced the supply-and-demand model for visual information in road traffic. The idea was extended in Schreuder (1988, 1993). Basically, it is an input-output model, a variation of the S-R model that is explained in sec. 10.4.2a. The idea was that road lighting would be only sufficient in quality and quantity if the amount of visual information supplied by the lighting installation surpasses or at least equals the amount of visual information that is needed for safe road traffic participation. The idea was worked out for road lighting but the model is applicable equally well for other types of outdoor lighting – for indoor lighting as well for that matter.

The visual information can be quantified in terms of visibility (Schreuder, 1998, sec. 9.2.2). The concept 'revealing power' was introduced by Waldram (1938) and Smith (1938) and further expanded by Van Bommel (1978) and Van Bommel & Caminada (1982) and by Narisada (1999, 2002, 2003); see also CIE (2002). In North America, the concept of 'Small Target Visibility' is introduced for this purpose; see Adrian (1993), Enzmann (1993), Eslinger (1993), Janoff (1993), Keck (1993) and CIE (1995). The idea was originally introduced by Gallagher et al. (1975) and is based on the ground-breaking work of

Blackwell (1946). See also CIE (1981) and Van Bommel & De Boer (1980, chapter 3.2). Several aspects of revealing power and Small Target Visibility are discussed in more detail in Schreuder (1998, sec. 9.2.2)

The supply-and-demand model looks, in its simplest form as given in Figure 10.3.1.

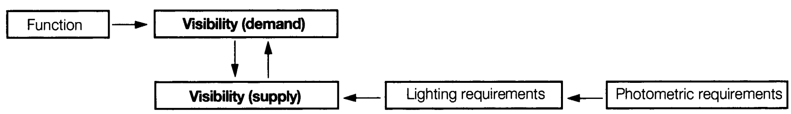

Figure 10.3.1: *The supply-and-demand model (requ. means requirements) (after Schreuder, 1998, Figure 10.1.2*

When thinking in cost-benefit terms, the model can be extended at the side of the functional requirements by the 'benefits', to be expressed e.g. in the cost savings by accident reduction, and at the other end by the 'costs', e.g. the costs of a lighting installation. In this way, the model might look as given in Figure 10.3.2.

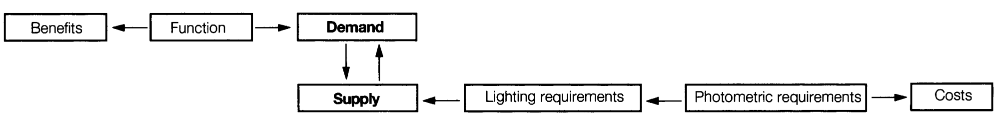

Figure 10.3.2: *The extended supply-and-demand model (after Schreuder, 1998, figure 10.1.2)*

The application of cost-benefit considerations in road lighting as well as in other road safety measures is quite common. See e.g. Schreuder (1998, Chapter 12). A number of more recent papers have been collected in CIE (2001).

(c) *Scenes and sequences*

As is explained sec. 10.4.2, taking part in road traffic as a driver, a cyclist, a pedestrian, or in another way, can be described in terms of a decision making process, where the decision is between a number of alternative manoeuvres. The outcome is the selection of the manoeuvre that will be performed. In the S-D-R process that is supposed to be at work here, the S represents the information – or stimulus – that is required to come to that decision. As is explained earlier, in vehicular road traffic the information is predominantly visual information. We will assume that most information needed for other modes of traffic is visual as well, although, particularly for pedestrians, auditory, and tactile information may be just as important, to such an extent that, given proper training, even visually impaired people may be able to walk unaided, provided the road infrastructure fulfills certain requirements (Schreuder, 1994a). For the sake of simplicity, however, most of the considerations in this chapter are related to car drivers.

The activities that are expected of drivers in order to drive properly and safely, as well as the decision making processes and the information processing that comes prior to the decisions, are commonly brought together in the term 'driving task'. When we use this term, it is implied that the processes themselves may, at least for a large part, apply as well to other users of outdoor lighting installations. In sec. 10.4.3, the driving task is discussed in more detail.

The visual information is derived in part from the surroundings, and in part from the store or memory. In order to be able to make this most appropriate decision, the driver must be able to establish for himself a picture of the surroundings, and more in particular of the conditions as they may be in the near future.

The picture of which we spoke above does not need to be complete: it suffices to know the principal features of it. These principal features are called the 'scene'. In order to be able to look into the immediate future, it is necessary to be able to extrapolate from the immediate past over a period of about equal length. 'Immediate' might mean in this context only a few seconds. Together this is called a 'sequence'. The sequence incorporates the expectations of the driver about the near future.

In secs. 10.4.3e and 10.4.3f, the different manoeuvres for car driving are discussed. The smaller, or elementary manoeuvres are related to the actual handling of the vehicle. A preview time of about three seconds seems to be sufficient in most cases, so that sequences must measure about six seconds. For 'higher' manoeuvres the sequences must be considerably longer; pre-warning signs for motorway interchanges are often set up a distance of two to three km.

The scenes need to be built up, or reconstructed, from a small number of individual elements in the field of view. Not all individual elements are equally important: it is possible to establish an order of priorities in them. The highest priority is given to the visually critical elements: when these elements are not observed in time, it is not possible to built a good scene, and accidents may happen. The manoeuvre that follows determines whether a particular element is visually critical.

(d) Modes of visibility

Usually, visibility is understood as a concept that does not need further consideration, as long as one is able to measure it. This is, for many visual tasks, not sufficient. In fact, it is often useful to make a distinction in different modes of visibility:

(1) 'Simple' observation or detection. This is related to the threshold measurements as are usually made in the laboratory;
(2) Conspicuity. This means the possibility for observation, taking into account all disturbances that are found in the real world;
(3) Recognition. This means the ability to classify the object under consideration in the right class to which it belongs. In most cases, one may recognize objects only if they are known in the first place: recognition presupposes earlier experiences. Adequate

scene reconstruction requires not only detection but conspicuity and recognition as well. It should be noted that the visual system is not just a set of passive filters; that means that one may not simply say: detection > conspicuity > recognition.

This aspect is discussed in sec. 9.1.7, when discussing the detection of point sources and in sec. 14.1.9, when discussing retroreflecting devices.

It is possible to make a crude estimation of the maximum number of visually critical elements in a sequence. The human visual system is able to perform some two to three fixations per second as a maximum, and during each fixation it is not possible to detect more than three to six objects. So each sequence of 3 seconds has to be built on no more than some 18 to 54 visual elements. It should be noted that this pertains exclusively to foveal observation; the peripheral observation cannot be applied, however, for critical observation.

(e) Visually critical elements

The visual scene comprises a large number of objects that possibly can de detected. Most of them are completely irrelevant for the driving task. Examples are things like a distant bell-tower or clouds in the sky. In contrast, a very small number is directly related to the driving past and must not be missed. These are called the visually critical objects. The term implies that dangerous situations or even accidents will occur when such objects are missed. Some examples are the brake lights of preceding cars; hazard warning signs etc. Other objects can be hazards although they need not be critical as regards the visibility. These are called 'dangerous obstacles'. Examples are guard rails, trees along the road etc. Furthermore, there are visual objects that not only are irrelevant for the driving task, but that cause disturbance of the visual task aspects or cause distraction of the driving task. Many are glare sources but also other objects may classify as 'harassing'. Examples are, apart from glaring light sources, advertisement signs along the road, redundant traffic signs etc. And finally, there are many objects that support the visual task aspects without being directly visually critical. Examples are road markings on slip roads, rows of lanterns or telephone poles etc.

The next question is, what elements should be regarded as visually critical. As indicated earlier, this depends on the manoeuvre that is to be made. Presently it is not possible to indicate precisely what visual elements must be seen without doubt. Considerable research effort has been made in this respect; both the systematic observation of driving a car, and the analysis of accidents and 'narrow escapes' were employed. Obstacles that form a hazard for traffic form only a small – be it important – fraction of the visually critical elements.

For the manoeuvres that are descibed in more detail in sec. 10.4.3, the following elements seem to be of special importance:

(1) For keeping the lateral position in the traffic lane: the lane markings and the horizontal general road markings, and the border of the pavement itself;

(2) For keeping the distance to the preceding traffic: obviously the preceding vehicle itself, and more in particular its markings like e.g. lamps and retroreflectors;
(3) For the emergency manoeuvres: a wide variety of objects, like signs and signals on vehicles, pedestrians and cyclists on or near the road, and obstacles like rocks and boxes.

One should take into account that these objects all need to be detected before they can be recognized as visually critical. Such objects are very common on the street, and they are therefore usually not critical at all. This underlines the need for an appropriate setting of the priorities for observation.

(f) The visibility of visually critical elements

It is not enough that the visually critical elements are visible; it is necessary that there is a large chance that they are effectively detected. The probability for an accident is not equal for each visually critical element: the consequences of missing a single road marking stripe are less severe than that of not detecting a pedestrian or a rock on the street. In this, the following aspects come into consideration:
(1) Does the element itself present a hazard, or is it 'only' a signal?
(2) Is the element standing on its own, or is it part of a group of elements?
(3) What are the possibilities to avoid a collision once the element is missed?

In principle, it should be possible to rank all visually critical elements in an order of priority as regards their need to be detected; at present, however, such ranking cannot be given (Padmos, 1984; Schreuder, 1984, 1988, 1998).

In general terms, it is rather simple to guarantee the visibility of the visually critical elements that are placed expressly as such on or near the road. The visibility can be described in rather simple, well-established rules that concern in the first place the contrast between the object and its background, or the absolute light intensity or candle-power when one deals with self-luminous objects like signalling lights. The conspicuity is primarily a matter of the supra-threshold contrast or the relation between the light intensity in relation to the adjoining disturbances. Again a number of 'rules-of-thumb' may be used. It is more difficult to guarantee the recognition: apart from the visibility and the conspicuity, the experience of the driver comes into play. Only objects that are well-known can be recognized. Training, education and information are essential.

It is more difficult to guarantee the visibility of objects that are not placed on purpose on the street. Most important are other traffic participants, and more in particular pedestrians and cyclists. Not only because they are the more 'vulnerable' groups of road users, but also because their means to carry markings and signalling lights are very much restricted. Additionally, one has to deal with all sorts of objects like stones and boxes, and curbstones. During the day they are visible only if the contrast is large enough; at night a general lighting is indispensable.

(g) The role of artificial light

Generally, the visibility of the elements is adequate during the day. At night, artificial lighting is essential. Artificial lighting comes in three types:

(1) Lighting equipment installed on or near the road – the public overhead street lighting;
(2) Lighting equipment installed on the vehicles;
(3) Guidance lighting.

The first gives the better possibilities to guarantee the visibility of visually critical elements. However, this type of lighting is expensive; furthermore, the costs of installation and maintenance are the burden for the road authorities. Vehicle lighting can only be used by vehicles with a considerable energy source, which implies a large engine; it can hardly be used by cyclists and not at all by pedestrians. Furthermore, it is not possible to see the road over a considerable length ahead, particularly if one is blinded by the lights of opposing vehicles. However, the lighting is fairly cheap and the costs are for the road users, not for the road authorities. The third type, the guidance lighting, offers a considerable contribution to road safety but not to the visibility of objects on or near the road. These three kinds of lighting for traffic are discussed in detail in Chapter 12 of this book.

Public lighting is similar to daylight: the light comes from all sides, so that objects may be rendered visible by means of their contrast to the background. This contrast is determined primarily by the illuminance on the surfaces and by the – diffuse – reflection of these surfaces. The luminance contrast is sufficient to describe the visibility as colours and colour differences play only a small role in road traffic.

The visibility of the majority of visually critical elements is guaranteed if the light-technical requirements are fulfilled. Self-luminous and retroreflecting objects have to comply with the packages of requirements that have been set up by the Commission Internationale de l'Eclairage CIE in collaboration with other international agencies like ECE, EEC and ISO. These requirements include luminous intensities, coefficients of retroreflection, colours, dimensions, shapes and arrangements of light signals, traffic lights and markings for roads and vehicles. For public lighting one may refer to the recommendations issued by the CIE concerning the luminance and the luminance distribution of the road surface, the glare restriction and the optical guidance. Many of these rules, standards and regulations are discussed as well in Chapter 12 of this book.

One must keep in mind, however, that even under ideal conditions of lighting and visibility it is likely that many visually critical elements will be invisible – or at least remain unobserved. At present, one cannot be certain whether this is the result of the lack of visibility of the object or of inattention from the part of the observer. But it means that even under ideal conditions, one has to reckon with road traffic accidents that result directly from defective visual input.

On roads without public street lighting, the situation is different. One has to be content with the lighting that is carried along by the vehicles. Pedestrians carry no light, and usually no retroreflectors either. Cyclists may carry lights, but as the available energy is limited, the lights will be only weak. Bicycle headlamps are barely sufficient to light the path immediately ahead, although the modern halogen lamps perform considerably better than the traditional lamps. Cyclist, however, carry retroreflectors abundantly. At the other hand, cars, trucks, motor cycles and mopeds are hardly restricted as regards the amount of energy that is available for lighting. But also for them it is not possible to light the path ahead over more than just a few tens of meters. When the perspective foreshortening of the road scene is taken into account, it is obvious that the road cannot be illuminated at medium or large distances – distances that are directly relevant for fast driving vehicles; areas from which the drivers require visual information. The situation is deteriorated in real traffic even further by the glare from the lights of opposing vehicles. This glare can be avoided only in exceptional cases, e.g. on one-way streets.

Both theory and practice indicate clearly that vehicle lighting is not sufficient for the detection of all visually critical elements. As a result, the accident risk on 'unlighted' streets usually is several times higher than the risk on similar streets with public lighting.

(h) Scenes and sequences for higher manoeuvres

At least three levels of manoeuvres are of particular interest for the description of the driving task:

(1) The level of complex manoeuvres;
(2) The level of elementary manoeuvres;
(3) The level of manoeuvre-parts.

The third one relates to the actual car handling, and can be disregarded here. In the earlier parts of this section, the concepts of scenes and sequences have been discussed for the elementary manoeuvres. A similar reasoning may be used to consider scenes and sequences for higher hierarchical levels of manoeuvres. The main difference is the time scale involved. As is explained in sec. 10.4.3, when considering the different manoeuvres on the level of complex manoeuvres, preview times of several to many seconds are needed for safe driving. For regular driving, values up to 20 seconds are common, whereas for emergency stops, a preview time of 5 to 7 seconds may be relevant. When considering driving on freeways with a speed of about 120 to 130 km/h, corresponding to about 35 m/s. these time intervals mean distances of up to 700 m for regular driving, and up to 250 m for emergency stops. The implication is, as has been pointed out already several times, that the reach of low-beam headlamps, even the most sophisticated systems that are described in sec. 12.2.5, are by no means sufficient to provide adequate lighting. Driving at those speeds requires additional information, like that of overhead road lighting or daylight.

(i) Pattern recognition

Pattern recognition is a rather recent branch of information technology (Backer & Duin, 1989). The concept can be understood, however, much wider than the digital image processing, such as is discussed in sec. 14.5.2. As a matter of fact, the high efficiency of the visual system of animals and humans could never be reached, if not certain aspects of pattern recognition were included in the system. There is obviously some overlap with the Gestalt considerations that are explained in sec. 10.2.1.

One aspect of pattern recognition is to eliminate the inherent 'noise' out of the image. Noise aspects are discussed in sec.14.2.3b. This is called image reconstruction. Another aspect goes one step further: image enhancement may even improve the image (Backer & Duin, 1989, p. 18). This might seem strange, because it seems to imply that information that is not in the received image, is generated. This information, however, stems from the memory data of the total system. Pattern recognition, in the true sense, is to recognize the inherent patterns from within the image.

In the psychology of the visual system, two aspects of pattern recognition are predominant:
(1) The recognition of a specific object, irrespective of the conditions of observation. This implies a classification system that allows to establish whether the object belongs to a specific class of objects. In sec.10.3.1d, this has been indicated as 'recognition'. This type of problems can be studied while using a structural or syntactic model of pattern recognition. Such models show three steps; the data input in the form of the description of the object, the actual classification of the object using the analysis of the syntax and the process where syntactic rules are defined for the recognition process to learn – to improve itself (Backer & Duin, 1989, p. 37). Thus, the data input and the classification by themselves are sufficient; the visual system, more in particular the decision making processes that are based on visual input require a continuous learning process in order to be effective.
(2) The classification of objects according to the class they belong to, irrespective of the details of their size and shape, and irrespective of the conditions of observation. This type of problems can be studied while using a statistical model of pattern recognition. Such models show two steps. The first step is to assume that all possible objects, that are supposed to belong to a specific class, can be represented by a point in a stochastic plane, in such a way that the locus of these points may be used as an approximation to the prototype of the class of objects. This is called the representation in a k-dimensional space (Backer & Duin, 1989, p. 35-36). The second step is the generalization: to assess in statistical terms the distance in the k-dimensional space between the specific object-point and the prototype-point. If that distance is smaller that some, previously and independently, established criterion, the specific object is assumed to be a member of the class of objects under consideration. As an example, we will use the same 'stop' sign as before. It is not sufficient to recognize the sign under all sorts of conditions of weather, lighting and traffic, and to classify it differently from other traffic signs. Also, stop signs of different designs – even unknown designs – must be recognizable, e.g. resulting from changes of legislature or different ways to write the word 'stop'. The last remark is not trivial; in Arabic countries and in Israel, the same stop sign is used but with different lettering.

The importance of these remarks about pattern recognition is that, just as with other aspects of recognition of objects in the surrounding visual field, not all details of all objects need to be visible, and been seen, in order to arrive at the right decision as regards the actions to be taken. An essential condition is, that there has been, in the past, sufficient time and opportunity to train for these decisions: animals and human beings need to train to be effective observers.

10.3.2 Expectancy

In the preceding parts of this section, the scenes and sequences have been discussed while assuming that a straight-forward extrapolation from the immediate will provide adequate information about the future. One may assume that this usually is the case. As a matter of fact, one of the most important and promising considerations in the reduction of road accidents is precisely to reduce the uncertainties that are inherent to the future (SWOV, 1965; Janssen, 1979; Koornstra, et al., eds., 1992; Vis & Krabbendam, 1994; Schreuder, 1998, sec. 8.1.4). In general observations, and more in particular in visual observations in road traffic, the pattern of expectations is of great importance. It is much more difficult to detect objects that are not expected than those that are expected. Much more difficult may mean that there is more time needed, that the luminance contrast or the colour contrast must be larger, etc. In road traffic, important factors are:

(1) Knowing the type of object in general – the overall experience as a traffic participant. Some examples: pedestrians in an urban street, rocks on a mountain road; preceding vehicles on a freeway;
(2) Knowing the situation – the local experience as a traffic participant. Some examples: children at a particular school exit, traffic humps ('sleeping policemen'), a specific, protruding tree.

Over the years, a considerable amount of research has been devoted to this subject (Broadbent, 1958; Norman, ed., 1976; Noordzij et al, 1993). Special attention should be given to the old but still very relevant studies of Griep about the influence of patterns of expectancy on the perception in road traffic (Griep, 1971).

10.3.3 Priorities of observation

(a) Objects and obstacles

In sec. 10.2.3e, it is explained that not all objects are equally important. Many only contribute to the noise – as is used in considerations on signal-to-noise ratios. Other objects are, as is indicated earlier, the visually critical objects. It is a part of the visual task to decide on the right priorities of observation; this means that the methods of visual perception should be such that the right objects are seen and the irrelevant objects are not seen. In other words, it is the visual task of the operator to find the visually critical objects from between the large mass of irrelevant – or even disturbing – objects that all 'cry to be seen'.

One way to find out in practice what type of objects on or near the road deserve the highest priority from the part of the car driver, is to look at the involvement in accidents of different classes of objects. One may call these objects risk-carrying objects. As regards the elementary manoeuvres that have been discussed in an earlier part of this section, the following groups of risk-carrying objects are relevant:

(1) Objects that are part of the road inventory, like e.g. lighting columns, delineators, traffic signs, advance warning signs, traffic signals, etc.;

(2) Objects that are part of the road itself, like e.g. road markings;
(3) Other traffic participants, notably preceding cars.

For manoeuvres that involve evading actions, the following groups of risk-carrying objects are relevant:
(1) Stationary obstacles on or near the road, like e.g. stationary vehicles, rocks and boxes on the road, lost car parts or parts of cargo, but also lighting columns, bridge supports, trees, crash-barriers etc;
(2) Moving objects like other traffic participants, more in particular cyclists and pedestrians, but also intersecting traffic and slow-moving preceding vehicles.

As an example, in Table 10.3.1, an extract is given from the statistical data that are collected each year about road traffic accidents in the Netherlands. The table serves only as an example. The data are a selection of the data over 1988 (CBS, 1989). More recent data are available, but they show the same trends.

Manoeuvre		**Accident type**	
number	**description**	**injury**	**fatal**
1	vehicles same road, same direction	5201	82
2	vehicles same road, opposite direction	3104	147
3 + 4	same road, turn off	8243	153
5 + 6	intersection	12036	299
7	with parked car	1307	25
8	with pedestrian	4054	192
9	object (except 931 and 951)	4308	254
931	crash barrier	549	28
951	loose object on or near the road	240	5
0	one-sided accident (without 011, 021, 022)	847	48
011	skidding on the road	1749	21
021	skidding off the road, straight road	120	3
022	skidding off the road, bend	101	1
	total	**41 859**	**1258**

Table 10.3.1: *Number over 1988 of injury and fatal traffic accidents, according to manoeuvres at the accident (numbers and classes derived from CBS, 1989; after Schreuder, 1998, Table 8.2.4).*

From Table 10.3.1. it follows that more that two-thirds of all injury accidents that occurred in the Netherlands in 1988 were between vehicles that took part in traffic; the majority is between moving vehicles. About 10% of the total number regards pedestrians, whereas more that 20% relate to stationary objects like trees and lighting columns, and to single-vehicle accidents like e.g. skidding. Collisions with 'loose' objects on or near the road occur, however, very seldom – about half a percent (0,57 %) of the total number of injury accidents. This is the category to which stones, rocks and boxes belong. This is important to note, because it is on objects like those that almost all considerations about visibility in road transportation are based (Blaser, 1990; CIE, 1981, 1990, 1992; De Boer, 1951, 1967; Dunbar, 1938; Roper & Howard, 1938; Schreuder (1964). For many decades, the object of $0{,}2 \cdot 0{,}2\ m^2$ did serve as the 'International Standard Object', only to be overtaken by the still smaller 'Small Target' of the STV-system. These 'standard objects' are discussed briefly in sec. 10.3.1b. These objects may serve reasonably well to describe the visual task of a motorist, as 'dangerous obstacles' they are not very relevant. And for other road users they are still too big to represent traffic hazards. Pedestrians, pedal cyclists and motor cyclists are bothered by loose pebbles on the footway or cycle track, or by raised pavement markers. Sporadic research has been made on these subjects (Anon., 1987; CIE, 1988; NSVV, 1983; OECD, 1971, 1975; Schreuder, 1980, 1981, 1986; 1989).

(b) Warrants for road lighting

When considering road lighting, the first and usually most important – and most costly question is whether a particular stretch of road requires lighting. The usual expression is that the stretch of road requires 'warrants' lighting. For this, the warrants for road lighting are considered. It has been generally accepted that the decision to light a road section or not, is for the politicians to make. The lighting profession may help to find the answer for this question. One of the few systems to set up warrants for lighting as a road safety measure has been given by Walton & Rowan (1974). They proposed to express in symbolic form the relation between road accidents (A), the traffic comfort (C) and the road and traffic parameters (P_1; P_2;...P_i....) as follows:

$$A = f_1\left(a_1 \cdot P_1; a_2 \cdot P_2; ... a_i \cdot P_i; ...\right) \qquad [10.3.1a]$$
$$C = f_2\left(b_1 \cdot P_1; b_2 \cdot P_2; ... b_i \cdot P_i; ...\right) \qquad [10.3.1b]$$

in which f_1 and f_2 are different functions and a and b are weighing factors. With the help of this sort of formulae one may set up warrants for road safety measures. A problem is that some of the 'functions' defined by Walton & Rowan cannot be quantified. So the method leaves room for 'gut feelings' and political judgments. In spite of that, the method is, in an adapted form, still used in the USA (Stark, 1998).

More common is to use cost-benefit analyses. The data are more easy to get, but they can include only monetary aspects or aspects that can be expressed in monetary terms. Expressing road accidents in monetary terms is difficult but possible; expressing driving comfort or subjective safety in monetary terms is hardly possible at all. What can be done is to make a comparison between road safety measures. If two measures have the same safety benefits and they have different costs, the comparison can be made accurately, even if it is not possible to express accidents in money. If there are different safety benefits as well, as is usually the case when a number of alternative safety measures are considered, an estimate of accident costs is necessary. On a small scale, cost-benefit comparisons have been made in the selection of road safety measures. When a number of safety measures compete for a limited budget, the outcome of the exercise will be that these measures are listed according to their priority, expressed in their respective cost/ benefit ratio (Elvik, 1995, 1996; Flury, 1984, 1995; Schreuder, 1993, 1998, 1998 b,c).

(c) The 'break-even-point'

The cost/benefit ratio indicates in how far a road safety measure pays for itself, the costs being those of the measure, and the benefits the costs of the accidents that are saved by the measure. In the following, a brief discussion on the cost/benefit aspects of road lighting will be given, where we will touch upon the situations in countries with different degrees of industrialization. The situation in the Netherlands in 1990 will serve as the starting point of the discussion. The data stem from Schreuder (1994b, 1995). The analysis follows from Schreuder (1998, Chapter 13; 1998a).

The total costs in 1990 of road accidents were estimated at about Euro $6 \cdot 10^9$ (COST, 1994; Flury, 1990, 1995, Appendix 2). The total costs per fatality are about Euro $2 \cdot 10^6$. This value is composed of two parts: the direct material costs and the indirect material costs (hospitalization, loss of labour etc). The costs of road lighting are for a two lane, two way rural trunk road with a design level of about 1 cd/m^2, about Euro 10 000 per km per year. Here again a part is materials and a part is wages. Further, it was found that about 1/3 of accidents happen at night and that 'good' road lighting might save 1/4 of that – combining to an 'efficiency' of 0,08 (Schreuder, 1998, Chapter 11).

The number of vehicles is about $6.5 \cdot 10^6$. The number of fatalities was about 1300. This leads to a number of $2 \cdot 10^{-4}$ fatalities per vehicle per year. Furthermore, is was found that cars travel each about 15 000 km per year. The cost/effectiveness of road lighting can be assessed as follows: the costs of accidents is, in a first approximation, directly proportional to the traffic volume, the road lighting is, again in a first approximation, constant. So there is a number of vehicles per day per km where the costs of saved accidents ('benefits') surpass the costs of lighting ('costs'). One might call that particular traffic volume the 'break-even point'. For the Netherlands, the break-even point for two-way two lane rural trunk roads with a design level of about 1 cd/m^2 is calculated as follows:

- the costs per fatality are: $2 \cdot 10^6$ (Euro);
- per veh.km per day this is: $2 \cdot 10^6/15\ 000 \cdot 365 = 0{,}36$ (Euro);
- taking account of the efficiency of lighting, the costs of accidents saved by good lighting per veh.km per day is about 0,03 (Euro);
- for n vehicles per day, it is $n \cdot 0{,}03$ (Euro) per km per day;
- the costs of lighting are 10,000 Euro per year per km, or about 27 Euro per km per day;
- the break-even point is where the two are equal: $n \cdot 0{,}03 = 27$, or $n = 900$.

It should be noted that this number differs considerably from the number given by Schreuder (1998) as a result of different assumptions and a different assessment of parameters. The same holds to a certain extent for the data given in the draft for a CIE-Guide for road lighting in developing countries (CIE, 1998). This might suggest that the values given here, particularly as regards their absolute value, are not more than approximations.

(d) The 'break-even point' of good lighting for developing countries

When one considers the break-even point for developing countries, two aspects must be taken into account: the number of fatalities per vehicle per year and the influence of the GNP on the wages-part of the costs of accidents and of lighting.

Although the data on the motor park and on accidents on a world-wide scale are notoriously inaccurate, there are suggestions of a relationship between the number of accidents per vehicle per year, and the per capita gross national income. The relationship is quite clear: poor countries have 10 to 100 times more fatalities per vehicle as affluent countries have (CIE, 2003a; Schreuder, 1998c). Some data are given in Table 10.3.2.

Countries	Income group	GNP	Fatalities per veh. per yr.
Industrialized	high	23 090	0,00028
Developing	upper middle	4370	0,00118
	lower middle	1590	0,00214
	low	300	0,0098

Table 10.3.2: *The relation between the GNP and the fatalities per vehicle per year*

In Table 10.3.2, countries are classified according to their GNP per capita in US$ (Weighed per income bracket; based on data from Anon 1995b; Table 1 'Basic indicators') and fatalities per vehicle per year (based on data of IRF, 1996).

It should be noted also that there is a very wide range in this relationship: in the same income bracket, the ratio may vary from a factor of 5 to a factor of 50. In order to get a better impression, the average values for four income groups have been determined in Table 10.3.3. Data are available for about 20 countries per income group. Details are given in Schreuder (1998c).

In order to estimate the values of the break-even point for different income group brackets, a number of further assumptions will have to be made. We will assume that the cars drive an equal amount in each country (15 000 km per year). Further, we assume that 1/3 of the costs of accidents are direct material damage costs. We also assume that 1/3 of the direct material costs both regarding accidents and regarding lighting represent equipment that has to be purchased abroad and is directly related to world-market prices; the other 2/3 is wage-related and is proportional to the GNP. This ratio is, however, not important as it will be canceled in the cost/benefit equation (it shows on both sides of the equation). Furthermore, we will assume that the percentage of night-time accidents and the efficiency of the lighting is equal for all countries.

The assessment of the break-even point as given for the Netherlands, has to be adapted in two ways, if we want to apply it to developing countries. First, the benefits are only 1/3 of that calculated for the Netherlands. That means that the break-even point for the highest income bracket would be $3 \cdot 900 = 2700$. For other income brackets, the value is directly proportional to the per capita GNP. See Table 10.3.3.

Countries	Income bracket	GNP	Break-even point veh. per day
Industrialized	high	23 090	2700
Developing	upper middle	4370	511
	lower middle	1590	186
	low	300	35

Table 10.3.3: *The break-even point for good lighting in vehicles per day for different countries (different GNP-brackets).*

10.4 Motivation and decisions

10.4.1 Motivation

(a) A description of motivation, motives and arguments

For people, just as for other animals, it is normal to act: they are active creatures. However, behaviour seldom is random; people usually have a reason to undertake some activity. Usually, there is a motive. Often, the motive has to do with the outcome of the action: many actions are goal-oriented. Not all, though. There are many activities that are undertaken just for the sake of the action itself.

Here, some definitions seem to be useful. In colloquial language, motivation is understood in two ways:
(1) The reason why somebody does something;
(2) The meaning behind the action.
Trying to reach a definition is made difficult because in colloquial language, but also in the psychological literature, the terms motivation and motive are often used as if they do mean the same. We will use here the descriptions as they are given by Drever. In general terms, a motive is understood as: "An affective-conative factor which operates in determining the direction of an individual's behaviour towards an end or goal, consciously apprehended, or unconscious" (Drever, 1968, p. 178). Motivation is "the term employed generally for the phenomena involved in the operation of incentives, drives and motives" (Drever, 1968, p. 178). Motives are the individual arguments to do something, whereas motivation is the general term for the complete complex involved. These are similar to the concepts that are introduced – without any foundation – by Krech et al. (1969), where 'motives' are the drives and 'motivation' the general concept.

We will also meet the reasoning post-hoc: the stories that are invented after the decision has been made, but before the action is performed, the stories that are invented so that the motivation looks good. "The motivation follows the action" (De Bono, 1969). There is no proper term for it; we will use, if required, the term 'argument' for that.

Motivation is particularly relevant, as it may provide the reasons that people act the way they do; these include one of the most intriguing riddles in human nature that people do things that hurt others, and even more so, often do things that hurt themselves. Aggression is one of them.

Motives are not always rational or even conscious. The reasons or arguments that are given after the action, are, however, usually just that. Usually there is time enough between reaching a decision and the beginning of the activity, to think of all sorts of 'arguments' that are, or at least seem to be, rational.

Motivation is a standard aspect of almost all psychological theories. A survey of most aspects that are particularly relevant for road traffic is given by Schreuder (1973).

(b) Studies about motivation

When one wants to restrict oneself, on methodological grounds, to the study of aspects of behaviour that are directly observable from outside of the individual, like the behaviorists pretend they are doing, there is no place for a theory of motivation, nor any need for it (Hebb, 1958), p. 175; Skinner, 1965, 1972; Sanders, 1972). A motivational construction "helps to account for behaviour more easily" (Cofer & Appley, 1964, p. 1.). Because "Scientific psychology, as currently defined, studies behaviour, a scientific study of behaviour must either stem from or arrive at a set of principles (or a system) in the context of which individual events are predictable. There are many causes of behaviour and motivation is only one of them" (Cofer & Appley, 1964, p. 1, 3, 11). This would mean that motivation is not open for psychological-scientific research (whatever that is supposed to mean). However, "Behaviour is a response to disequilibrium" (Cofer & Appley, 1964, p. 11). This implies that there is a stimulus-response situation, as is described in sec. 10.4.2a. All behaviour then seems to be the result of some sort of physiological discomfort, or "biological primitive want that results in drives" (Hebb, 1958, p. 155). "The conception of motivation adds nothing, has no explanatory value, in the understanding of reflex activity" (Hebb, 1958, p. 175). According to others, human behaviour can be described only in part – in a very small part – in terms of conditional reflexes (Giorgi, 1970, p. 83). In sec. 10.1.9, when discussing conscience, is as been explained that the human mind is much more than just a bunch of conditioned reflexes.

(c) Some characteristics of motivation

There is no generally accepted theory of motivation; it is often stated that each psychological theory has its own theory of motivation (Cofer & Appley, 1964, p. 4). There is one thing in common, however. The theories all try to explain human and animal behaviour. In sec. 10.1.9, where different aspects consciousness are discussed, the instinct is mentioned as a source for the drives – or as motives. Closely related to this is the theory of Freud, where it is stated that the source of it all is to satisfy internal drives (Graumann, 1969, p. 16; Fletcher, 1968, p. 173).

Motivations have to do with tension in two ways: there are tension-raising and tension-reducing motivations (Krech et al., 1969, p. 498). The concepts are derived from Maslov (1954, 1968). However, in traditional psychological textbooks, almost all attention is devoted to tension-reducing motivations, whereas there tension-raising motivations are often completely disregarded (Hebb, 1958). The latter, however, are predominant in all sorts of risk-taking. As an example, since the Mount Everest was climbed in 1953 for the first time, well over one thousand people have reached the summit. About 175 people have died in the process. See e.g. Hillary (2000).

Affects can, by means of a some preparation, change suddenly in will-acts (Graumann, 1969, p. 14, quoting Wundt, 1908, p. 219). Will – or volition – is, as is explained in sec. 10.1.8.e, one of the four psychological functions. These acts of will are directly preceded by changes in feelings, in emotional contents or in interpretations that are called 'motives' by Wundt. This idea comes close to the Stimulus-Response model that is explained in sec. 10.4.2a. According to this view, the motive is the incentive for an act of will.

This idea is followed up by De Hoog (1970). A clear distinction has been made between motive and motivation. The first concerns opportunistic aspects, whereas the second includes elements of impellents. Motives are related to the biological life functions, whereas motivations are related to the conscious existence. Motivation is a conscious process that only occurs when there is a clear fascination, that is, an intentional interest.

(d) A classification of motives and motivations

Establishing a classification of motives is made difficult by the fact that the different theories about motivation, as far as they exist, do not very well agree. Two aspects are clear, however. First, the most direct, or primitive, motivations are related to the physical condition, where a physiological equilibrium seems to be more important than a minimum in energy use. This leads to demands concerning oxygen, water, food, and the maintenance of the normal bodily temperature (Hebb, 1958, p. 155). There is, however, some disagreement in which way these primitive demands can – and must – be expanded. Often, the need to copulate, the care of the young, and the need to avoid injury are added (Hebb, 1958). A further possible extension is the demand for power, that in itself may lead to self-gratification (Mulder, 1972, p. 15, quoting Hobbes, 1651, Nietsche, 1887a and Sullivan, 1947, p. 6; 120). Sometimes, even more items are added, like e.g. social desires – humans cannot survive without help from others, and constructive drives like creative and intelligent actions (Creedy, 1939). Although these aspects are undoubtedly important when considering motivation, it seems that they are more complex than that they should be classified as 'primitive'.

The second aspect on which many theories seem to agree is that, at the other end of the scale of human activities, human beings tend to spend a lot of time and effort on enterprises that, when finished, produce not the slightest advantage or profit, leave alone that the result can be described in terms of some physiological parameter. One may find that the people concerned, go on with their efforts even when they are certain that the goal never will be reached. As has been mentioned in an earlier part of this section, some motivations can result in a high personal risk for injury and even death. Several psychologists avoid the subject (Hebb, 1971). Others play down the importance of these motivations (Vernon, 1971; Krech et al., 1969, p. 497). According to Freud (1916), these motivations are nothing but sublimated drives. For more details about this classification, see Schreuder (1973, section 1.2.3).

A proposal for a classification of motivations is given in Table 10.4.1. This proposal is based on the fact that motives can be subdivided as aimed at:
(1) Biological orientation;
(2) Existential acceptation;
(3) Social actualization.
This subdivision is given by Schreuder (1973) and is based on unpublished lectures of De Hoog (1970). The classification is made on the 'Response' (as in Stimulus-Response). It refers to the levels of consciousness that are discussed in sec. 10.1.4d.

Response level type	**Biological instincts** cybernetic		**Existential motives** opportunistic	**Social motivation** creative
feed-back	open loop	closed loop	closed loop	closed loop
tension	reduction	increase	increase	increase
species	rutting	selection of mate	gaining leadership	group activities (family)
self	eating etc.		self realization	works of art

Table 10.4.1: *A classification of motivations. Based on Schreuder (1973) and De Hoog (1970).*

(e) Risk homeostasis

A few words about the concept of risk-homeostasis. The idea behind this concept is that improving the safety of actions automatically will be followed by an increase in risk taking to such an extent that the outcome is always exactly zero, whatever measures are taken; hence the term homeostasis (Asmussen, 1972; OECD, 1972; Wilde, 1982). Experience shows that there indeed is such an inverse relation. However, it is difficult to estimate the extent of this negative feed-back, because the accident data already contain the effect. So, if the result is zero it might mean that the safety measure has no effect or that the homeostasis is perfect. In some cases, it is clear beyond doubt that, on other than statistical grounds, the measure must have a positive effect, whereas the net effect is about zero. This is the case for drainage asphalt (Tromp, 1993; 1994). It has been suggested that the reduction of splash-and-spray, combined with the reduction of the risk of hydroplaning enticed the drivers to drive faster, which possibly results in more accidents. Unfortunately, the researchers did not take the trouble to measure the speeds! Some accident countermeasures have even a negative total effect, so that the increased risk taking more than counteracts the safety benefits. A well-known case is the introduction of ABS (Anti-blocking systems) in passenger cars (OECD, 1990). It seems that the same was found when introducing mandatory seatbelt use. It has been suggested that this negative effect is linked in particular with newly introduced accident countermeasures. This suggestion has never been tested seriously.

More important for the subject of this book are those accident countermeasures where the net effect is positive, notwithstanding any possible increase in risk taking. What we mean here is the effect of road lighting on road accidents, that is discussed in detail in sec. 12.1.1, as well as the effect of road lighting on crime and street violence, that is discussed in detail sec. 12.1.2. In both cases, the net result is usually – be it not in all individual studies – positive, even when the negative feed-back of risk taking is taken into account (Aelen & Van Oortmerssen, 1984; CIE, 1968, 1992a; De Clercq, 1985, 1985a; Elvik, 1995; Fisher, 1973; Hargroves & Scott, 1979; OECD, 1971, 1975, 1976, 1980; Schreuder, 1983, 1985, 1988a, 1994c, 2000; Vis, 1993, 1994).

10.4.2 Decision making models

(a) S-R and S-D-R models

As described briefly in Schreuder (1998, p. 138) the most simple model of a decision making process is the simple S-R model, the notorious Stimulus-Response model of the behavioristic theories of old. Although behaviorism as an ideology is definitely dead, the S-R model is still very useful to describe automatic behaviour (Bohm, 1963, p. 206). It can describe the behaviour of many automatic 'robotic' machines (see e.g. Anand & Zmood, 1995; Bok, 1958; Wiener, 1950, 1954). However, when decisions play a role, these have to be an integral part of the model. Schreuder (1973) introduced for this the S-D-R model, where D signifies the decision. In order to be able to describe more complex decisions, two more elements have to be added. The first is the memory, where the desired outcome of the process is compared to the experience gained in earlier, similar situations. The second is the feed-back loop, which allows to compare the outcome of the decision process to the objectives of the process. Details are given in Schreuder (1970, 1970a, 1972, 1973, 1977) where special attention is given to decision processes that are related to driving a car. Decision making in relation to policy making in business and in government is discussed in Bross (1965) and Gore (1968).

Assuming that the input and the output (S and R respectively) are related to the same senses, in case of car driving to the visual sense, it is feasible to link the output to the input. In this way, the model gets a cyclic structure (Schreuder, 1973). Furthermore, decisions in driving take place on different levels (Schreuder, 1974, 1998). A number of cyclic decision making models can be put one on top of the other, forming something that looks like a barrel, hence the term 'barrel-model' was suggested (Schreuder, 1973). According to the usual physical aspects of time that are described in sec. 10.1.5a, exactly cyclic happenings are not possible.

The cyclic models, including barrel-model, are conceptual models that do not describe the time aspects of happenings. Therefore, they may contain loops, e.g. feed-back loops etc. These models form a part of a research area that did receive a lot of attention in the 1970s and 1980s: the 'Analysis of the driving task' (Griep, 1972; Janssen, 1986).

Because decision making processes are studied in relation to human behaviour, the study of decisions was restricted to those that lead to actions. Decisions that did not lead to any activity were disregarded (Van Schilfgaarde, 1968; Toda, 1972). Although the decision making processes were considered as essential in the driving task analysis, still they did not get much explicit attention. Probably the reason is that decisions are made within the 'black box' that, according to behavioristic doctrine, could not be opened and even, according to some, were actually empty (Guthrie as discussed in Thomson, 1968, p. 229; Hebb, 1958, p. 2; Sanders, 1972). In this respect, it is interesting to refer to the much-quoted conference that was organized by OECD in Rome in 1972. The proceedings of that conference offer a comprehensive collection of traffic participation models (OECD, 1972). Although a number of presentations that were made during that conference, deal in considerable detail with decision making processes, the sub-heading 'Decision' is missing. Some of these important and often even ground-breaking papers are those by Asmussen (1972), Böcher (1972), Mackie (1972), McKnight (1972), Older & Grayson (1972) and Price (1972).

(b) Feed-back models

The second point, introducing a feed-back loop, is common in all technical control systems (Anand & Zmood, 1995). A feed-back loop signifies the essential difference between an 'open loop' and a 'closed loop'. It may be noted that 'open loop' systems actually do not contain any loop at all.

In Figure 10.4.1, an open loop model for decision making is described graphically. The graph depicts a S-D-R model where 'information' represents the stimulus and 'activity' the response. As is explained earlier, 'experience', or memory, is added.

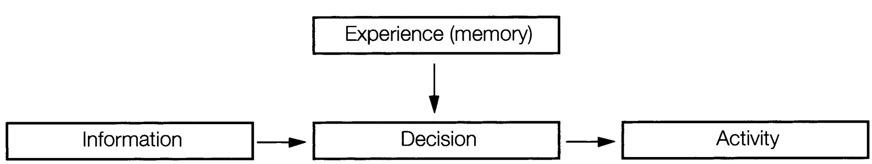

Figure 10.4.1: *An open loop model for decision making*

Control systems must be closed loop systems, otherwise the result or output cannot influence in the input.

In Figure 10.4.2, a closed loop model for decision making is described graphically. The feed-back loop is added to the earlier graph. Again, the graph depicts a S-D-R model where 'information' represents the stimulus and 'activity' the response, with 'experience' added.

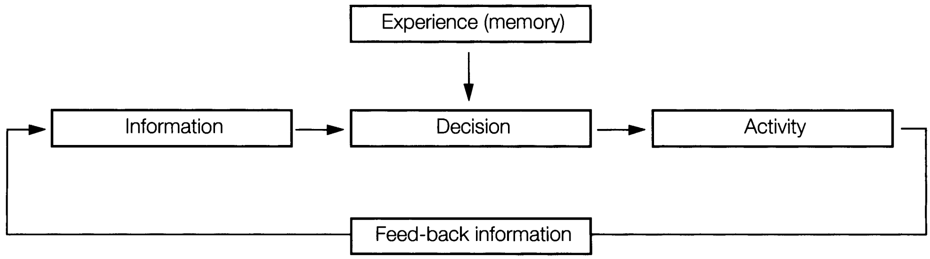

Figure 10.4.2: *A closed loop model for decision making*

A classic collection of this material is given in the proceedings of a series of NASA-sponsored conferences (Anon., 1969). A contribution of major importance was that of Krendel & McRuer (1969). See also Barwell (1973), Broadbent (1958) and Krendel & McRuer (1968). The feed-back loop in decision making models for the description of the driving task were introduced by several of the speakers who attended the OECD conference in Rome (OECD, 1972). A survey is given in Schreuder (1973). A special case is the supply-and-demand models introduced by Schreuder (1970, 1970a). These are discussed in the sec. 10.3.1b, particularly in the Figures 10.3.1 and 10.3.2. See also Schreuder (1991, 1994d, 1985b, 1998).

(c) *Reactive and pro-active decisions*

Decisions fall into two main groups. The first group is the decision simply to react to happenings in the outside world. In terms of the descriptions given earlier in this section, they are open loop systems: the outcome has no influence on the input. They are called 'reactive decisions'; they often have the characteristics of conditioned reflexes. As is explained in sec 10.4.1c, in psychology they are often called stress reducing, or tension reducing, motives or actions. Often they have a heuristic character. Most of the actions in traffic belong to this group. They depend on experience, and they can be improved by training. The second group is the decision to select a certain strategy. In terms of the descriptions given earlier in this section, they are closed loop systems: the outcome has a definitive influence on the input. As is explained further-on, they look like the decisions made in steering a vessel: a course is set, and deviations from the course are corrected well before the risk of collisions or of grounding is acute. They are called pro-active decisions. As they depend mainly on cognition rather than on experience, they can be improved primarily by education and schooling.

Allowing for the feed-back is essential when we think about the policy implications of decisions. Policy might mean the actual activities of politicians and legislators but also the decisions of a car driver or the helmsman of a sailing boat. In steering or 'governing' a State, a car or a boat, the first thing to do is to define the goal of the activity – of the trip. Then, from the goal, the direction in which one must travel to arrive at the goal must be defined. This is sometimes called the 'Sollwert'. Then, after setting off, during the whole trip, the course must be checked at regular intervals. This checking is done by comparing the values of the direction at the specific time (the so-called 'Istwert') to the Sollwert. If there is a discrepancy greater then a predetermined margin, the course must be corrected. This is the feed-back loop. The wording of this reminds us of steering a sailing boat; the idea can be applied to all trips, literally or as a figure of speech. Comparing the Istwert to the Sollwert at regular intervals and correcting the course accordingly is pro-active control; just waiting until the trip is concluded and, in case the goal is missed, to embark on a new trip to reach the goal this time, is reactive control. It is obvious that pro-active control is to be preferred over reactive control. However, this involves not only deep insight in the processes at hand, but also long-term planning – activities in which politicians and legislators nor car drivers do not usually excel! The whole process is described in some detail in Schreuder (1985a).

(d) Bottom-up and top-down models

Finally, one may make a distinction in bottom-up and top-down models. In bottom-up models, the information is gathered at the 'grass roots' and in a process of abstracting transferred upwards towards the actual decision making level. In top-down models it is assumed that the decision maker has a broad plan how to decide; the actual decision is just an example of many possibilities. One may recognise here the steps of inductive reasoning and of deductive reasoning; in view of the use of feed-back as discussed in the preceding sections, it is clear that following a sequence of the deductive and inductive steps is to be preferred – just what is usually suggested in experimental research as well as in logical reasoning. In the wake of the doctrines of reductionism, usually a preference for the bottom-up model was expressed. Careful experiments did show, however, that for visual information processing, the top-down models seem to correspond much better to reality (Theeuwes, 1992).

10.4.3 Preview and the driving task; foresight in driving

(a) Looking ahead while driving

In the following part of this section, we will discuss several aspects of what is usually called 'the driving task'. The driving task requires a considerable amount of information, for the greater part visual information. We will focus on factors and measures for improving the visual information; emphasis will be placed on the artificial road lighting and on the road markings. The considerations explained in this section are based to a large extent on Schreuder (1991, 1994d,e), where more details can be found.

The basic need is to look ahead while driving. The term coined for this is 'foresight'. It should be stressed here, that the idea of 'foresight' primarily puts emphasis on only one of the different aspects of the driving task or the preview mode; another major aspect of the driving task consists of car following or the pursuit mode. Car following is dealt with, but only as far as the foresight aspects are concerned. The discussion is on foresight; it is not meant to be a comprehensive discussion on all aspects of the driving task.

'Looking ahead' might seem an over-simplification. In complex traffic situations, 'looking ahead' can be a complicated matter where a number of different objects need to be seen. Still, the concept of 'foresight' can be used, because there is only one driving task, in spite of the fact that the visual field is complex.

(b) Road safety aspects

Road traffic basically is nothing but the set of activities that is aimed at reaching some destination. All disturbances that may lead to reaching the destination later, with more difficulty, or not at all, are unfavourable for the purpose of the traffic, and should be avoided as far as possible. There is some likelihood with health: the normal state is the healthy one, and disturbances are illnesses. Using this analogy, normal road traffic is often compared to healthy traffic, and disturbances like traffic jams and accidents are compared to illnesses.

Disturbances always have the aspect of a conflict: there is always a conflict of interest between the healthy traffic and the disturbance. Conflicts can be classified, and be placed in an hierarchy, beginning at the lower side with simple meetings; higher up there are severe conflicts that disturb the flow of traffic, and still higher one finds the accidents. It is customary to place fatalities at the top of the hierarchy.

This hierarchical approach has two important consequences. The first is that the frequency of occurrence diminishes while going from low to high: the number of meetings is much higher than the number of fatalities. The second is that there seems to be a gradual increase in severity going from the one extreme to the other. These two aspects are important when one tries to use conflicts as an alterative measure to characterizse road safety instead of accident statistics. The conflict method as a tool in road safety research is explained in detail in Kraay (1979).

These considerations are essential when one tries to identify the basic concepts of the present road traffic system as compared to the system of other modes of transport. Rail traffic and civil air traffic are essentially non-conflict modes of transport. This does not mean that there are no conflicts or accidents; what we mean is that the system is designed in such a way that conflicts are absent; in other words, as long as the system works as designed, there cannot be any conflict and therefore no accident. There is no possible way that two trains, or two planes, can occupy in a way that is accepted by the system, the same rail or air space. The reasoning is that, when no conflicts can occur, a *fortiori* no accidents are possible.

Road traffic, and street car, or tram, traffic, and naval traffic as well for that matter, operate on a completely different principle. Conflicts are accepted. It is assumed that the traffic system, or the – collective of – the traffic participants will operate in such a way that, although conflicts may be frequent, accidents will be avoided – or rather, will be limited to a socially acceptable level.

(c) Task aspects

The set of decision making processes that has to be followed by a car driver is usually called the 'driving task'. As indicated above, the usefulness of the activities are essential for our considerations; this means that taking part in traffic is done not random, but to some purpose. The road traffic system is considered as being essentially functional. As is explained in secs. 10.4.3e and 10.4.3f, the driving task is performed on different levels; these levels are characterised by different manoeuvres.

Obviously, the purpose of taking part in traffic is to reach the trip destination. It is convenient to subdivide this purpose in three distinct goals, although in reality they are very much intertwined. The goals each have their sub-tasks. The three sub-tasks are:
(1) Reaching the destination by selecting and maintaining the correct route;
(2) Avoiding obstacles while under way towards the destination;
(3) Coping with emergencies while performing the two other sub-tasks.

The sub-tasks are quite different in nature. The first sub-task – the selection and maintenance of the route – involves decisions that are made for a large part even before the beginning of the trip. When the decisions are incorrect, the result is that the destination will not be reached, or not reached in time, resulting in loss of time and/or money – and often a lot of frustration. The loss may be called 'economic'.

The second sub-task originates while driving. It refers to discontinuities in the run of the road, and to the presence of other traffic participants. The decisions relate to the avoidance of the hazards that are presented by the discontinuities and the other participants. When the decisions are incorrect, collisions may result. Apart from not reaching the destination with its economic loss, the consequences are further the losses of goods and properties, and maybe even injuries, or even fatalities. The consequences are of a road safety nature. It should be noted that drivers often choose another route when they expect to meet discontinuities or traffic participants; in this way, the decisions on the higher level are influenced.

In both cases, the essential feature is that there is adequate time to acquire and process the necessary information, to make the decision, and to execute the manoeuvre. In many instances, this is not the case. Unexpected and unwanted emergencies may arise, that require a fast reaction of the driver in order to avoid collisions. This is the third sub-task: coping with emergencies. Usually, the information on which the decision must be made is inadequate, incomplete or even wrong, the time for making the decision is very short, and the time to execute the manoeuvre is often simply not sufficient.

(d) Foresight

Taking action costs time. First, the visual observations must be made; after that, the decision must be made, and finally, the action must be performed. It is customary to discern the following time-elements:
(1) Detection time;

(2) Reaction time;
(3) Decision time;
(4) Action time.

The time required for the action will includes the time needed to prepare for the action, e.g. the shifting of the foot from the accelerator to the brake pedal. See also Eckert (1993, p. 102-106). Obviously, a decision can only be adequate when the time to make it, is available. This implies that the object that make the manoeuvre necessary, must be visible at a distance large enough to make the observations and the decision, and to execute the manoeuvre. The required time interval is described as 'foresight'. Foresight can be expressed in distances or in time intervals, because, when the driving speed is known, the distances and the time intervals can easily be converted into each other.

(e) A hierarchy of manoeuvres

Manoeuvres can always be considered as a means to reach a goal, in traffic terms the destination. Means and goals can be listed in an hierarchical system in such a way that the means at a certain level is a sub-goal on a lower level. Means and goals are only relative concepts. Manoeuvres are usually listed in an hierarchical system (Asmussen, 1972; Schreuder, 1973, 1974). In broad terms, there are three levels: the strategic level, where the higher decisions are made about the selection of the trip destination and the route. These decisions are usually made before the start of the actual trip. The tactical level, where the decisions concerning the manoeuvres are made, and the operational level, where the decisions concerning the vehicle handling are made.

As has been explained earlier in this section, the driving task refers to the manoeuvres. The main interest is therefore on the tactical level as indicated above. Within that level, three levels, or sub-levels, are of particular interest for the description of the driving task In each level the relevant manoeuvres can be listed. This has been explained in the following scheme.

(1) The level of complex manoeuvres.
    The major complex manoeuvres are:
    - just going on (as a result of the relevant decision);
    - negotiating a curve;
    - overtaking and passing a preceding vehicle without opposing traffic;
    - overtaking and passing a preceding vehicle when opposing traffic is present;
    - passing a (priority) intersection;
    - passing an intersection with traffic signals;
    - passing a roundabout;
    - coming to a stop for a T-junction, or for a traffic signal.
(2) The level of elementary manoeuvres.
    The elementary manoeuvres are:
    - just going on;
    - adjusting speed;
    - swerving around;
    - leaving the traffic lane;
    - coming to a stop.

(3) The level of manoeuvre-parts.
The manoeuvre-parts are:
– just going on;
– adjusting the speed (to the desired speed or to the speed of the preceding vehicle);
– adjusting the lateral position within the driving lane.

The hierarchical structure of the manoeuvres results from the fact that each manoeuvre represents (is the outcome of) a decision. Each decision has a 'way' and a 'goal'. The way must be followed in order that the goal can be reached.

(f) Manoeuvres in road traffic

A car is a surface vehicle, implying that there are two degrees of freedom for movement: lengthwise and crosswise (indicated here with x and y). In this respect, a car is similar to a vessel, that also has two degrees of freedom, but different from a train (one degree of freedom) or a plane (three degrees of freedom).

In principle, the selection of the values of x and y (and all time derivatives) is up to the driver; the decisions are made on line and in situ – meaning that there are no other authorities like traffic control or time-tables. In reality, things are rather different. Restrictions of a physical, behavioural or legislative nature make that the actual possibilities for drivers are very limited indeed; in fact, only four are open for manipulation by the driver in normal traffic:

- dx/dt; the forward driving speed;
- d^2x/dt^2; the lengthwise acceleration or deceleration;
- y; the lateral position;
- dy/dt; the crosswise speed.

And even these four cannot be chosen at will as a result of the presence of road limits, speed limits, vehicle performance and other traffic.

This means that all traffic manoeuvres essentially have to be composed of these four parts.

Using these restrictions, the sub-tasks can be specified further. The end result is eight different sub-tasks, each involving different combinations of the information processing and of the degrees of freedom available for manipulation:.
(1) Maintaining the lateral position within the driving lane;
(2) Maintaining the speed;
(3) Maintaining the route (the course) on straight stretches and in curves;
(4) Overtaking: changing traffic lanes;
(5) Overtaking with opposing traffic;
(6) Adjusting speed for discontinuities or other traffic;
(7) Adjusting speed and lateral position for discontinuities or other traffic;
(8) Coping with emergencies.

In each of these eight cases we can indicate what manoeuvres may be required; for each manoeuvre we can indicate the type of information that is required to make the decision, and the moment in time when the information must be available in order to make the decision in time. Thus, on the basis of the appropriate visually critical elements, for each of the eight cases the preview can be indicated. It should be kept in mind that a manoeuvre at a specific level includes in principle all manoeuvres at all lower levels. This includes the acquisition of the information that is needed for these lower manoeuvres.

There is one more variable: the type of road. For the elaboration of the system and for the determination of he preview, three types of road are selected as examples. The full description and the derivation of the preview is given in detail in Schreuder (1991). Here, only a summary of the results are given. See also Schreuder (1994e; 1998).

The three classes of road, that serve as an example, are:
(A) Class A: Urban roads (thoroughfares and all urban roads with a traffic function) with a nominal driving speed of 15 m/s (about 50 km/h);
(B) Class B: Rural trunk roads (primary roads) with a nominal driving speed of 25 m/s (about 90 km/h);
(C) Class C: Rural freeways (motorways, limited access highways) with a nominal driving speed of 35 m/s (about 125 km/h).

(g) Foresight distances for Class A roads

Urban roads (thoroughfares and all urban roads with a traffic function) with a nominal driving speed of 15 m/s (about 50 km/h). See Table 10.4.2.

Manoeuvre	**Foresight** (m)	**Visually critical objects**
Lateral position	45	– road markings
Speed control	45	– road markings
Curves	150	– road markings, light columns, delineators
Overtaking with opposing traffic	450-750	– light columns, opposing vehicles
Stopping for discontinuities	60	– road markings, delineators, pre-warning signs, pre-warning signals, traffic signs, traffic signals
Emergency manoeuvres		
• swerving	45	– (road markings), obstacles, other traffic
• stopping	55	– obstacles, other traffic

Table 10.4.2: *Foresight for Class A roads.*

(h) Foresight distances for Class B roads

Rural trunk roads (primary roads) with a nominal driving speed of 25 m/s (about 90 km/h). See Table 10.4.3.

Manoeuvre	Foresight (m)	Visually critical objects
Lateral position	75	– road markings
Speed control	75	– road markings
Curves	375	– light columns, delineators
Overtaking with opposing traffic	600-1250	– light columns, opposing vehicles
Stopping for discontinuities	175	– delineators, pre-warning signs, pre-warning signals, traffic signs, traffic signals
Emergency manoeuvres swerving	125	– obstacles, other traffic stopping
	140	– obstacles, other traffic

Table 10.4.3: *Foresight for Class B roads*

(i) Foresight distances for Class C roads

Rural freeways (motorways, limited access highways) with a nominal driving speed of 35 m/s (about 125 km/h). See Table 10.4.4.

Manoeuvre	Foresight (m)	Visually critical objects
Lateral position	105	road markings
Speed control	105	road markings
Curves	700	light columns, warning signs
Overtaking without opposing traffic	280-420	light columns, other traffic
Stopping for discontinuities	350	pre-warning signs, pre-warning signals
Emergency manoeuvres swerving	250	obstacles, other traffic stopping
	270	obstacles

Table 10.4.4: *Foresight for Class C roads*

(j) Conclusions

As a conclusion, it can be indicated that for urban roads with a traffic function, the required foresight is for stationary objects between 45 and 150 meters, for overtaking up to 750 m, and for emergency manoeuvres about 50 m.

For rural trunk roads (primary roads), the required foresight for stationary objects is between 75 and 375 m, for overtaking up to 1250 m, and for emergency manoeuvres about 140 m.

For rural motorways, the required foresight is for stationary objects is between 100 and 700 meters, for overtaking up to about 400 m, and for emergency manoeuvres about 250 m.

It should be stressed that these values of the required foresight are larger, and often very much larger than the values that are usually quoted in the literature; also they are much larger than the values that are commonly in use in driver training and education. The reason is that the values that are commonly in use are based on juridical premisses, where it is required by law, that the driver must be able to stop his vehicle in the time and in the space that is available and that can be overseen as being available. For this, one usually takes a very short overall reaction time (e.g. 1 sec, corresponding to a very alert driver who reacts to objects or situations that are fully expected) and a very large braking retardation (e.g. up to 5 or even 7 m/sec^2, corresponding to the legal minimum, or even to the practical maximum for good new vehicles on dry roads respectively). Neither assumption is relevant for normal traffic, and in combination they are completely wrong.

The consequence is of using incorrect values for the required foresight that are very much too short is, that many technical solutions and technical equipment is not adequate, and that much of the information given to the driving population is dangerously misleading.

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11 Technology and light-techniques

In this chapter, the physical principles of light emission are briefly discussed. Incandescent lamps, just as all temperature radiators, emit light as if it were a collection of light rays, whereas gas discharge lamps and semiconductor lamps emit light as if it were a stream of particles – of photons. The colour of the light can be influenced by fluorescence. All equipment that is discussed in the different chapters of this book, can be treated and designed by means of the laws of geometric optics.

Outdoor lighting illuminates the objects or areas over which no roofing or ceiling is provided. It is installed for a variety of purposes, which are indispensable to make our modern social life at night efficient and safe. It may seem that there are two different schools of lighting design, aesthetic and technical lighting design. This book is restricted to the technical lighting design for functional lighting.

Outdoor lighting installations basically consist of several elements: lamps, luminaires and supporting structures. These elements are discussed in this chapter. An important aspect of all lighting is its efficiency. It follows from the energy flow in the outdoor lighting system. For the subject of this book, the Upward Light Ratio is essential, because the upward luminous flux is the primary cause of light pollution.

Further, the basic elements of outdoor lighting design are discussed. Most recent design methods are based on the CIE-approach to road lighting design. Essentially, the CIE-approach is a check and not a design tool. An 'expert system' is still lacking, where the requirements are formulated and the design parameters follow. In the present-day simplified design methods, glare considerations as well as light pollution are disregarded. Apart from the traditional CIE-based design methods for outdoor lighting, special attention is given to low-pollution design methods for outdoor lighting. An outline for a method for low-pollution design methods for road lighting is presented. A simplified design method is proposed, that takes the restriction of the upward light flux as its starting point. Also, several examples of the simplified low light pollution design method are given.

Finally, a new approach to road lighting design, based on visibility, is discussed. This approach is based on the recent research of Narisada.

11.1 The physical principles of light emission

11.1.1 The physics of light

(a) Geometric optics

There are two ways to look at light as a physical phenomenon. One is to consider light as a collection of light rays, that show no further details. This is called the phenomenological approach to light. Optical imaging, which is studied in geometric optics, is treated in this way. Light rays are straight as long as there is no reflection or refraction. This approach is used exclusively in all lighting calculations, both in luminaire design as in the design of lighting installations (Correa da Costa, 2000; Forcolini, 1992; Schreuder, 1967). Geometric optics are used in graphical design methods like Baer (1990); Barrows (1938); Bean & Simons (1968); Öztürk (2000), as well as in computer-aided luminaire design (Platinakov et al., 2001). Geometric optics are dealt with in the classics of optical literature, like e.g. Longhurst, 1964; Feynman et al., 1977, Vol. I, sec 26 and Van Heel, 1950. The same geometric optics are widely used in the design of optical instruments, optical telescopes included. Not exclusively so; some details are designed with other light aspects in mind.

The principle law of geometric optics is Fermat's principle (Feynman et al. Vol. I, p. 26-4). This principle states that a light ray always takes the shortest possible path; more precisely, when media of different refraction indexes are involved, the path that takes the least time. One of the consequences of Fermat's principle is that light rays can be reversed: all results of geometric optics are invariant with respect to the direction of the light. Fermat's principle is a special case of the Principle of Least Effort, one of the basic principles in Nature.

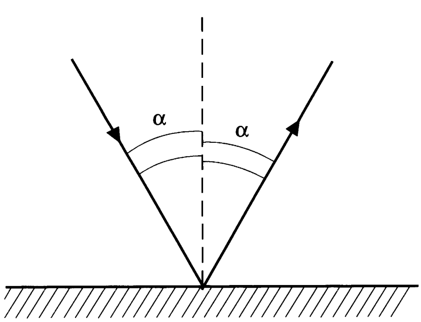

Figure 11.1.1: *Huygens' Reflection Principle. After Schreuder, 1998, Figure 4.5.1.*

From it, the well-known principle of reflection, usually ascribed to Huygens, is derived. The principle says that the angle which is formed by the incident ray of light with the normal on the surface, equals the angle which the reflected ray of light forms with the normal (Schreuder, 1998, p. 34). This principle is depicted in Figure 11.1.1.

The second important principle of geometric optics relates to refraction. It is usually ascribed to Willibrord Snell, and therefore it is often called Snell's Law. If a light ray travels from a medium with a low index of refraction into a medium with a higher index of refraction, the ray is deflected at the bordering surface towards the normal on that surface. If a light ray travels from a medium with a high index of refraction into a medium with a lower index of refraction, the ray is deflected at the bordering surface away from the normal on that surface. This is depicted in Figure 11.1.2a and 11.1.2.b.

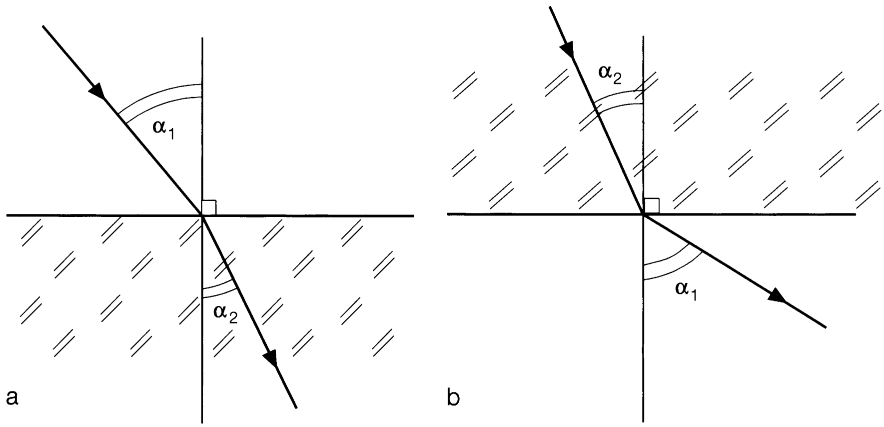

Figure 11.1.2: *Snell's Law. After Schreuder, 1998, Figure 4.5.5 and 4.5.6.*

The reflection and the refraction involving curved (non-flat) surfaces, can be approximated by using the tangent to the surface at the point where the light rays strike it. Thus, Huygens' Reflection Principle together with Snell's Law are sufficient for the design of every optical instrument. Non-spherical surfaces can be assessed by using the appropriate computer software. It may be added that both rules can be derived 'rigorously' from the.Maxwell Field Equations.

(b) The duplicity of light

Light can, as is well-known, be regarded as either as an electromagnetic wave or as a stream of rapidly moving particles, or photons. See e.g. Illingworth, ed. (1991, p. 266). The two ways understanding light are mutually exclusive. The first is described by classical phenomenological physics, the second by relativistic quantum mechanics (Feynman et al., 1977, Chapter 1-26 and 1-37 respectively). In the first, light is characterized by its wavelength or the frequency. These are related as follows:

$$\nu = \frac{\lambda}{c} \qquad [11.1.1]$$

with:
ν: the frequency (Hz);
λ: the wavelength (m);
c: the speed of the light (m/s).
See Schreuder (1998, eq. 4.2.1).

In the second, light is characterizsed by the momentum m carried by the photons, expressed as follows:

$$m = h\frac{\nu}{c} \qquad [11.1.2]$$

in which h is 'Planck-constant', equal to 6,626 076 · 10^{-34} J·s (Illingworth, ed., 1991, p. 354).

This distinction is directly relevant for day-to-day lighting engineering as well as for the restriction of light pollution. The reason is that from the four major lamp types that will be discussed lateron in this chapter, the first (the incandescent lamps) can be described in terms of classical phenomenological physics, where the corpuscular nature of light may be disregarded, whereas the other types (gas discharge lamps, fluorescent lamps and semiconductor lamps) can be described exclusively in terms of quantum physics.

(c) *Thermal radiation*

At all temperatures, any body will emit radiation, the characteristics of which depend on the temperature of the body (Illingworth, ed., 1991, p. 480). A body is called a blackbody or a full radiator is a body that absorbs all radiation. This implies that the emissivity is equal to unity (Illingworth, ed., 1991, p. 39). The radiation of a blackbody can be fully described by two equations. Details are given in Moon (1961, sec. 5.03) and in Hentschel (1994, se. 5.1). See also Illingworth, ed. (1991) and Breuer (1994, Volume I). The first equation is:

$$J = C_1 \cdot T^4 \qquad [11.1.3]$$

This equation (the Stefan-Bollzmann's Law) describes the total energy J emitted by a blackbody at a temperature T, with C_1 a constant. This equation describes the maximum light emission and therefore also the maximum luminous efficacy that may be reached by any light source that is based on the principles of blackbody radiation. The concept of the luminous efficacy is discussed in sec. 11.3.2b. More in particular, it proves directly that incandescent lamps never can be 'efficient' light sources.

The second equation that describes the blackbody radiation is:

$$\lambda_{max} = \frac{C_2}{T} \qquad [11.1.4]$$

This equation (Wien's Law) describes the wavelength λmax at which the maximum energy is emitted by a blackbody at a temperature T, with C_2 a constant. The law of Stefan-Bollzmann may be regarded as an integration of the law of Wien. As is discussed in sec. 8.3, each wavelength corresponds with a specific colour. This equation shows directly why light sources that are based on the principles of blackbody radiation, like e.g. incandescent lamps, go from invisible, emitting only infrared radiation, to red to yellow and to blue-ish in aspect when they are heated up. In Figure 11.1.3, the effects of the law of Wien are depicted.

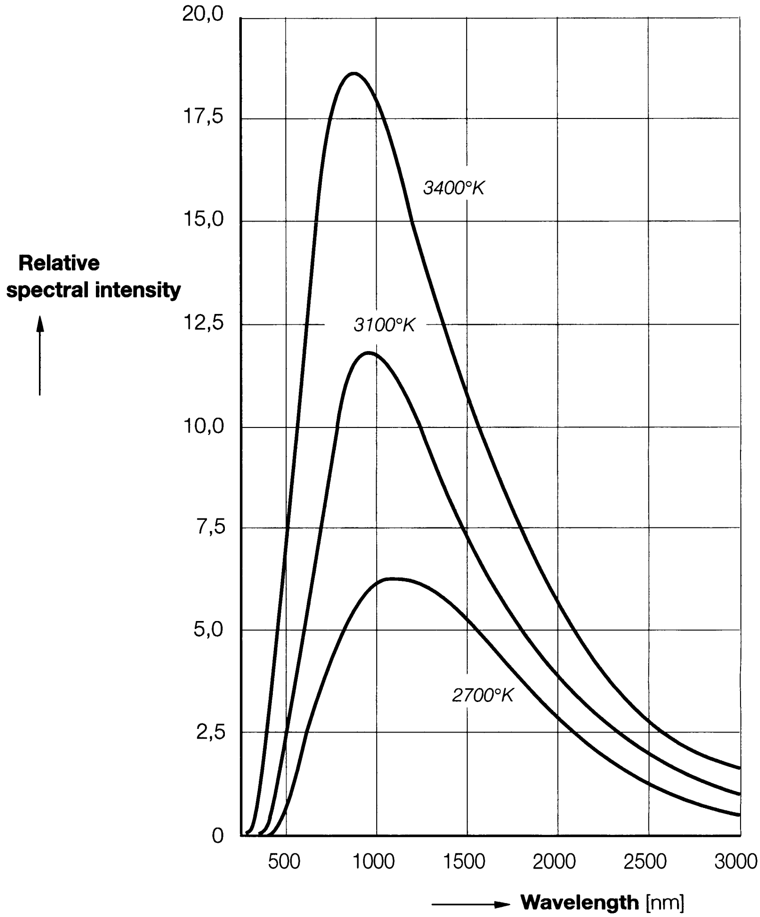

Figure 11.1.3: *The maximum intensity moves up to shorter wavelengths at increasing temperature. After Schreuder, 1998, Figure 4.2.3.*

(d) Incandescent lamps

Before dealing with electric incandescent lamps, it must be noted that most 'ancient' non-electric lamp types like wax lamps, candles, oil and kerosine lamps are incandescent lamps as well. So are gas lamps. The envelope is heated by the gas flame, and becomes an incandescent body (Gladhill, 1981). In all cases, the fuel, which is usually a hydrocarbon, contains small carbon particles. The heat of the flame makes them glow and emit light, so they are temperature radiators and must be classified as incandescent lamps. In industrialized countries their use is very much restricted, but they are the main light sources in many developing countries (Schreuder, 2001). As regards carbon-arc lamps, the gas discharge or plasma in the open air hardly gives any light, but it heats up the small carbon particles that are detached from the carbon points. Also here the heat makes them glow and emit light, so they are temperature radiators as well and must also be classified as incandescent lamps.

Most modern incandescent lamps are electric filament lamps. An electric current is passed through the filament. Because the electric resistance of the filament material, the filament heats up. Depending on the actual construction of the lamp, the operating temperature may be selected within a wide range, from low-temperature infrared and heat sources up to high-intensity light sources. In most modern lamps, the filament is made of tungsten and sometimes of carbon. In the past, also other materials have been used, such as tantalum and osmium. It may be noted that the electric arc lamps of the past as well as oil lamps and candles use carbon for the actual incandescent source. Now, the melting point temperature of tungsten is about 3650 K (Hentschel, 1994, Table 5.2). For practical reasons, the filament temperature in standard incandescent lamps is considerably lower. A value of 2500°Celsius (corresponding to 2773 K) is given by Baer (1990, p. 179). No general value will be found in the literature as the actual temperature depends on the lamp type, the wattage and the design life time. Other values for the filament temperature in standard incandescent lamps that are quoted often range from about 2600 K to about 2850 K (Philips, 1989, part 8, sec. 4.2). More in particular, the lamp life depends heavily on the filament temperature. As an example, a lamp with a filament temperature of 3000°Celsius would have a life only 0,2% of that of a lamp with a filament temperature of 2500° (Baer, 1990, p. 181).

All visual impressions are restricted to a wavelength region between about 400 nm to about 700 nm. Radiation with a wavelength shorter than 400 nm or longer than 700 nm may have all sorts of physical or physiological effects; they will, however, never will be 'light'. Now, from Figure 11.1.3 it will be clear that a blackbody of about 2700 K does not emit much energy in total and the small amount of energy that is emitted, falls mostly in a wavelength area well above 700 nm. It is sometimes stated that incandescent lamps are good heaters but poor light sources!

Finally, it should be mentioned that most practical materials hardly resemble blackbodies. Metals are 'selective radiators', i.e. the radiation relative to that of a blackbody differs for different wavelengths. Some examples are given in Table 11.1.1.

Material	**Temperature (K)**	**Relative emission at** λ **= 665 nm**	λ **= 463 nm**
Tantalum	2400	0,404	0,450
Platinum	1800	0,310	0,386
Nickel	1400	0,375	0,450
Gold	1275	0,140	0,632
Molybdenum	2400	0,341	0,371

Table 11.1.1: *Values of the spectral radiation factor of some metals. After Moon (1961, Table XVII, based on data of Worthing, 1926).*

Strangely enough, the table as given by Moon does not include the two materials that are widely in use as incandescent materials in light sources; viz.: carbon and tungsten. As regards carbon it is only remarked that "it approximates a nonselective radiator – a grey body" (Moon, 1961, p. 124). No data on the total emission have been given. For tungsten a graphical representation is given. See Figure 11.1.4.

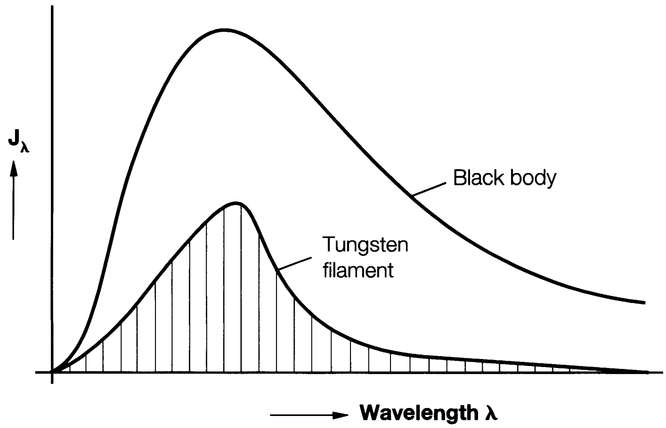

Figure 11.1.4: *The emission of tungsten compared to that of a blackbody for 3038 K. After Schreuder, 1998, Figure 4.2.3. Based on data from Moon, 1961, fig. 5.10.*

The total emission of tungsten is between 0,46 and 0,42 for temperatures between 1200 K and 2800 K (Hentschel, 1994, p. 116).

One might wonder why, in spite of these disadvantages, the incandescent lamp is far out the most popular lamp type in the world. The reason is not to be found in their efficiency but in a number of other characteristics. Some of these are discussed in sec. 11.3.3. The most important ones are:

(1) Incandescent lamps show a continuous spectrum; therefore, they have an excellent colour rendition. In fact, the 100% value of the colour rendering index is defined as that belonging to incandescent lamps (sec. 8.3.6);
(2) Incandescent lamps are very versatile. One may find them in all sizes and shapes. Therefore, they are suitable in an excellent way to a great variety of lighting applications;
(3) Incandescent lamps can be connected directly, without any.ballast to the electricity grid;
(4) And finally, incandescent lamps are very cheap.

It should be noted that the major benefit of incandescent lamps, being the continuous spectrum, must be regarded as a negative aspect in relation to the reduction of light pollution, more in particular in relation to astronomical observations. As is discussed in more detail in sec. 1.2.5, one of the most effective countermeasures against light pollution is to filter out the part of the spectrum that is of minor interest for the observations. In this respect, monochromatic or quasi-monochromatic light sources like the low-pressure sodium lamps, have distinctive advantages. Even other types of gas discharge lamps that have many spectral lines and that in a way seem to approach lamps with a continuous spectrum, allow to filter out at least part of the disturbing light. The continuous spectrum of the incandescent lamps, however, makes filtering not possible.

(e) Bosons, baryons, and fermions

As has been indicated earlier, light can be regarded not only as an electromagnetic wave, but also as a stream of rapidly moving photons. Photons belong to the family of elementary particles that are characterized by their 'spin' being either 0 or 1. They are called bosons. They follow the Bose-Einstein statistic (Illingworth, 1991, p. 379). This means that any number of such particles may exist in the same quantum state. For all practical purposes, it means that their number is not limited. One may make or destroy as many photons as one likes. This is, of course, the basic characteristic of light. Light can be generated in lamps, and destroyed by absorption. A summary is given in Breuer (1994, Volume 2, p. 363). Contrary to photons, other familiar elementary particles, like e.g. electrons, neutrons, and protons, are fermions. They have a spin of 1/2. They follow the Fermi-Dirac statistic (Illingworth, 1991, p. 379; Breuer, 1994, Volume 2, p. 363). Their characteristic is that only a limited number – usually only one – can be in a specific quantum state. Almost all elementary particles are baryons. "Baryons are all elementary particles that can undergo strong interactions. They all have a mass equal to or greater than that of a proton. Baryons are thus Fermions. An additive quantum number called the baryon number can be defined. The total baryon number is conserved in all particle interactions" (Illingworth, 1991, p. 32). In a technical sense, one of the 'Great Conservation Principles' is that the baryon number is conserved (Feynman, 1990, p. 62). In non-technical terms, it means that one cannot create nor destroy baryons – or fermions – at will, contrary to bosons. So baryons are not suitable as 'light'.

(f) Quantum aspects of light; gas discharges

As is explained in an earlier part of this section, the quantum aspects of light are characterizsed by the momentum m carried by the photons, which is expressed as follows:

$$m = h\frac{\nu}{c} \qquad [11.1.2]$$

with h: 'Planck-constant', equal to 6,626 076 $\cdot 10^{-34}$ J·s (Illingworth, ed., 1991, p. 354)

Gas discharges are physically and technically rather complicated. We will give a brief explanation, based on the 'classical' work of Oranje (1942). Theoretical details are given in Elenbaas, ed. (1959, 1965). Details about the construction and the application of lamps are given in De Groot & Van Vliet (1986) and in Meyer & Nienhuis (1988). See also Baer (1990); Breuer (1994); Hentschel (1994); Kuchling (1995) and Schreuder (1998, sec. 4.3).

The construction of all gas discharge lamps is basically very similar. They consist of a tube, usually made of glass, of quartz or of a translucent ceramic material. The tube can have any shape, but usually it is straight. It contains two electrodes that are, via a ballast, connected to the main electric supply. One is the negatively charged cathode and the other is the positively charged anode. In almost all cases, an alternate electric supply is used of 50 or 60 Hz. That means that, 50 or 60 times per second. the cathode and the anode change their function. Under the right conditions, that are discussed in detail in further parts of this section, a 'gas discharge' will take place. The main function of the tube is to contain the gas discharge and to help to maintain the conditions that are required in order to keep the discharge going. Therefore, the tube is called the 'discharge tube'. For short, sometimes the term burner is used, although it is, of course, not correct, because nothing actually 'burns'. The function of the ballast is explained in sec. 11.4.1d; what happens with gas discharge lamps at higher frequencies is explained in sec. 1.2.5b.

In modern outdoor lighting, only mercury and sodium are used in discharge lamps. Because, at room temperature, mercury is a fluid and sodium is a solid, it is really the vapour phase that is relevant here. In the past, this was sometimes expressed in the lamp nomenclature. In order to get a vapour pressure high enough to allow an effective operation of the lamp, its temperature must be rather high. As is explained in sec. 11.3.4, gas discharge lamps only operate in an optimum fashion within a narrow temperature range because for optimum lamp operation, the vapour pressure must be kept within narrow limits. It is well known that the vapour pressure depends heavily on the temperature. This is contrary to traditional incandescent lamps where the lamp temperature has little influence on lamp efficiency. Halogen lamps require a specific lamp – or bulb – temperature, not only for optimum operation but also for a long lamp life. We will come back to this point in sec. 11.3.3f. Because both mercury and sodium are mono-valent, both terms 'atom' and 'molecule' may be used.

When the lamp is in operation, negative electrons are emitted from the cathode that travel under the influence of the voltage difference between the two electrodes, towards the anode. In the process, they may collide with the atoms of the gas in the tube. When this happens, one or more of three effects may take place (after Oranje, 1942, sec. 3). In all three cases, there is some form of energy transfer from the electron to the atom. The energy comes from the kinetic energy of the electrons, that get that energy from the voltage difference between the cathode and the anode – thus, ultimately, from the electric supply of the lamp. The three effects are:

(1) At low energy levels, the collision is a elastic one. Both electron and atom stay unchanged; only their speed and direction of movement – their momentum – may change. Elastic collisions do not contribute to the generation of light in the lamp. In the process, some of the energy may be converted into heat. As has been mentioned earlier, some heat generation is needed to bring to the lamp at the right temperature for optimal operation. Too much heat, however, is just a loss. It is one of the most difficult aspects of lamp design to keep the temperature in the right range;

(2) At higher energy levels, the electrons that collide with the vapour atoms may cause one or more of the electrons of that atom to shift into an higher energy level. This effect is called excitation, and can be described as the electron circling the atom nucleus in a higher orbit. The electrons come into an excited state (Illingworth, ed., 1991, p. 162). In order for this to happen, a precise amount of energy is required. Any surplus energy of the electron is transferred into heat. After a very short time, usually in the order of 10^{-7} seconds, the electron falls back into its ground state, emitting the same amount of energy that was absorbed earlier. Taking into account the equations [11.1.1] and [11.1.2], the energy corresponds to a very specific frequency or wavelength of the light. This, of course, is the spectral line that corresponds to that quantum transition;
(3) At still higher energy levels, the electron may knock one or more of the electrons out of the atom. The electrons are free and join the electrons coming from the cathode; the atom with less electrons is an ion. The process is ionization. For knocking out a specific electron out of a specific atom, again a very precise amount of energy is needed. Any surplus energy of the electron is again transferred into heat. The ions have a positive charge, and begin to move towards the cathode. In moving, most ions meet a free electron and recombine again to a neutral atom, emitting again the absorbed ionization energy. Again here, a specific spectral line will be emitted. As mercury and sodium atoms have many electrons, and each electron can be in many different states, the possible number of spectral lines is very large. The choice to use mercury and sodium in gas discharge lamps is governed by the fact that for these atoms, and for these atoms only, most strong spectral lines are emitted in a wavelength range that is in, or very close to, the range of visible light. Details may be found in Schreuder (1998, sec. 4.3, figures 4.3.1 and 4.3.2). See also Elenbaas, ed. (1965, fig. 1.10) and De Groot & Van Vliet (1986, fig. 3.6).

When the vapour pressure is low, the spectral lines are very sharp, but their intensity is low. When the vapour pressure in chosen higher, all sorts of additional elastic collisions occur, resulting in a broadening of the spectral lines. This effect is used in special types of high-pressure sodium lamps, where a further increase in the vapour pressure results in an improved colour rendering. Such lamps are in particular suitable for flower gardens (Akutsu et al., 1984).

Using a high vapour pressure results in a smaller lamp with a corresponding increase in light source luminance, even if the total luminous flux may be lower. Thus, low-pressure sodium lamps emit an almost pure monochromatic light, whereas high-pressure sodium lamps emit a spectrum that contains, although not being exactly continuous, most colours. As is explained in sec. 1.2.5, this makes low-pressure sodium lamps very suitable for outdoor lighting near astronomical observatories, and high-pressure sodium lamps particularly suitable for general outdoor lighting purposes.

(g) Fluorescence

Fluorescence is short-term luminescence (Illingworth, ed., 1991, p. 177). Luminescence is produced when atoms are excited, as by other radiation, electrons etc. and then decay to the ground state (Illingworth, ed., 1991, p. 276). In many cases, the emitted radiation is of longer wavelength than the incident electromagnetic radiation. This is called Stokes' law (Illingworth, ed., 1991, p. 177).

In low-pressure mercury discharges, almost all energy is emitted in the region of near-ultraviolet wavelengths. It may be helpful to recall that ultraviolet – or UV – radiation, in spite of the fact that it is often called 'UV light', is not 'light' at all, because it does not provoke any sensation of 'light' in the retina. Fluorescence is very helpful to convert this invisible and harmful radiation into visible light by coating the inner surface of the discharge tube by appropriate chemical substances. A suitable selection of materials allow to reach light with a high intensity, an almost continuous spectrum and a very good colour rendering. Additionally, coating the inner wall of the tube prevents the harmful ultraviolet being emitted as it is absorbed by the glass. The resulting lamp type, usually called the 'fluorescent tube' did allow the 'lighting revolution' of the 1960s to occur.

Fluorescence is applied in other types of light sources as well, in order to improve their colour characteristics, such as in high-pressure mercury lamps and in LEDs.

(h) Semiconductor light; LEDs

Crystalline materials can be classified according to their resistivity. Electric conductors have a resistivity of up to 10^{-10} ohm · cm, whereas electric insulators have a resistivity of up to 10^{22} ohm · cm (Kittel, 1986, p. 159). Between those, there is a wide range of crystals that are usually called semiconductors, having typically a resistivity between 10^{-2} and 10^{9} ohm · cm. Traditional semiconductors are germanium, silicium, and gallium arsenide. As a note on terminology; compound materials with a chemical formula AB, where A is a trivalent element and B is a pentavalent elements are written as III-V (three-five) components (Kittel, 1986, p. 193; Illingworth, ed., 1991, p. 427-429).

Semiconductors are more than just poor electric conductors or poor electric insulators. They show a very special character, which makes them the most important material of modern time. We will briefly explain why, and why in some cases these materials may act as light sources. We will make use of the thorough, be it rather dated, treatment of Kittel (1986) and of the surveys of Illingworth, ed. (1991) and of Heinz & Wachtmann (2001). See also Heinz & Wachtmann (2002).

Atoms have a number of shells, where, in an equilibrium state, their electrons may stay. The number of shells and the number of electrons in each shell is determined by the atom number – the sort of material we are talking about. Gas discharges and fluorescence, that are discussed in an earlier part of this section, depend on the way that electrons may jump from one shell to another. Metals are a special type of material. They are characterized by the fact that their electron number is such that almost all fit into a restricted number of shells; almost, but not all. One or more electrons are 'left over'; they have to move into a shell with a higher energy level. When such atoms are grouped into a pattern , like e.g. a lattice or a crystal, the following happens. Those 'extra' electrons can move freely, almost as a fluid or a gas, amongst the lattice of ions that represent the rest of the atoms when an external electric field is applied. This is called the free Fermi gas (Kittel, 1986, Chapter 6). A more detailed consideration shows that the electrons in crystals are arranged in energy bands, separated by gaps for which no wavelike electron orbits exist (Kittel, 1986, p. 159). If one band is completely full, and the next higher – as regards energy levels – is completely empty, there are no free electrons. This means, that there is not a possibility for an electric current to flow, when an outside electric field is applied; the material is an insulator for electricity. Usually, the lower band is called the valence band and the higher the conductivity band. When one band is about half filled – say between 10 and 90 percent – with electrons, a free Fermi gas can develop; such materials are electric conductors. However, when one band is almost completely filled or almost completely empty, the material becomes – at room temperature – a semiconductor (Kittel, 1986, p. 159).

The characteristics of the semiconductors at different temperatures depends on the width of the 'forbidden' band between the valence band and the conductivity band. At 'absolute zero temperature' (0 K), the semiconductor acts as an insulator. At a certain temperature, the thermal motion of the electrons may allow for some of them to jump the gap, causing some 'sort of' conductivity. When the temperature rises, more electrons may cross the gap, until at the end the material is almost an electric conductor (Kittel, 1986, p. 184).

The picture changes completely when impurities, in very small quantities, are added to the semiconductor material. Usually, this is called doping (Illingworth, ed., 1991, p. 124). Some elements may fit, because of their size, reasonably well in the lattice, but they may have a larger or a smaller number of electrons. This would mean that there is a surplus of electrons or, contrary to this, a lack of electrons. In semiconductor language, there is a surplus of 'holes', that is, holes, where an electron would fit in. In the first case, one speaks of an 'n-type' semiconductor, in the second case of a 'p-type' semiconductor. (Breuer, 1994, Volume II, p. 317). Where the p-type semiconductor and the n-type semiconductor meet, one speaks of a p-n junction. Of course, the operation of semiconductor diodes and of transistors is based on these phenomena.

In a semiconductor diode, two complementary effects may be notes. The first is a photo-electric effect. When the diode is hit by electromagnetic radiation, electron-hole combinations are formed that may transport energy (but not electric charge, as they are electrically neutral; Kittel, 1986, p. 296-297). This allows to use them as photo-elements, either as a switching device or as a measuring device (Hentschel, 1994, p. 77-78). See also sec. 14.5.1. The second is the opposite effect: the diode will emit light, when a voltage is applied over the barrier layer in such a way that a current flows only in the forward direction (Durgin, 1996). By doping with materials that have a valence that differs from that of the carrier material, usually germanium or silicium, excess electron-hole pairs will be generated. When these excess electron-hole pairs recombine in such a way that an electron in the conduction band recombines with a hole in the valence band, a photon is emitted. This, rather complicated, process is described in Heinz & Wachtmann (2001, p. 200-201). The actual light source is the p-n junction. The light intensity is proportional to the number of excess electron-hole pairs. The useful light output depends on the quality of the crystal, and particularly of its surface, the colour of the light will depend on the material used (Illingworth, ed., 1991, p. 266). Fluorescent materials may be included in the device to alter the emitted colour.

The efficiency of LEDs may be illustrated by comparing the energy flow of a signal for traffic control, equipped with LEDs or with incandescent lamps. An example is depicted in Figure 11.1.5.

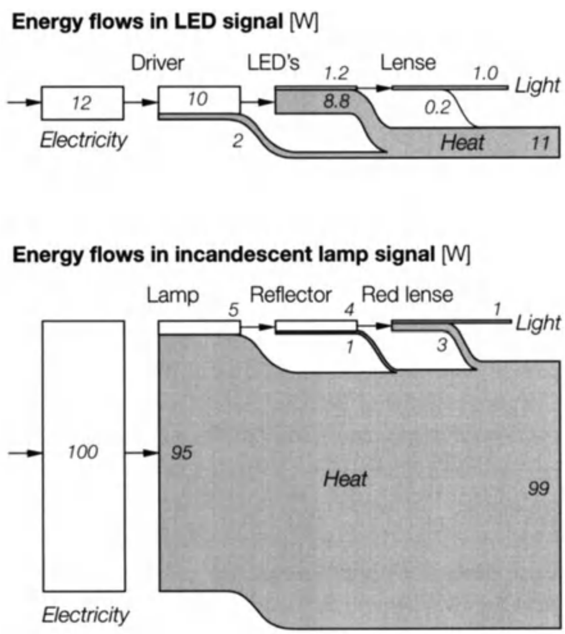

Figure 11.1.5: *The energy flow in road traffic signals. (top) LED light sources (bottom) incandescent lamps. After Zandvliet & Van Geldermalsen, 2002, p. 4.*

The technological development of LEDs has been very fast. The luminous efficiency or efficacy increased dramatically over the years as a result among others of the introduction of new materials. See Table 11.1.2.

Year	Efficacy (lumen per Watt)	Chemical formula
1970	0,4	GaP
1975	1	GaAsP
1980	3,5	AlGaAs
1987	10	AlGaAs
1995	12	AlInGaP
1997	21	AlInGaP

Table 11.1.2: *Luminous efficacy for red LEDs. Based on product information given by Hewlett Packard (Anon., 1996).*

More recently, LEDs reached 50 lm/W (Heinz & Wachtmann, 2002, figure 4; Visser, 2000). A prognosis of future efficiency is given in Table 11.1.3.

Month	Year	Efficiency (lm/W)
February	2002	20
August	2002	24
February	2003	32
August	2003	38
February	2004	49
August	2004	55
February	2005	61

Table 11.1.3: *Prognosis about the increase in efficiency of LEDs. After Johnson, 2002, fig. 6. Based on data from Posselt, 2002*

Until recently, LEDs were used mainly for signalling purposes. The high performance allow LEDs to be used for general lighting as well (Visser, 2000). The main advantages as compared to traditional incandescent and fluorescent lamps are (Schreuder, 2001a):

(1) New developments make that the luminous efficacy is similar to that of fluorescent tubes and superior to halogen incandescent lamps. It should be noted in passing that the usual definition of luminous efficacy cannot be applied directly to LEDs. Some adaptation is needed (CIE, 1997).

(2) Their practical life is very much longer. Instead of a few thousand hours, a life of 100 000 or 200 000 hours – 11,4 years or 23 years – is commonly quoted (Durgin, 1996, Visser 2000). However, there is a light depreciation to be accounted for. According to the manufacturers, the relative light output is over 90% for the first 10 000 hours. It is expected to drop to about 70% at 100 000 hours (Anon., 1996). We will come back on the negative effect of temperature etc. on life.

(3) Low energy consumption. A LED array of 7 W might replace a 70 to 150 W incandescent lamp in traffic signals (Durgin, 1996; Haazebroek, 2000).
(4) Small dimensions. LEDs measure only a few millimeters in stead of 5-15 cm for traditional lamps (Koteris, 2000). This makes them particularly suitable to the application of low-pollution road marking systems (Jongenotter et al., 2000). See also Bylund (2002).

Disadvantages are that the colour rendition of white LEDs is sometimes inferior to that of incandescent lamps. Also, the temperature has a considerable influence on the light output and on the lamp life. These disadvantages are, however, slight when compared to the advantages.

As an example, we quote some data about a luminaire that houses 24 white high intensity LEDs. The intensity is 20 cd, the life 100 000 hours (Patlite, 2002).

11.2 General aspects of outdoor lighting

11.2.1 Outdoor lighting and light pollution

Outdoor lighting illuminates the objects or areas over which no roofing or ceiling is provided. As discussed in the further part of this section, outdoor lighting is installed for a variety of purposes, which are indispensable to make our modern social life at night efficient and safe. For each of the purposes, the lighting requirements to be met and the techniques of lighting to achieve the requirement are different.

It should not be forgotten, that also the light from indoor lighting installations, particularly that from the higher floors of tall buildings, can also be a source of light pollution. The light from poorly designed lighting equipment mounted on the ceiling, as well as the light reflected from the walls, furniture, and the floors in brightly lighted interiors is emitted at night through windows, if they are not shut off by curtains or blinds. Therefore, it is recommended to close these windows at night, as far as possible, by curtains or blinds, in case indoor lighting is necessary. It may be noted that in most big cities, the custom is the other way around: most offices in conspicuous high-rise buildings, stay brightly lit, because of the promotional aspects of the light, although most of them are deserted at night. Nevertheless, in this chapter only the lighting systems, which are actually installed outdoors, will be discussed.

As regards their construction, large-scale outdoor lighting installations consist of a number of elementary outdoor lighting systems. The elementary outdoor lighting system consists of the combination of a luminaire, equipped with one or more lamps, and supporting structures of the luminaire.

The outdoor lighting is used for variety of application fields. Major application fields are:
(1) Urban areas and residential streets.
(2) Roads for motorised traffic.
(3) Outdoor sports.
(4) Outdoor works.
(5) Other applications.
Each of these applications will be discussed briefly in turn below.

It must be stressed, that the requirements on the lighting installations are closely related to the environmental zones that are explained in sec. 3.4.1. The zones must be taken into account in many details of the lighting design.

In further parts of this section, the principal concept of these five major application fields will be briefly discussed. But before this discussion, a number of other, more general, aspects of lighting design have to be explained.

11.2.2 General issues of outdoor lighting design

(a) Aesthetic and technical lighting design

It seems that there are two different schools of lighting design. The objective of the first school is to design lighting installation so as to make it conspicuous and aesthetically beautiful in the landscape at day and nighttime. That of the second school is to make the objects or the area to be lit easily visible or detectable for functional purposes at night, with a minimum of visual disturbing effects. This does not imply, of course, that the former completely disregards ease of seeing and latter disregards the beauty of the appearance of the installation in daytime.

In the following, we will confine ourselves to the technical lighting design for functional lighting, which is dealt with by lighting engineers.

(b) Differences between interior and outdoor lighting

It is important to realize that there is a difference between the lighting for interior and for the outdoor, or exterior lighting. Interior spaces are enclosed by the walls, the ceiling, and the floor. These surfaces, under lighting conditions, function as reflectors of the luminous flux from the luminaires in the interior, in a variety of directions. Between the surfaces in the interior, often inter-reflections of the luminous flux occur. The inter-reflections increase the illuminance levels on almost all the surfaces in the interior. As a result, under interior lighting conditions, even the surfaces in the shade behind the object onto which the direct luminous flux from the luminaires does not strike, and the shadows behind the object, become less dark.

In cases of outdoor lighting, on the contrary, there is no ceiling to reflect the direct luminous flux, and walls are restricted to facades of buildings, trees etc. Therefore, there is only limited extent of inter-reflections between the surfaces in the lighted area. Consequently, there is hardly any increase in the illuminance level due to inter-reflections, and shadowed surfaces stay dark. This is especially striking when the lighting level is low, because, as is explained in sec. 9.1.2, the relation between luminance and brightness is not a linear one. As a result, the contrast of the luminance or the brightness between the lit and unlit surfaces, is much stronger than under interior lighting, particularly under outdoor lighting conditions with low lighting levels. Also, the shadows and the shade behind the object also are darker than those in the interior.

The illuminance and the luminance over a surface, which direction is roughly parallel to the direction of the luminous flux from the luminaire, varies noticeably when the location of the luminaire is slightly displaced to the direction perpendicular to the surface. This shows that the location of the luminaires with respect to the surfaces to be lit, has considerable influence on the luminance or the brightness of the surface. The spatial location of the luminaires, therefore, is of importance, particularly, under outdoor lighting conditions for sports and in working areas. To determine the spatial location of the luminaires, drawings of the vertical cross sectional arrangements of various objects to be lit on the lighted area are helpful.

To simplify the matter, for many sports lighting, a number of standardized luminaire arrangements are given in the CIE recommendations for various sports (CIE, 1986).

(c) Lighting for specific objects

Some objects, such as the balls that are used in sporting games, are seen from various directions, when observed outdoors. If such objects, when lit from behind, are seen against dark background, it will be difficult for the observers to see the object properly. In the lighting design, when determining the illuminance level and the location of the luminaires, the reflections from the ground, which illuminate the underside of the object, and the height and speed of the object in the air, have to be taken into account. Details are given in sec. 11.2.8, where the lighting design for sports facilities is discussed.

(d) The concept of uniformity

In various recommendations for outdoor lighting, recommendations regarding the lowest uniformity of illuminance or luminance are given. Usually, the illuminance uniformity is given as a ratio, E_{min}/E_{max} or E_{min}/E_{ave}, where E_{min} is the minimum value of the illuminance on an lighted area, E_{max} is the maximum value, and E_{ave} is the average value. The uniformity of the luminance is defined in a similar way.

It is important to note, that the recommended values for the lowest limit of uniformity should not be applied automatically for the whole area, if the area is very large and the observers are not moving swiftly.

As an example, suppose that a very large area for outdoor work is to be lit. In this example, we assume the following points.

- The area has a length of 300 m;

- The distance between two points on the area, one with the maximum illuminance (E_{max}) and the other with the minimum illuminance (E_{min}) is 250 m;
- The requited uniformity ratio (E_{min}/E_{max}) for the whole area is 0,2;
- The illuminance over the area from the point of the maximum illuminance to that of the minimum illuminance varies gradually and smoothly.

Under such lighting condition, workers at any point on the area will see the area in front of them quite uniform.

(e) *Influences of the lighting of building interior on light pollution*

It must not be forgotten that the light from lighting equipment that is mounted on the ceiling, and the light reflected from the walls, furniture, and the floors in brightly lighted interiors, and that is emitted through windows, that are not shut off by curtains or blinds at the higher floors of tall buildings at night, is also a source of light pollution. It is therefore advisable, if lighting is necessary, to close, as far as possible, the windows at night by curtains or blinds. Nevertheless, in this section, only the lighting systems, which are installed outdoors, i.e., outdoor lighting systems will be discussed.

(f) *Construction of outdoor lighting systems*

As is mentioned earlier in this section, a large-scale outdoor lighting installation consists of a number of elementary outdoor lighting systems. The elementary outdoor lighting system consists of a luminaire with lamps, and a supporting structures of the luminaire, such as poles, posts, towers or other structures on which the luminaires are mounted. Depending on the scale of the area to be lighted, and the purpose of the lighting, a number of elementary outdoor lighting system of different types are combined, arranged, and installed.

To realize the required lighting conditions over the area the type of the lamps, and the location, inclination and orientation of the luminaires have to be determined with great care, while applying detailed lighting calculations that are based on skilled technical knowledge and engineering experiences. It must be emphasised here that any unscientific attempt intending to eliminate the light pollution without proper technical knowledge or engineering experience, may lead to unexpected adverse results or sometimes serious economic losses.

(g) *Elements of outdoor lighting systems*

At present, many types of elementary lighting systems are used to establish a variety of purposes of the outdoor lighting in a most efficient and economical way. The elementary outdoor lighting systems can be categorized by the types of the lamps and the luminaires employed, by the mounting height of, and by the types of the supporting structure of the luminaires. Each of the elements will be discussed briefly in turn in the following parts of this section.

11.2.3 Light control of the luminaires and lighting installation

To realize an outdoor lighting installation with a high energy efficiency, but at the same time with a minimum of light pollution, it is necessary to utilize the luminous flux emitted from the luminaires as much as possible, and aim it to the directions where lighting is necessary.

Normally, the light from luminaires is spread out as the distance from the luminaire increases. In the case that the luminous flux from the luminaire stays within a relatively narrow angular range, one may speak of the 'beam' of the luminaire. A luminaire that performs in this way, is often called a projector. No luminaires can be constructed, that are able to keep all the light emitted by the lamp within the small angular range of a narrow light beam. Always, some light will 'escape' from the beam as a result of light scatter in the optical media. However, as the sharpness of the light control of the luminaire improves by means of more precise optical systems, the amount of light scattered beyond the limits of the beam will be decreased. For the design of lighting installation of high efficacy with minimum light pollution, luminaires with sharp optical control have to be selected.

As is explained in sec. 11.6, the efficiency of outdoor lighting installations is not only determined by the efficiency of the lighting system. The spatial location, orientation, and inclination of the luminaires also have a remarkable influence.

When a high mounted luminaire is used to illuminate an horizontal plane, the edges on both sides of the light beam from the luminaire intersect with the horizontal plane – or the ground – with two different angles. Part of the luminous flux is emitted beyond the edges of the light beam. This part of the luminous flux, beyond the light beam, is usually wasted as it falls in unnecessary directions. It may cause light pollution in the vicinity of the lighting installation or even far away from it.

It is obvious that the area that is illuminated by the light from outside the actual light beam increases as the intersecting angle between the limiting line of the far end of the light beam and the horizontal ground decreases.

To minimize the light pollution, it is important to increase that intersecting angle. This is done by increasing the mounting height of the luminaires. As the mounting height of the luminaires increases, the lengths of disturbing shadows behind a lighted object become shorter.

11.2.4 Reflection from lighted surfaces and shielding of reflected light

Sky glow is not only the result of the direct light emission from the luminaires, but also of the reflection from the lighted surfaces. Most common surfaces in the outdoors have a reflection factor less than about 25%. This value corresponds to the reflection factor of cement concrete, used for building construction (Narisada, 2001, 2003).

To minimize the reflected luminous flux for visible surfaces, including that spilled out to the adjacent areas, one may avoid over-lighting, or avoid colours of high reflection factors for building constructions, or shield reflected light by building constructions or bushes. These measures are discussed in a further part of this section.

(a) Avoiding over-lighting

Over-lighting is lighting where the light levels are considerably higher than those that are required by lighting recommendations or lighting standards. To avoid over-lighting, it is important to select a lighting level adequate for the type or function of the lighting, while ensuring lighting conditions where the required details of objects can be discerned. As is explained in sec. 11.2.5, the output of the equipment and thus the lighting level in the installation, decreases with the progress of time. By using a higher level in the design stage, the effect of depreciation can be taken into account. Over-lighting can be avoided by selecting the correct maintenance factor in the design stage.

(b) Avoiding colours of high reflection factors for building constructions

Lighted facades of buildings reflect a considerable amount of the luminous flux beyond the area to be lighted. To reduce the luminous flux reflected to the unnecessary directions, it is recommended to use a finish for building facades, that is non-specular and has a low reflection factor. Also, a greater distance between the facade and the luminaires, in relation to the height of the building, is preferable to eliminate specular reflections.

(c) Shielding reflected light by building constructions or bushes

Placing shields around the lighted area can reduce a part of reflected light from the lighted surfaces. Constructions with a low reflection factor, or dense bushes are suitable for this purpose. As mentioned earlier in this section, most of the surfaces of building have a reflection factor less than about 25%, corresponding to that of cement concrete. Buildings with low reflection factors, for example less than 10%, can absorb more than 90% of reflected luminous flux. Bushes with many trees absorb much more light.

12.2.5 Maintenance

(a) Maintenance of the lighting level

Lighting installations cannot always have a lighting level precisely as required in the recommendations or standards. Usually, the light level in a lighting installation is not constant throughout its life; it decreases gradually, mainly due to accumulation of dirt or dust over optical surfaces, deterioration of lamps and of optical characteristics of mirrors, reflectors or transparent cover.

The reduction in the lighting level can be reclaimed, at least in part, by cleaning the luminaires, or by replacing old and deteriorated lamps. When the installation is new, the lighting level can be regained to a level very close to the new conditions by cleaning the equipment. As time elapses, however, even after cleaning, the lighting level does not come back to the new value as a result of luminaire deterioration, mainly due to corrosion of metal parts, and to lost of transparency of the glass or plastic optical elements. Apart from that, the lumen output of the lamps decreases, but also their lumen-per-Watt performance. The efficacy of the lamps, that is explained in sec. 11.6, will be reduced. As time elapses even further, the lamps will stop burning altogether. This is the end of the life of the lamps. However, as is explained further on in this section, it is too late by then to replace the lamps.

To achieve objectives of the lighting, under the lighting conditions even at the moment when the lighting level reaches the lowest value, the critical object must still be visible. In other words, the lighting level recommended has still to be maintained.

This means that the lighting designer should know the percentage decrease in the lighting level between the new conditions and the lowest acceptable conditions. This is expressed in the maintenance factor.

(b) The maintenance factor

In the design of a lighting installation, the designer has to take this depreciation into consideration, so that the lighting installation is able to keep an adequate lighting level, higher than the recommended lighting level, at any time. When the lighting level is calculated, the deterioration has to be taken into account by increasing the lighting level. The increase in the lighting level has to be determined so as to maintain that required lighting level, even when dirt or dust accumulation reaches its maximum before the cleaning, and when the lamps are close to being replaced. This means that the lighting installation is designed for a higher level of lighting than is laid down in the recommendations or standards. The ratio (E_2/E_1) between the lowest possible lighting levels of the installation is just before cleaning and lamp replacement (E_2), and those at the initial stage (E_1), is called the maintenance factor. The design value of the light level must be (E_1/E_2) times higher than the minimum value that is required by lighting recommendations or lighting standards.

It is the lighting designer who must decide the maintenance factor, but only after consulting the owner of the lighting installation about the cleaning intervals and the maintenance costs. The cleaning intervals have to be determined on the basis of:
(1) The conditions of dirt and dust accumulation in the environment in which the lighting installation is located;
(2) The air and dust tightness of the luminaires that are proposed;
(3) The aging performance of the lamps in terms of the luminous output, the nominal life of the lamps;
(4) The cost of labour or other factors for maintenance.
As is explained in a further part of this section, selecting the best maintenance factor may save a considerable amount of money.

The maintenance factor is established by taking the cleaning intervals and the lamp replacement intervals into account. This means that if the intervals of cleaning of lighting equipments and lamp replacement are short, then a higher maintenance factor can be taken. If the intervals are long, then a lower maintenance factor must be taken. To be able to set a high maintenance factor, and to avoid over-lighting due to low maintenance factor, the owner of the lighting installation must apply short cleaning intervals and short lamp replacement intervals. The optimum replacement interval of the lamps is not determined by the actual lamp life, but by the system efficiency. At short maintenance intervals, the maintenance costs are high, as a result of frequent cleaning and lamp replacement. Energy costs, however, are lower because the lamps that are used, are almost new all the time. At the optimum maintenance factor, the decreasing energy cost will compensate for the increasing maintenance costs.

(c) *Lamp replacement*

The selection of the best moment to replace lamps in a lighting installation, is a complicated matter. Obviously, burnt-out lamps must be replaced. As the life of lamps is a stochastic phenomenon, lamps burn out at irregular moments. Replacing each individual lamp, when it has burned out, would require an individual lamp replacement as well. It must be done at short notice, because usually, the installation will not fulfill the requirements of the recommendations or standards, when an appreciable number of lamps has burned out. This is an expensive and labour-intensive burden for the lighting maintenance agency to bear. Usually, it is cheaper to replace all lamps in the installation at the same time. This is called group replacement. As is mentioned earlier, a long group replacement time interval would mean a low maintenance factor and consequently a high initial lighting level. This could easily result in over-lighting. It should be mentioned immediately that by using a dimming installation, over-lighting can be avoided, while still a long group replacement interval can be selected.

It is a complicated matter to select the optimal group replacement interval. Not only lamp life and luminaire deterioration must be taken into account, also lamp costs, lamp efficacy drops, and damages to the electric network or to the ballasts in case of a burn-out, must be taken into account. Furthermore, the costs of lamp disposal, the possibilities to recycle parts of them, and costs of labour and of electric energy must be accounted for.

It is not possible to give a general recommendation, but it seems that, at least in industrialized countries with high labour costs, for almost all types of lighting installations, except the very small ones, group replacement is usually to be preferred over individual lamp replacement. It should be stressed that in this statement, environmental considerations, waste disposal, and light pollution have been taken into account.

11.2.6 Lighting for urban areas and residential streets

In this application field, lighting for roads and other public areas for pedestrians are included. The objectives of the lighting for urban area are:

- to prevents crimes;
- to prevent the traffic accidents on the streets;
- to make the urban area enjoyable and attractive.

(a) *The prevention of street crime*

Street crimes and vandalism cause fear for crime and sense of insecurity for pedestrians (inhabitants and tourists) in the urban areas. The sense makes them reluctant to go out in their place of residence after dark. Consequent reduction in the number of 'well-intending' people going out reduces the pedestrian traffic on the streets and other public spaces. Streets with only a few well-intending pedestrians, encourage criminals to commit their crimes. The consequent increase in crime incidences accelerates the sense of insecurity and people become more reluctant to go out. The effects on the social control are discussed in sec. 12.1.4.

The reduction in pedestrian traffic reduces the possibilities for witnesses on the streets when crimes occur. This situation strengthens the confidence of criminals to commit even more crimes. Such an increasing criminal situation reduces the probability of police arresting the criminals (CIE, 1995). The street, finally, becomes really insecure.

This shows that a fear for crime or a lack of a sense of security creates a vicious circle, which increases crime incidences, and finally leads to real insecurity. Good lighting for streets, on the other hand, diminishes the fear for crimes or the sense of insecurity of (well-intending) inhabitants. It encourages them to go into town for pleasure after dark, and an enjoyable atmosphere will be created in the town. At the same time, the good lighting makes potential criminals less intent on committing their crimes for fear of being witnessed and possibly being arrested by the police. Further, good lighting makes activities of the police chasing and arresting criminals, and investigating the crime much easier and more effective. This will result in an increase in the ratio of arresting criminals. The increases in the ratio, further encourages the inhabitants go into town and increases the possibility of the crimes as well as the criminals being witnessed when criminal acts occur.

One of the reasons which causes the sense of insecurity is that the surroundings are dark, or the lighting conditions are poor. However, it is generally assumed that, on very dark streets, there is hardly any street crime. For the inhabitants, it is hard to use the street, and the criminal can see nothing, which also means that the it is difficult for the criminal to run away 'safely' from the crime site via the dark streets.

However, if the street is lit, but poorly lit, this may help the criminal, but it is harmful for pedestrians. This is discussed in sec. 2.5.3 (Narisada, 2002). This is because the eyes of the criminal, who normally keeps lurking in a dark place for a considerable length of time, adapt fully to the luminance of the dark place. On the other hand, the eyes of the pedestrians, who just have come into the poorly-lit street from a well-lit street, shop, home, or restaurant, are still adapted to the relatively high luminance but do not have enough time to adapt to the darkness, which takes, normally, some minutes, depending on the lighting conditions. Consequently, the eyes of the potential criminal are highly sensitive in the dark environment, whereas those of the pedestrians have only a low sensitivity. Therefore, the criminal can discern details of the approaching pedestrians from a distance, especially when the background is light, and select his quarry easily. They can escape rapidly through a dark street, whereas the pedestrians cannot see anything in the dark and cannot recognize the suspicious activity of the potential criminal, until the criminal makes contact. This evidently shows that the poorly lit street does not assist the pedestrians but supports the potential criminal. The energy consumed by the poorly-lit lighting installation therefore is a complete loss for society. This is a kind of light pollution against society and the environment. From this, an important conclusion can be drawn that the lighting of streets has to be planned in a systematic way in the whole town and should not leave any short stretch poorly-lit.

To obtain advantageous effects for pedestrians in the street, the street lighting must provide a level of lighting, which fulfills certain visual requirements. The CIE Guide for the Lighting of Urban Areas states that under street lighting conditions, the observer must be able to recognise any sign if another person is likely to be aggressive, at least from a distance of 4 m, so as to have a sufficient time to take appropriate evading action (CIE, 2000; Caminada & Van Bommel, 1980; Van Bommel & Caminada, 1982; Van Bommel, 1982). The road lighting level for pedestrian traffic is given in the CIE recommendations (CIE, 1995). Good lighting brings about further advantages, also for pedestrians, because the quality of the pictures recorded with surveillance video cameras, located above the street level, will be improved at night.

(b) The prevention of road traffic accidents

In many towns, small streets, and residential areas that carry hardly any motor traffic, and only little, if any, nighttime pedestrian traffic, do not have any sidewalks at all. In many countries, such streets have no public lighting, or, at best, some guidance lighting, that does not illuminate the scene, but only gives a suggestion about the run of the road. In most industrialized countries, however, even such streets have a fair amount of public lighting. This lighting has the character of security lighting, its main function being to allow the police to make thorough surveillance. More specifically, the street lighting has to fulfill the requirements for adequate crime prevention, as is discussed in sec. 2.5.3.

For urban streets that carry a considerable amount of nighttime traffic, the lighting must be adequate. If the traffic is mainly motor traffic, it is recommended to install a road lighting system that allows for motorized traffic, and fulfills the requirements for the lighting for motorized traffic (CIE, 1977, 1995, 2001). If the traffic is predominantly pedestrian traffic, the requirements for pedestrian traffic lighting need to be fulfilled (CIE, 1995, 2000).

(c) Lighting of building facades

The lighting for bridges, buildings, bushes, churches and other religious buildings, factories, fountains, flower beds, monuments, ponds, rivers, statues, trees, towers, shops, waterfalls, etc. makes the night scenery of the site more beautiful and more enjoyable. For the sake of simplicity, all these objects will be called 'buildings' in this section.

The illuminated exterior of building creates a sense of amenity. The concept of amenity is discussed in sec. 2.5.4. The lighting attracts tourists and promotes the bustle of the town at night, when nothing would be visible, unless lighting is installed. The nighttime scheme is quite different from the daytime scene, because the light comes from a different direction. During daytime, the daylight comes from the sky, whereas at night, the artificial illumination comes mostly from the ground. To this, the light from the windows, that are dark during the day, should be added. This presents another attraction of the buildings at night. Sometimes, classical palaces, castles, governmental buildings, headquarters of big companies, railway stations, airports, banks have floodlighting, to emphasise their function as status symbols. Many aspects of city beautification are discussed in sec. 2.4.

The well-lit high-rise buildings in major towns have a function of a landmark. The landmarks give orientation and help drivers and tourists travelling in an unfamiliar town at night, and prevent waste of fuel energy to stray in the town, as long as, of course, a GPS guiding system is not available.

It is important to note, however, that a building is a part of the landscape – or 'cityscape' – of the town in which the building is located. The lighting of the building must be designed carefully so as to fit in the surrounding landscape and not interrupt the landscape in other parts of town.

If a building is over-lighted, then surrounding elegant buildings and the landscape will be reduced into black darkness. If it is brightly lighted in heavy, coarse colours, the whole landscape around the building may look ugly after dark. Sometimes, over-lighting of a building leads to a competition in the lighting of other buildings nearby. The consequence is wasting energy and spoiling the landscape. The lighting of buildings must always be designed in conjunction with town planning and the nearby landscape.

For lighting buildings, there is a maximum distance between the luminaires and the facade that allows an optimal lighting of the facades. When the buildings are very tall, the available space is often not enough to reach that optimum distance. When the whole facade is to be lit from below, the angle of elevation needed to aim the luminous flux up to the top of the building is very high. Under such lighting conditions, a major part of the luminous flux projected upward is reflected and wasted toward the sky and may make the sky glow stronger. This reflection is greatest for glass facades of most types of office buildings, but may be considerable as well for other structures. Furthermore, it is difficult to aim the projectors properly, so that a lot of light may 'miss' the building altogether, and disappear directly into the sky. This type of spill light is often the largest contribution to urban sky glow. Consequently, it is recommended to not to use upward floodlighting for tall, slender structures, like spires of churches, bridges, etc., but to invent another way to enhance their conspicuity.

It is important, that the lighting of building facades be done in a way that is best-suited way for the particular buildings. To establish good results without causing light pollution, a highly skilled design technique and high level of lighting engineering is essential.

11.2.7 Lighting of roads for motorized traffic

(a) *The objective of road lighting*

The main objectives of road lighting for motorized traffic are to provide lighting conditions under which drivers can drive their vehicles safely and comfortably, and can discern necessary visual information reliably and easily.

Already in an early stage of the development of motorized traffic, the motor vehicle accidents caused more deaths than any other type of accident. The accident figures show that the deaths in 1925 in the USA were about 11,9 per 100 million vehicle-kilometers (Anon., 1963). Obviously, traffic accidents were one of the national problems already in the early 1920s. In later years, the road accident death tolls became less, most likely as a result of better cars and better roads, and probably also by better educated drivers. Some effects are depicted in Figure 11.2.1.

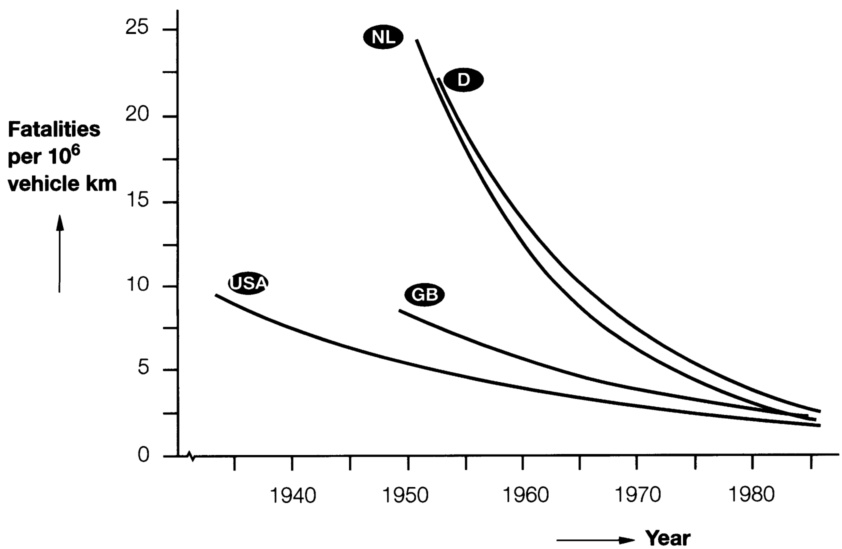

Figure 11.2.1: The reduction in accident risk in some industrialized countries. After Harris, 1989, Figure 7.

In the 1930s, as a result of introduction of the first types of high-pressure metal vapour discharge lamps, systematic investigations on the relation between road lighting and accidents have started in a number of countries in Europe and North America. Details are discussed in sec. 12.1.1. Based on the extensive investigations concerning visual problems that have been made since then, traffic engineering problems and lighttechnical problems have been published widely in papers, reports, and articles all over the world. On the basis of these investigations and engineering experiences, in 1965, the first international recommendations for lighting of public thoroughfares were published by the CIE (1965). Since then, during these about 40 years, further investigations have been conducted in many countries, including Japan, on which the fundamentals of road lighting have been established (Narisada, 1971, 1995, 1999; Narisada & Karasawa, 2001, 2003, 2003a; Narisada et al., 1997). As is discussed in sec. 12.1, the effects of road lighting on the reduction of the traffic accidents after dark have been surveyed extensively. Road lighting is accepted as the most effective accident countermeasure at night (CIE, 1968, 1992a; OECD, 1971, 1980).

(b) Visibility of obstacles

In order to avoid hazardous situations, drivers need to discern information of the types that are listed below at a sufficient distance ahead, so that they can select the required driving manoeuvre in time. This is the basis of the driving task of the driver, classified in three levels. These levels are called the positional, situational, and navigational levels, or the steering level, the level of elementary manoeuvres, and the level of complex or compound manoeuvres as they are termed in sec. 10.4.3 (Schreuder, 1998, sec. 8.2.1). A comprehensive list of almost all possible task elements is given below:

- Variations in the run of the road, such as curves, diversions and conversions, delineators;
- Lateral position of the car with respect to the driving lane; road markings;
- Presence or absence of traffic obstructions;
- Present position on the route towards the trip destination;
- Indications of traffic signs and traffic signals;
- Junctions or interchanges at which the direction has to be changed to take the route towards the destination;
- Presence of other vehicles, driving ahead or behind;
- Variations in the lateral position of, and in the lengthwise distance to other vehicles ahead and behind (tail lights, turning indicators and brake lights etc.);
- Pedestrians on the sidewalk or on the carriage way;
- Last vehicle in a traffic jam;
- Accident sites and construction sites;
- Bus stops;
- Infants, unfastened pets, or people with suspicious behaviour on the sidewalk or on the carriage way;
- Obstacles, or vehicles stopping or parking on, or adjacent to the road;
- Damaged spots on the road surface;
- Puddles or frozen spots on the road surface; fog, rain, mist and smoke ahead etc.;
- Others.

A number of these aspects is discussed in sec. 10.4.3 as well. To make drivers able to discern the above visual information, reliably and easily, a level of the lighting, which yields fairly uniform and a sufficient average luminance and the illuminance over whole carriage way, is necessary. On the basis of extensive investigations during almost 70 years, the quality criteria of road lighting are given in the CIE Recommendations for the lighting of roads for motor and pedestrian traffic (CIE, 1977, 1995, 2000; De Boer, ed., 1967; Van Bommel & De Boer, 1980; Schreuder, 1998).

(c) Visual guidance by means of road lighting

As mentioned above, the objectives of road lighting are to provide lighting conditions under which the drivers can drive their vehicles comfortably and can discern necessary visual information reliably and easily. Under good road lighting, therefore, the drivers, who are going into a steep curve or a complex junction, are guided by advanced information, by means of the road lighting regarding the run of the road. This is the visual guidance provided by the road lighting, which gains advantage over the automobile headlighting. Visual guidance was often called 'optical guidance' in the past (CIE, 1977).

A further significant and important guiding function of road lighting is the direct visual guidance. The direct visual guidance is given by the configuration of the luminaires in the perspective view against the sky. It is useful at sharp curves, steep inclines, diversions, roundabouts, or complex junctions, particularly in fog or in low-level lighting conditions.

If, however, in the lighting installation, the direct guidance is disregarded or poorly designed, the installation may guide the traffic in the wrong direction and may cause serious accidents. This is particularly true near sharp curves, steep inclines, diversions, roundabouts, or complex junctions, particularly in fog or in low-level lighting conditions. This may be a case of misguidance, often due to improper direct guidance of the road lighting. To provide adequate direct guidance by means of road lighting installations for.complex road configuration, it is necessary that the designers of the installations have extensive technical knowledge and practical experience at their disposal. See also secs. 7.1.4c and 11.2.6b.

11.2.8 Lighting for outdoor sports

(a) Recreational and spectator sports

From the lighting viewpoint, a distinction should be made between two kinds of sports, i.e., recreational sports and spectator sports. The recreational sports are sports for players themselves, whereas the spectator sports are sports for presentation in front of many spectators. The principal factor, which causes the difference in lighting for the two kinds of sports, is the size of the sport facility in which sports are played and spectators watch.

Whichever the type of the sport, for recreation or for spectators, the field on which sports are played, in some sports called the 'pitch', is similar in size for each type of sport, although some differences may exist. The size of the spectator stand for spectator sports, however, differs considerably according to the importance of sports, for amateur or professional, for regional or international. As the matches increase in importance, the number of expected spectators will increase as well. Accordingly, the size of the spectator stands expand and the distance between the playing field and the far-end spectator at the top of the spectator stands increases. To watch or enjoy the details of the movements of balls and the players in the sport matches, the far-end spectator needs a high level of lighting on the playing field. Thus, the size of the spectator stands is one of the most important factors for determination of the lighting level to be provided for spectator sports.

(b) Lighting the balls used in sport

For many kinds of outdoor sports, a ball or balls in a variety of size, shape and colours are used. For some other sports, specific equipment is used, like e.g. javelins, arrows, etc. In many sports, the balls or the equipment will fly high in the air above the field, often at considerable speed. Sometimes, balls are hit up to a height of some tens of metres above the ground, e.g. in baseball and in golf.

To enable players to react instantaneously to the movements of these flying objects, they need to be able to see these fast-moving object clearly, continuously and reliably from a considerable distance. They need to estimate the point of contact.

The director, the spectators, and the umpires also need to watch fine differences in the moving of the flying objects and players from distant locations and in different directions. The objects flying in the air over the ground must therefore be well lit from many directions, uniformly and over the full flying course, so that all persons involved can see the objects at any relevant point.

If the apparent size of the object to be seen is smaller, or as the apparent speed of the flying object is higher, it is for the spectators more difficult to see or to follow the moving of the object during the game.

The apparent size of the object is in inverse proportion to the distance between the object and the observer. The apparent speed of the object seen by the spectator, on the other hand, is determined by the angular velocity of the object. The angular speed of the flying object is in inverse proportion to the distance between the object and the observer, and the component of the speed of the flying object for the direction perpendicular to the line of sight.

The apparent size of, and the angular speed of, the flying object seen by the spectator close to the game is larger and higher than those seen by the far end spectators. This partly compensates the influence of the distance between the game and the spectators on the ease of seeing for the flying balls or the equipments used in the sports.

(c) Movements of players

In many sports, the players on the field are rapidly moving and changing the location and the direction of their motions, while running, rolling or bouncing on the ground, depending on the type of sport. In some sports, like athletics, the course of movement is quite predictable, whereas in other sports, like soccer football or field hockey, the movements have an unpredictable component, that may surprise even the 'expert' viewers. The director, the players, the spectators, and the umpires have to watch fine differences in these complex motions from very different directions and different locations.

The lighting of outdoor sports therefore must illuminate the playing field, the sport participants, the balls and other equipment used for the sports, with sufficient light level, from all possible directions for all persons involved. It should be noted that persons and equipment often are seen with the playing field as a visual background, but also often the grandstands or even the sky, that, obviously, is dark at night. The contrast may therefore vary, for the same object, very much in only a short time span. In this respect, the spacial location of the luminaires with respect to the playground has to be determined with great care. If the special location of and the number of the luminaires is wrong, then dark, sharp and ugly shadows will be cast on the ground surface behind the players.

(d) Glare

During the play, the players are conducting furious activities. They change their location, positions, and the direction of the line of sight, vertically, horizontally and at a slant, by turning their head or body, in many, sometimes random, ways. During such activities, severe glare may be experienced, if the high luminous intensity from the projectors, or their intensive luminance, will strike directly into their eyes. They will suffer from disability glare. In the worst case, even after changing the line of sight, players have trouble to see properly for a while, due to hindrance from after-images. One might consider this as a case of blinding glare. A well-known example is the glare that many goalkeepers in soccer football may experience. Rumors say that the glare from the lighting installation is sometimes intentionally used to favour the home team! The physiological and the psychological effects of glare are discussed in detail in secs. 9.2.2 and 9.2.3.

There is more to it. In many sports stadiums, not only the players, but also the spectators may be disturbed by glare, and so are the TV cameras. More important still, the light from poorly adjusted projectors not only causes glare, it is very likely that the same light causes unacceptable light pollution. This is easy to understand, as the directions of light emission that are related to glare, are close to the directions that are related to light pollution. The relation between glare and light pollution is explained in sec. 1.2.

(e) Colour of the light

In spectator sports, in addition to the colour of complexion of the players, the colour of their sports garments is an important element. Often, the name of the nation, or the sponsor's name, appear conspicuously on the shirts of the player, and so do the numbers they wear. To reproduce the colours correctly and attractively, the choice of lamps for lighting, in terms of colour temperature and the colour rendering are important. Further details on the colour temperature and the colour rendering properties of lamps, are discussed in detail in secs. 8.3.2, 8.3.7 and 8.3.8.

The spectator sports are frequently broadcasted on TV. The colour reproduction characteristics of combination of the lamps and colour cameras, together with the lighting level is also important, especially when new lamps or new TV system is introduced. In many respects, the requirements for TV registration are even more severe than for the spectators.

If TV cameras are used from the daylight conditions to the artificial lighting conditions in the evening, continuously, the shift of colour of the light during the dusk has to be taken into account. To minimize unnatural shift in apparent colour, the lamps, whose colour temperature is between 4000 K and 6500 K is recommended to use by the CIE (CIE, 1989).

11.2.9 Lighting for outdoor work areas

There is a great number of occasions, where outdoor work is conducted at night. For example, CIE Guide for lighting exterior work classifies the outdoor works into the following 12 work areas (CIE, 1998).

- Building sites,
- Canals and locks,
- Filling and service stations,
- Harbors,
- Industrial yards and storage areas,
- Parking lots,
- Petrochemical industries and other hazardous industries,
- Power, electricity, gas, and heat plants,
- Railway areas,
- Saw mills,
- Shipyard and docks,
- Water and sewage plants.

It might be added, that 'open pit mining' and 'heliports' do not appear in this list, probably because CIE has appointed separate technical committees on these subjects. As it is, the list is long enough.

To provide adequate lighting conditions for doing the work in these areas, a number of factors have to be taken into consideration, like e.g. the fineness of the details in the visual task, ranging from 'very rough' to 'fine', the movement of pedestrians and vehicles, ranging from 'very slow' to 'fast', and the extent of safety and security of people and property necessary in the outdoor area.

From this, the major outdoor working areas are classified into the following three types, according to the major objectives:
(1) Lighting for outdoor tasks;
(2) Lighting for movements of vehicles and of products;
(3) Lighting for safety and security for work areas.

In each work area, all the lighting aspects are combined, so as to establish the overall objective of the lighting.

It is common knowledge that the speed and the accuracy of visual performance improve with the increase in the lighting level. In other words, an insufficient level of lighting may lead to inaccurate, slow and unreliable results, and to a loss of materials, time and energy. In extreme cases, the workers themselves may be in danger.

On the other hand, excessive lighting results in a waste of energy, in an increase in the light pollution by reflection from the lighted area, and in lighting costs. The lighting level must be sufficient but not excessive for visual requirements. To determine the adequate lighting level, the fineness of the visual task has to be carefully examined. To assist the lighting designers, the CIE classifies the outdoor work for fineness of the task to be done, movements of pedestrians, and traffic and safety and security (CIE, 1998).

Concerning fineness, quick handling of large units and/or solid bulk are categorized as 'very rough' work. Continuous handling of large units and/or freight handling are categorized as 'rough' work. Work with tools, e.g. like that of a carpenter, is categorized as 'accurate work'. The work for electrical and machine installation is categorized as 'fine work'. As the task increases in fineness, a higher level of lighting is necessary.

In essence, the lighting for movements of vehicles and of workers (pedestrians) in the working areas is similar to the lighting of general roads for motor and pedestrian traffic, such as is explained in an earlier part of this section. However, the type of vehicles moving in the outdoor work areas, include not only regular cars and vans, but also bulldozers, cranes, forklifts, heavy trucks, and power shovels, etc. The driving speed of these motorised vehicles is low. As a consequence, the average traffic volume is low as well. The drivers or operators do not need to look a long distance ahead. For these reasons, the lighting for movement of traffic or pedestrians is designed on the basis of the illuminance concept.

The movements in the outdoor working areas are not only relevant to the vehicles and the pedestrians (workers). The materials, parts, units, solid bulk, freight, and blocks, etc., lifted by cranes or fork lift trucks, shovelled up by power shovels, dumped from dump trucks, etc., are also moving. Workers have to take notice of these moving objects, depending on the working conditions. Therefore, the visual task of workers in outdoor work areas, are more complex and random when compared with those in normal walking movements on streets and sidewalks.

The lighting of outdoor work areas has to provide the lighting conditions, which allows the workers to discern the relevant movements and details of the visual task, with sufficient fineness, ease and reliability, without experiencing any disturbing glare.

11.2.10 Other applications

There are a number of outdoor working areas in agriculture, fishery, security, waste management, etc., that may be compared to the more or less standard lighting solutions that have been described in the earlier parts of this section. There are, however, a number of other outdoor activities, that should be classified differently, such as, rescuing operations, and other emergency operation such as occur in water floods, hurricanes or typhoons, landslides, earth quakes, explosions, fires, massive accidents of transportation systems or production systems, and terrorist acts, etc. Almost all happen unexpectedly, and in general, are not the subject of normal outdoor lighting considerations. As regards light pollution aspects, it is usually understood that the priority for calamities is higher than that of environmental protection, light pollution included.

11.3 Lamps for outdoor lighting

11.3.1 Light emitting principle and groups of lamps

(a) Principles of light emission.

The physical principles of light emission are discussed in detail in sec. 11.1. Fundamentally, the efficacy, the colour of the light, the colour rendering properties and other electrical and physical characteristics of the lamps are different for different lamp types. They depend on the physical phenomena of the light generation on which the lamp is based. The luminous efficacy is described in sec. 11.3.2b. The colour of the light is discussed in sec. 8.3.7, and the colour rendition of lamps in sec. 8.3.8. The discussion about lamps will be restricted to electric lamps. Electric lamps are classified into three major groups, depending on the principles of light generation.

(1) Incandescent lamps;
(2) Gas discharge lamps;
(3) Semi-conductor lamps.

The physical principles of these lamp groups are discussed in sec. 11.1.

(b) General construction of electric lamps

Almost all electric lamps, except some types of semiconductor lamps, consist of four elemental parts.

(1) The light-emitting element.
(2) An outer bulb or envelope to protect the light emitting element.
(3) A mounting structure on which the light emitting element is fixed within the lamp.
(4) One or two caps to connect the lamp to the electric source.

Incandescent lamps have a filament structure and discharge lamps have an arc tube as their light-emitting element.

(c) Designation of lamp types

In most cases, lighting engineers use the lamp designation from the lamp constructing company they know best. For many local lighting schemes this is sufficient, but brand names are not common in general literature, and they are not suitable when the lamp types are discussed on an international base. In order to overcome these draw-backs, the International Electric Commission IEC proposed a set of international lamp designations. They are given in Table 11.3.1.

Lamp category	Common designation (usually Philips)	ILCOS designation
Standard incandescent lamp	GL(S)	I
Halogen incandescent lamp	–	H
Fluorescent tube	TL	F
Compact fluorescent tube	CFL;SL;PL	FS;FB
High-pressure mercury lamp	HP	Q
ditto, fluorescent	HPL	QE
Metal halogenide lamp	HPI	M
High-pressure sodium lamp	SON	S
Low-pressure sodium lamp	SOX	L

Table 11.3.1: *Common and International Lamp Coding System (ILCOS. After Schreuder, 1998, Table 1.1. Based on IEC, 1993)*

It should be noted that the success of the ILCOS system is only limited. In this book, we have avoided to use too many abbreviations of lamp types. If done at all, often the Philips designations are used. In that case, this has always been mentioned.

11.3.2 Lamps as an energy conversion device

(a) Energy conversion efficiency

As has well been understood, the lamp is an energy-converting device from the electric energy into the visible radiation – the light. However, only a fraction of the total energy consumed by the lamp is converted into visible radiation. Other fractions of the energy that is consumed, are converted into invisible optical radiation, such as infrared and ultraviolet radiation. The remaining energy is transformed to heat, which heats up the lamp itself, the luminaire, and the surroundings. It is important to note that the heat, which warms the lamps up is an absolute necessity to maintain proper and efficient electrical, physical, and chemical operating conditions of the burning of the lamp.

The ratio of energy converted into visible radiation to the total energy consumed by the lamps is the energy conversion efficiency of the lamp. Examples of energy conversion efficiency of typical lamps are shown in the Table 11.3.2.

It is worth noticing that, as can be seen in Table 11.3.2, even modern discharge lamps have only about 3 times the energy conversion efficiency of incandescent lamps (30% as compared to 10%).

Lamp category	Efficiency (%)
Incandescent lamps (Gas filled)	10,0*)
Tubular fluorescent lamps	28,0
Compact fluorescent lamps	19,5
Low-pressure sodium lamps	40,5
High-pressure mercury lamps	16,5
Metal halide lamps	24
High-pressure sodium lamps	31,0

Table 11.3.2: *Examples of conversion efficiency of lamps. After Meyer & Nienhuis, 1988 and Anon., 1987*).*

(b) *Efficacy of the lamps*

The energy conversion efficiency, however, is not fully relevant to the visual efficacy of normal lamps. Visual efficiency implies as a ratio of the amount of visible light output generated by the lamp to the amount of the electric energy consumed by the lamp. The amount of light output must be measured to correspond to the brightness sensation induced in the human visual system by the visible energy stimuli on to the retina.

The difference between the energy efficiency and the visual efficiency is caused by the psychophysical properties of human visual system to the visible energy. It is shown that, even when equal amount of visible energy with different wavelengths stimulates onto the same location of retina, the brightness sensation takes place in the eye is not the same. This is due to the difference in the brightness responses of the retina to the visible energy for different wavelength ranges. As has been explained in detail in sec. 8.2.2, the spectral response of the retina is internationally standardized by CIE/ISO as the standard spectral luminous efficiency curve, or V_λ-curve, on which the measurements of light is based.

The visible energy that is either measured or calculated, taking account the internationally standard spectral luminous efficiency curve, is the basis of the photometric quantities. They are the basis of the luminous flux, the luminous intensity, the illuminance, the luminance, etc. The photometric units and their definitions are discussed in sec. 14.1.2.

The efficacy or visual efficiency of the lamp is defined as a ratio of the total amount of the luminous flux in lumens (lm) generated by the lamp to the amount of total energy in watts (W) consumed by the lamp burning. Due to the difference in the two units between the luminous flux in lumens and the energy consumed in watts, the term efficacy (lm/W), instead of efficiency (%) is used. In energy terms lm/W is dimensionless, because both the lumen and the Watt represent 'work'. In practice, however, the lm/W-expression is more convenient than the %-expression. This brings about the difference between the energy efficiency and the efficacy of the lamp. The efficacy of lamps must not be confused with the energy efficiency. In Table 11.3.3, examples of the efficacy of typical lamps.for outdoor lighting are shown.

Lamp category	**Type**	**Watt**	**Efficacy** (lm/W)
Incandescent lamp	Krypton filled 100 Volt	90	17
Incandescent halogen lamp	110 Volt	130	18,5
Fluorescent tube	White	40	77,5
Fluorescent tube	Triple bands	32	105
Metal halide lamp	Scandium*	400	100
Low-pressure sodium		180	175
High-pressure sodium		360	132

Table 11.3.3: *Examples of the efficacy of typical lamps for outdoor lighting. After Anon., 2003.*
**) other metals are added*

11.3.3 Incandescent lamps

The incandescent lamps have a filament or filaments in the outer bulb, as the light-emitting element. In modern lamps, the filament is always made from tungsten. The reason is its high melting point temperature and the fact that the mechanical properties do not change appreciably until a temperature close to the melting point temperature. A disadvantage is the fact that tungsten cannot be cast, so that filaments are always made by 'drawing' the sintered material. In order to enhance the efficiency of the light source, the filament is 'coiled' into a spiral; sometimes, the process of coiling is repeated, so that there are 'coiled-coiled' lamps. In the past there have been even 'coiled-coiled-coiled' lamps. When the filament is heated by the electric current up to a certain temperature, then the light is emitted. As is explained in sec. 11.1.1c, the characteristics of the material are the cause of the fact the light emission is considerably lower than that of a 'blackbody' or Planckian radiator of the same temperature. As the temperature of the filament increases, the luminous flux generated by the filament is increased. When the filament temperature reaches at the elevated temperature of about 2500 K, the filament becomes 'incandescent' and the lamp comes to the nominal burning conditions. Details of the construction and of the operation as well of the physical properties of incandescent lamps are described in detail in Barrows (1938), Hentschel (1994), Moon (1961), and Schreuder (1998).

Incandescent lamps are divided into two sub-groups. One is the normal or standard incandescent lamp and another is the halogen incandescent lamp.

(a) Normal incandescent lamps

The incandescent lamps form a huge family, as regards the size, shape, colour and finish (clear, diffuse, or coloured) of the bulb appearance, as regards energy consumption, nominal voltage, output luminous flux, caps, type of the filament, burning position, etc. Referring to the lamps for general lighting, as the normal incandescent lamp, the construction and the principles of the incandescent lamps for outdoor lighting will be briefly given here.

(b) Construction of the incandescent lamps

A normal incandescent lamp for general lighting consists of a spherical or an oval bulb made of glass or hard glass, a coiled tungsten metal filament, a supporting mount of the filament and a metal cap to fix and to connect to the electric source. Most lamps for outdoor lighting use have a clear outer bulb.

(c) Temperature of the filament and the luminous output

As mentioned in the foregoing, the incandescent lamps generate the luminous flux by the light emitting phenomena of the high temperature incandescent metal filament. Physically, the efficacy of the lamp improves as the temperature of the metal filament increases. A drawback of the increase in the filament temperature, however, is the increase in the speed of evaporation of the filament metal. The increase in the speed of evaporation of the filament metal leads to a shortening in the lamp life. Furthermore, the evaporated metal deposits onto the inner surface of the outer bulb of the lamp. This causes the outer bulb to appear black as the burning hours progress. For obvious reasons, this phenomenon is called the 'blackening' of the lamp. Blackening reduces the transmittance of the bulb and causes a rapid decrease in the luminous output of the lamp. The decreases in the luminous flux output by blackening deteriorate the efficacy of the lamp accordingly. Furthermore, the absorbed energy increases the bulb – and thus the lamp – temperature, reducing lamp life even further.

(d) Balance between the efficacy and the lamp life

In almost all incandescent lamps, an inert gas (Nitrogen, Argon, Krypton etc.) or a mixture of inert gases is put into the bulb. The gas pressure acts as a counter force to the evaporation pressure of the filament and thus prevents, or at least reduces, the evaporation of the filament. For obvious reasons, these lamps are called 'gas-filled lamps', contrary to the more rare 'vacuum lamps'. Due to the convection caused by the heated gas in the bulb, however, a part of energy consumed by the lamp is lost through the bulb into the outside atmosphere, and consequently the temperature of the filament decreases for the same electric energy fed to the filament. This brings about a reduction in the efficacy of the lamp. For this reason, the gas pressure to be pressed into the bulb is limited at an appropriate level to establish a balance between the efficacy and the blackening. At present, no drastic improvements in the efficacy and/or the life of the normal incandescent lamps can be expected. Consequently, the useful life of incandescent lamps is quite limited; see Table 11.3.4, where a number of different characteristics for various incandescent lamp types for outdoor lighting, as examples, are listed.

Type	Length (mm)	Cap. type	Luminous flux (lumen)	Normal life (hours)
J220V500W	118	R7S	8 750	2000
J220V1000W	208	R7S	21 000	2000
J220V1000W/I	138	wires	23 000	1000
J220V1500W	248	R7S	33 000	2000

Table 11.3.4: *Characteristics of various incandescent lamps for outdoor lighting. After Anon., 2003.*

Because many other lamp types have a lamp life much superior to that of incandescent lamps, the use of the normal incandescent lamps is rapidly diminishing for outdoor lighting. They are superceded by halogen incandescent lamps or gas discharge lamps.

(e) Advantage of incandescent lamps for light pollution

One noticeable advantage of the normal incandescent lamps relevant to the light pollution, however, is the fact that they can easily be dimmed. Several other lamp types may allow dimming as well, but one may adjust the luminous output of normal incandescent lamps simply by varying the input voltage of the lamps. By means of such a simple adjustment in the luminous output, the lighting system can provide various lighting levels that may be necessary for different purposes or functions. As an example, some areas need a high lighting level for limited occasions only and for limited durations during the year. During most of other periods, the area may used for other purposes, requiring a much lower lighting level or a lighting that is less uniform over the whole area. An installation with adjustable incandescent lighting enables to adjust the lighting levels easily and simply. In this way, one can get two advantages: by avoiding unnecessary excessive lighting, a reduction in the light pollution and a saving of electric energy for lighting. It should be noted that by dimming, the filament temperature drops, with the result that the lamp life increases but the lamp efficacy decreases. In sec. 10.4.1c, the dimming of other lamp types is discussed briefly.

(f) Halogen incandescent lamps

To improve the efficacy of the incandescent lamps without reducing the life of the lamps, the so-called halogen incandescent lamp was introduced. This method was invented in 1959 by G. Zebler. The construction and the operating principles of the halogen lamp are as follows. The metal filament is housed in a small bulb or a narrow tube, depending on the lamp type. The bulb or tube is usually made of quartz. Quartz is a transparent material, able to withstand much higher bulb temperature than normal glass, without losing its mechanical strength. In the quartz bulb or tube, an inert gas is pressed in the bulb with much higher pressure than normal incandescent lamp. The function of this high-pressure inert gas is explained later in this section. Details of the operation of halogen incandescent lamps are given in Hentschel (1994, sec. 5.2.2).

Some types of halogen incandescent lamps have an infrared reflection coating on the inner surface of the bulb. A part of the infrared radiation reflected back by the coating contributes to heat the metal filament and to increase the efficacy of the lamp.

(g) *Blackening of small sized lamps*

By means of a high gas pressure, the evaporation of the filament metal during lamp burning is greatly reduced. The application of the small bulb or the narrow tube brings about another advantage. Because there is only little space between the filament and the bulb wall, the gas convection, which carries energy from the filament to the bulb wall is reduced and consequently the convection losses as well. However, small bulbs or narrow tubes are more prone to blackening of their inner surface, due to the evaporation of filament material.

(h) *Halogen cycle as a countermeasure against bulb blackening*

To overcome the problem of bulb blackening, a halogen – such as iodine – is added to the filling of the lamp, allowing the so-called halogen cycle to develop. The halogen cycle takes place between the filament metal evaporated and halogen vapour in the bulb or the tube. The evaporated metal near the filament, due to very high temperature, diffuses toward the inner wall of the bulb or the tube where it is cooler than near the filament. Iodine forms a gaseous compound with tungsten metal around the inner wall. As the temperature around the inner wall of the bulb or tube is kept higher than about 250°C, the iodine compound is kept the gaseous state and, by convection, is moved towards the filament. Due to the very high temperature of the filament, the iodine compound is decomposed to the metal and the iodine. The metal deposits on the relatively cool spot on the filament and iodine repeats the process again. The principle is the same when other halogens are used. The process is described in Hentschel (1994, sec. 5.2.2).

(i) *Advantages of the halogen incandescent lamps*

Earlier in this section, a brief explanation has been given of the halogen cycle in the halogen incandescent lamp. In this way, the blackening inside the bulb or tube of small dimension is prevented. Consequently, the halogen lamps may reach a high efficacy, long life and less decrement in the luminous output during the life, while keeping the excellent colour rendering properties of regular incandescent lamps. The halogen lamp is widely used as the motorcar headlamps and the outdoor lighting installations, although some of them are being replaced by modern gas discharge lamps (Sec.12.2).

11.3.4 Discharge lamps

(a) *General construction of discharge lamps*

Gas discharge lamps utilise the light emitting phenomena when electric current passes through the gas or metal vapour contained in the arc tube, often called the 'burner'. The basic types of the discharge lamps were invented in the 1930s. For the history of these lamps, see the 'classical' works of Oranje (1942) and Elenbaas, ed. (1959, 1965). Since then, many kinds of discharge lamps have been developed and used. The most remarkable features of discharge lamps are the high efficacy, the long life and, in many types, the high luminance of the burner. The colour of the light and the colour rendering properties, however, of the earlier types of gas discharge lamps were poor. Since then, they have improvement greatly – at least for most lamp types. Consequently, modern gas discharge lamps are used in most larger lighting installations, both indoors and outdoors. The physical characteristics of gas discharges are described in some detail in sec. 11.1.1f. See also Hentschel (1994, sec. 5.1.2).

One more remark about the colour characteristics of gas discharge lamps. In sec. 11.1.1f, it is mentioned that the spectrum of low-pressure sodium lamps is (quasi-)monochromatic. This is due to the physical characteristics of the discharge and is thus inherent to this lamp type. It has been explained in sec. 1.2.5 that, as regards light pollution, this monochromatic character is often felt as an advantage. The poor colour quality is taken for granted.

The principal elements of discharge lamps are an arc tube, from which the light is emitted, a mounting structure, which supports the arc tube in a fixed position, the outer bulb, which protects the arc tube from various influences from the environment, and one or two caps, which connects the lamp to the electric source for burning.

The arc tube is the most important part of the discharge lamp. In the arc tube, gas or gases, and/or metal in which discharge takes place are contained. The arc tube is made of transparent glass or quartz. In many lamp types, aluminium ceramics are used, which is able to withstand the high temperature and the pressure of the discharge, the chemical attack by the high temperature metal vapour during operation of the lamp burning and is still transparent – or translucent – for the appropriate wavelengths. At each end of the arc tube, an electrode is provided to make the gases or vaporised metal can be discharged. Many types of discharge lamps have no outer bulb, like e.g. the fluorescent lamps that will be discussed later in this section. The arc tube plays a double role as the arc tube and the outer bulb at the same time.

(b) Groups of discharge lamps: basic discharge lamps

The discharge lamps are categorised into three major groups. In historical order of invention, the first group is the (basic) discharge lamps for various gases and metal vapours, which have a clear bulb, through which bright arc tube and discharge are visible while lamp operation. Throughout this book, we will call a gas discharge lamp a 'basic' lamp if the bulb is not coated with fluorescent material. Also, in this case, the arc tube does not contain any halogen compound. A variety of the basic discharge lamps has been developed by using various gases and metals to be vaporised. The basic discharge lamps for outdoor lighting used at present are the low-pressure sodium lamps and the high-pressure sodium lamps.

(c) Groups of discharge lamps: fluorescent discharge lamps

The second group consists of the fluorescent discharge lamps. They have an outer bulb on the inner surface of which the fluorescent material is coated. Neither the arc tube nor the discharge of this group of lamps is visible through the outer bulb. The coating of the inner surface of the outer bulb is the only difference in the appearance between the basic discharge lamps and the fluorescent discharge lamps. To this category belong the high-pressure florescent mercury lamps, which widely used for street, road, and sports stadium lighting (Van Bommel & de Boer, 1980). The primary purpose of the fluorescent coating is to improve the colour quality of the lamps by adding more red light to the predominantly green or bluish light of the traditional high-pressure mercury discharge. Because of the large amount of mercury in the lamps and because of the rather low efficacy, colour-corrected high-pressure mercury lamps are replaced in modern lighting installations by the more efficient high-pressure sodium lamps and by the metal-halide lamps with better colour quality.

A very important part of the second group are the fluorescent tubes. These lamps operate a low-pressure-mercury discharge that emits mostly ultra-violet radiation. The fluorescent coating is essential in order to get any visible light out of the lamp. The fluorescent tubes are predominantly in use in interior lighting, although they are common as well in outdoor lighting, particularly in the lighting of residential streets, where the traditional fluorescent tubes are replaced more and more by the compact fluorescent lamps.

(d) Groups of discharge lamps: metal-halide discharge lamps

The third group consists of the metal-halide discharge lamps. The basis of the metal-halide lamps is the high-pressure mercury discharge lamp with a clear bulb. In the arc tube of the metal-halide lamp made of quartz or alumina ceramic, however, in addition to mercury metal, halide compounds of rare earth metals are contained (Meyer & Nienhuis, 1988). The spectra emitted from the added rare earth metal vapours improve the colour, colour rendering and the efficacy of the original high-pressure mercury lamps. The metal-halide discharge lamps are used for lighting of large sized sports stadiums, squares, etc., where whitish colour and good colour rendering is necessary.

A description of the different lamp types and of their construction and operation is given in Hentschel (1994, sec. 5.2.3-5.2.9).

(e) Nomenclature of basic discharge lamps

The colour, colour rendering, efficacy, the luminous flux of the lamps are different. They depend on the kind of the gases or of the vaporised metals that are used, on the vapour pressure etc. Discharge lamps are named, normally, by the pressure of the gas or vapour during operation and the name of the gas or metal from which major light is generated in the arc tube. In the cases of the metal halide lamps, no pressure is mentioned in the name.

The most frequently used metals for the discharge lamps for outdoor lighting are mercury and sodium, which have a low melting point temperature. As mentioned already, the pressure of the gas or the vapour during operation influences the characteristics of the lamps, such as the colour, the colour rendering, the luminous efficacy. At present, the most widely used lamps are the high-pressure sodium lamps and the metal-halide lamps.

The nomenclature of gas discharge lamps that commonly used at present, differs somewhat for different manufacturers. Therefore, as mentioned in sec. 11.3.1c, an internationally accepted nomenclature of lamps is introduced. See Table 11.3.1

(f) *Ignition and discharge of the lamps*

As has been explained in sec. 11.1.1f, gas discharges are based on the ionization and the subsequent recombination of the atoms in the gas or vapour. These processes do not require a very high voltage difference between the cathode and the anode. However, in order to start the gas discharge by allowing the electric current to pass through the gas or the vapour, a much higher voltage is needed. When the gas or the vapour in the arc tube is ignited, then discharge takes place and consequently, light is generated. In most discharge lamps, at the very beginning when the discharge is started, the temperature of the metal is low, and equals the ambient room temperature; consequently the vapour pressure is low. As the arc tube is heated up by the discharge, the temperature of the metal vapour and the vapour pressure of the metal increase gradually and finally reach a stable condition of discharge. In most gas discharge lamps, this takes several minutes. For almost all gas discharge lamps, special gear – usually called a 'starter' – to ignite the discharge is needed.

11.3.5 Fluorescent high-pressure mercury discharge lamps

(a) *Principle*

The arc tube of high-pressure mercury discharge lamps emits, in addition to the visible radiation, invisible radiation in the ultra-violet wavelength range. By applying fluorescent materials, the invisible ultra-violet radiation can be converted into radiation in the visible light. This is the principle of the fluorescent discharge lamps.

(b) *Construction*

The fluorescent high-pressure mercury discharge lamps have an outer bulb, the inside surface of which are coated with the fluorescent materials. The ultraviolet radiation emitted from the arc tube strikes the fluorescent coating and it is converted into visible light. The additional visible light adds new colours to the spectrum; thus, the colour and the colour rendering properties are improved.

(c) *Difference between high-pressure mercury lamps with clear bulb and the high-pressure fluorescent mercury lamps*

In appearance, size and shape, the high-pressure fluorescent mercury discharge lamps are quite similar to the basic high-pressure mercury discharge lamps, except in the appearance of the outer bulb. While the bright arc tube of the basic discharge lamp is visible through the clear outer bulb during the operation of the lamp, the arc tube of the fluorescent mercury discharge lamp is not visible because the inner surface of the outer bulb is coated with the fluorescent material. Consequently, the brightness of the fluorescent mercury discharge lamp is much lower than the basic discharge lamp, and the size of the light emitting area is much larger than that of the basic discharge lamp of the same wattage.

(d) Optical control and light pollution

The degree to which the light of a lamp can be directed by the optical systems in the luminaire – the 'light control' – depends on the ratio between the dimensions of the actual light source and those of the optical means in the luminaire. This implies that it is theoretically hardly possible to design a compact and precise optical control system for such a lamp with a large light-emitting surface. Consequently, the high-pressure fluorescent mercury lamps are usually only used in luminaires with rough optical control, luminaires that have a wide spread of light. It can be envisaged that the use of the high-pressure fluorescent mercury lamps was a part of the background cause of the light pollution in the past. See also sec. 12.4.4.

11.3.6 Metal halide lamps

(a) Historical background

The basic high-pressure mercury lamp was invented in the 1930s. Since then, the lamps have been used widely for various applications, such as the lighting of streets, roads, factories, sports facilities, etc. A major drawback of the lamp was the unpleasant colour of the light and the poor colour rendering properties. It was understood that the unpleasant colour and the poor colour rendering was caused by a lack of spectral light in some important wavelength ranges in the light generated from the mercury discharge. The colour qualities were improved by the fluorescent mercury lamps that were developed around 1960, as mentioned in sec. 11.3.5. However, that lamp type had another drawback as regards light control.

To improve the colour of the light and the colour rendering properties without relying on a coated bulb, attempts were made already in early stage of development in the 1930s, to add other metals, which emit, if vaporised with an appropriate vapour pressure, the spectral colours lacking in the light generated from the basic high-pressure mercury lamps. These first attempts, however, were not successful, since the melting temperature of the metals that were used, was much higher than that of mercury. These metals did not evaporate with a sufficient vapour pressure under the operating temperature in the arc tube of the mercury lamps. In addition, it was known that the vapour of these metals, when very hot, become chemically aggressive and attacked the material of the electrodes as well as the arc tube itself; also, they caused serious blackening of the lamp.

(b) Introduction of the halogen cycle

To solve the problems, metal-halide compounds were applied, the vapour pressure of which is much higher than the elemental metal substances. (Reiling, 1961). As is the case in halogen incandescent lamps, the compound near the wall of the arc tube is evaporated by the heat caused by the discharge. When the compound gets into the high temperature zone in the discharge, the compound is decomposed.

Consequently, the spectral colours of the vaporised metals are emitted and mixed with the spectral colours of the mercury discharge. At the same time, the blackening of the arc tube due to attack by the added metals was prevented. By selecting metals, in addition to the improvements in the colour and the colour rendering of the lamp, an increase in the lamp efficacy has been resulted. In modern metal halide lamps, dysprosium and other rare earth metals are used as metals.

11.3.7 Semiconductor lamps

As has been explained in sec. 11.1.1h, the physical principles of the light generation in semiconductor lamps differs from those of incandescent lamps and of gas discharge lamps. The semiconductor lamps generate luminous flux from light emitting phenomena when the electric current passes through the light emitting diode. For outdoor lighting, however, at present, semiconductor lamps are not used at a large scale, except for traffic signals and some signal lamps for automobiles. However, a new development should be mentioned, where light emitting diodes (LEDs) are used in self-luminous road markers on roads where a full traditional road lighting installation is not warranted, but that cannot be left completely dark for reasons of road safety. Some examples are given in sec. 7.1.4c, where the emphasis was primarily on the reduction of light pollution. Also, the reduction of energy usage was taken into account. See also Jongenotter et al. (2000).

11.3.8 Features of lamps for outdoor lighting

Each of the above lamp types has specific advantages and specific disadvantages. The advantages and the disadvantages of a lamp type differ for application conditions. In the following section, the advantages and the disadvantages of the lamps for outdoor lighting are summarized in general terms. Some remarks have already been made in the foregoing sections. See also CIE (1993).

(a) Normal incandescent lamps

The advantages of the normal incandescent lamp are: (1) small size of the light emitting area, (2) good colour and colour rendering, (3) easiness in dimming operation. The small size of the light emitting area makes easy to design good optical system. The disadvantages are: (1) low efficacy, (2) short life, (3) less mechanical accuracy than modern lamps. The mechanical accuracy of the lamp gives a strong influence on the performance of optical system of the luminaires.

(b) Halogen incandescent lamps

The advantages of the halogen lamp are: (1) higher efficacy of the lamp than normal incandescent lamp, (2) longer life of the lamp than normal incandescent lamp, (3) compact size, (4) good colour and colour rendering, (4) less depreciation in the output luminous flux during the life, (5) small size of the light emitting area, (6) high mechanical accuracy. The lamp makes it possible to use them in compact luminaires with good optical control.

(c) Low-pressure sodium lamps

The advantages of the low-pressure sodium lamps are: (1) the highest efficacy in all lamps, (2) less depreciation in the luminous flux, (3) long life, (4) yellow monochromatic light, (5) ignition possible at low ambient temperature conditions. The use of the monochromatic light from the low-pressure sodium lamps for outdoor lighting is one of the most effective ways to reduce the interference against the astronomical observations. The disadvantages of the low-pressure sodium lamps are also (1) yellow monochromatic light, (2) large size of the light emitting area. The yellow monochromatic light makes it difficult to perceive colours of the illuminated objects under sodium lighting. The large size of the light emitting area makes difficult to design an optical system of compact and good light control.

(d) High-pressure mercury lamps

The high-pressure mercury lamps without fluorescent coating bulb were widely used for large sized lighting installations until around the 1950s. Due to bluish colour of the light and poor colour rendering, the lamps have not been used for outdoor lighting at present.

(e) Low-pressure fluorescent mercury lamps (Fluorescent lamps)

Fluorescent lamps may have a tubular or a circular shape. The tubular lamps are often called 'fluorescent tubes'. Many modern fluorescent lamps have a compact shape by folding the tube, and are called compact fluorescent lamps. The advantages of the low pressure fluorescent lamps are: (1) high efficacy, (2) good colour and good colour rendering, (3) long life, (4) less light depreciation, (5) dimmable characteristics. The lamps are widely used for most of the interior lighting. Compact lamps are also used for street lighting in residential areas and gardens. The disadvantages of fluorescent lamps are: (1) large size of the light emitting area, (2) relatively low luminance, (3) small output luminous flux, (4) difficulty of ignition at low temperature, (5) dependence of the luminous output and the efficacy on the ambient temperature. Due to the large sized light emitting area it is difficult to design a compact optical system with precise optical control. The dependence of the ignition and the luminous characteristics of the lamp on the ambient temperature make it difficult to use the lamp for large sized outdoor lighting installations.

(f) High-pressure fluorescent mercury lamps

The high-pressure fluorescent mercury lamps were widely used for most of outdoor lighting installations in the past. The advantages of the lamps at the time were: (1) high efficacy, (2) whitish colour, (3) long life, etc. In recent decades, however, most of advantages have been lost, due to introduction of the high-pressure sodium lamps. The disadvantages of the lamp at present are: (1) low efficacy, (2) large sized area of light emission, (3) mercury waste in broken lamps. The efficacy of the high-pressure fluorescent lamps is about a half of that of the high-pressure sodium lamps.

(g) High-pressure sodium lamps

The advantages of the high-pressure sodium lamps are: (1) high efficacy, (2) high luminous output, (3) long life, (4) small sized area of light emission, (5) lesser depreciation, in the luminous output during the life hours, (6) compact size. All these advantages make the lamp most suitable for outdoor lighting installations at present. The disadvantages of the lamp are: (1) too reddish-yellow colour of the light, (2) unsatisfactory colour rendering properties. Though, a type of the high-pressure sodium lamps with improved colour and colour rendering have been developed, the efficacy of the lamp, however, is lower and used for special applications only.

(h) Metal-halide lamps

The advantages of the metal-halide lamps are: (1) high efficacy, (2) compact size, (3) large luminous output, (4) whitish colour, (5) small size of the light emitting area, (6) high luminance, (7) excellent colour rendering properties. The disadvantages are: (1) shorter lamp life, (2) relatively rapid depreciation in the luminous flux, (3) instability of the colour of the lamp for burning hours and burning position (horizontal, vertical, etc), (4) mercury waste in broken lamps. The average life of the lamp is about half of that of the high-pressure sodium lamps. For these disadvantages, the application of the metal-halide lamps is, for general outdoor lighting, still limited.

11.4 Luminaires

11.4.1 General aspects of luminaires

A luminaire is a device, which distributes the luminous flux generated by a lamp or lamps for the necessary directions and restricts that for the unnecessary directions. The luminaire, includes all the items necessary for fixing, operating, protecting the lamp or lamps, and for connecting them to the supply circuit, depending on its type and on the application requirements (Van Bommel & De Boer, 1980).

(a) Photometric functions of the luminaire

The photometric functions of luminaires in an outdoor lighting system are to control the direction and the distribution of the luminous flux generated by the lamps, to change the brightness and/or the colour of the lamp. To adjust the direction of the luminous flux, some luminaires have a device by which the direction of the light projected by the luminaire can be varied (See also sec. 12.4.4). In addition, a visual function is required to decorate the daytime as well as the nighttimes appearance of the lamp to suite the environment where the lighting is to be installed.

(b) General construction

Basically, the luminaires for outdoor lighting consist of five elementary components. They are: (1) a housing; (2) a lamp holder; (3) auxiliary devices; (4) electric wiring and (5) an optical system (not in order of importance). These elementary components have a variety of constructions, from a luminaire to another, in shape, size, design, and materials. It is therefore difficult to give one general explanation for all the points concerning these components. Below, barring possible exceptions, only typical points will be described and explained.

(c) Housing

The function of the housing – also called the chassis – is to house the lamp and other elementary components and to protect them from mechanical, physical, electrical and chemical influences caused by the environment (Van Bommel & De Boer, 1980).

Mechanical shocks, vibrations, wind pressure and accumulation of dust and dirt due to the 'breathing' of air in the luminaire during lamp burning cycles, etc. are included in the mechanical influences. Unusual changes in ambient temperature and humidity, etc. are included in the physical influences.

Ingression is caused by cyclic changes in the air temperature in the lamp compartment in the luminaire housing and consequent changes in the air pressure. While lamps are burning, the temperature and the consequent air pressure in the lamp compartment increases and if the tightness of the housing is insufficient, a portion of the air leaks out from the compartment. Some time after the lamp is extinguished, the air temperature decreases gradually and finally is cooled down to the ambient temperature. In the course of cooling, the air pressure in the lamp compartment decreases accordingly to a pressure lower than the normal atmospheric pressure surrounding the luminaire. If the tightness of the lamp compartment is imperfect, to supplement the leaked out volume of the air, the same amount of the air is leaked back in the lamp compartment, together with moisture, small particles of smoke, of chemical materials, of dust and dirt, etc. floating on the atmosphere. Such cycle of pressure variations in the lamp compartment is called the 'breathing' of a luminaire. The breathing is repeated every time when lamp is turned off and, during a long time, the particles that got in, accumulate on the outer surface of the lamps and the optical system and also the inner surface of the luminaire cover glass. The consequence is a heavy deterioration of photometric performance of the luminaire, due to loss of the luminous flux. With this in mind, it is sometimes suggested to use open luminaires in stead of luminaire that are inadequately sealed (sec. 11.7.1).

Lightning strikes and contacts with high voltage external wiring, etc. are included in the electric influences. Finally, corrosion caused by chemical liquids, water, gases, smoke, and – more in particular – the influence of environmental pollution are included in chemical influences. When exceptional external conditions are expected, the housing is fabricated with special way of construction using special materials and/or materials with special coating, treatment or finishing.

Evidently, the housing must have an opening through which the light of the lamp can leave the luminaire. In most modern luminaires for outdoor lighting, the opening of the housing is tightly covered with a light transmissible cover, made of glass or plastic. They are in a form of a clear plate or a bowl, with or without prisms or diffusing finish. The cover must fulfill severe requirements particularly as regards its tightness against the ingression of water and dust. The ingress protection is expressed in the well-known IP-numbers. Details are given in Schreuder (1998, sec. 13.3.2., tables 13.3.3 and 13.3.4). Luminaires with an open reflector without a light transmissible cover were widely used in the past for lighting of streets and roads. In such open luminaires, the lamp and optical system are exposed to the atmosphere. Dust and dirt will easily accumulate in open luminaires causing a rapid decrease in the luminous output of the luminaire. Open luminaires are not used often any more in modern street and road lighting installations in industrialized countries. It must be stressed, however, that the cover needs to be really tight. Modern outdoor lighting standards and recommendations require that luminaires for outdoor use must be in agreement with the ingress protection class of IP 65 or better. If the cover is not really tight, the 'breathing' of the luminaire will cause severe accumulation of moisture, dirt and dust within the luminaire, resulting in an even more severe deterioration of its photometric performance than an open luminaire. Therefore, contrary to the more general trend, open luminaires are still used on a large scale in developing countries. Details are given in Schreuder (1996, 2001). Open luminaires for use in simple installations are briefly discussed in sec. 11.7.3. It must be noted as well that, for open luminaires that are mounted precisely horizontal, the ULR that is discussed in detail in sec. 11.6.6, is exactly zero – a fact that is considered to be very favourable for the restriction of light pollution.

(d) Other elementary components

The other elementary components of the luminaire housed in the housing are, the lamp holder, the auxiliary devices for lamp operation and the wiring to supply electric energy to the lamp. The lamp holder is self-explanatory. The auxiliary devices housed in the housing are the ballast, and the igniter or the starter for discharge lamp.

The ballast is a device which controls the electric current of the discharge lamp. The ballast has a number of functions. One is to act as a resistance – or rather impedance – in the circuit. All gas discharges have a 'negative resistance coefficient', which means that the electric resistance of the lamp decreases when the current increases. This is, of course, different from an Ohm resistance, which does not depend on the current. Without an external resistance, a gas discharge circuit would immediately be overloaded, resulting in a short-circuit, or even worse.

It should be noted that, in an alternating current circuit, the resistance and the impedance are not the same. For a magnetic coil, which is the principal component of ballast, the Ohm-resistance is the same for alternative current and the direct current. In an alternating current circuit which includes a magnetic coil, there is a phase shift between voltage and current, which depends on the frequency. The compound effect is called the impedance. Impedance not always causes energy loss. The good quality ballast therefore is made to produce maximum impedance with minimum resistance, to minimize the loss of energy and the excessive temperature rise. It is, however, customary – if not completely correct – to use 'resistance' and 'impedance' as synonyms.

Further, the ballast is a transformer that transforms the external voltage into the required lamp voltage that usually is considerably lower than the mains voltage. Thirdly, the ballast is a stabilizer to counteract external disturbances, particularly as regards deviations in the mains voltage. Next, in many modern installations, the lamps operate at a high frequency of several kHz in stead of the common 50 or 60 Hz of the traditional mains network. This allows for a considerable increase of the photometric performance of the lighting installation. See also sec. 1.2.5b. The ballast converts the frequency accordingly. And finally, in many modern installations, the light output of the lamps is adjusted to the momentary requirements. This is called 'dimming'. Modern ballasts often include the required dimming devices.

So, a gas discharge lamp cannot operate without its appropriate ballast. As it always represents some electric resistance, there are always ballast losses. These losses can be quite considerable. Almost all lamp manufacturers publish their lamp data in such a way that they only refer to the lamps themselves. When considering or when designing lighting installations, the ballast losses must be taken into account additionally. One of the major improvements in the overall efficiency of lighting installations is to reduce these ballast losses. An important improvement is the high-frequency lamp operation that has been mentioned above.

Igniters and starters have a similar function, viz. to start the gas discharge. As is explained earlier in this section, the gas or vapour in the lamps at rest are molecules of different metals or of different compounds of metals. These gases of vapours do normally not conduct electricity. In order to get the gas discharge started, a very high voltage is needed – often well over 1000 Volt. This high voltage causes a discharge not unlike a lightning discharge in the gas or vapour that is sufficient strong to ionise a number of the atoms of the gas or vapour. When sufficient atoms are ionized, a plasma is generated that allows the regular gas discharge to develop at the normal operating voltage of the lamp. This operating voltage is much lower than the ignition voltage. The igniter and the starter are sometimes incorporated in the ballast; sometimes they are separate units, depending on the lamp type. Often, the igniter – or 'ignitron' – is built into the lamp itself. Some luminaires do not house ballast in the housing to make the luminaire light and compact. The ballasts are located in the lower part of the pole or on the frame construction at the top of the tower, depending on the technical conditions.

(e) Optics

The function of the optical systems in luminaires is, as is well known, to distribute the luminous flux generated from the lamp towards the directions necessary to light and at the same time to eliminate the light emission toward the directions unnecessary or disturbing. This usually called 'light control' or 'optical control'. The optical system is one of the most important elements of the photometric performance of the luminaire. It determines the efficiency of the lighting system and the prevention of light pollution. The details of the optical system will be discussed in the next section 11.4.2. See also sec. 12.4.4. The principles of geometric optics are explained in sec. 11.1.1a.

11.4.2 Optical systems

The optical system determines the photometric performance of the luminaires. The two main principles to direct the light in the desired direction – the light control – that are used in outdoor lighting luminaires are reflection and refraction. The corresponding elements of the optical system are mirrors or reflectors and lenses or prisms. See sec. 11.1.1a.

(a) Reflection

One of the bases of the optical system for luminaires for outdoor lighting is reflection. When the luminous flux from a light source strikes a point of a flat surface, a part of the luminous flux is reflected, and the remaining flux is absorbed. The ratio of the amount of the reflected luminous flux to the total incident luminous flux is the reflection factor.

The direction of the luminous flux after reflection, however, is significantly different, depends on the combination of the reflection properties of the lighted surface and the size of the light-emitting area of the lamp.

All the modes of the reflections are classified between two extremes, the specular reflection and the diffuse reflection.

(b) Mirror in combination with a small light source

When a very narrow, almost parallel beam of light strikes a point of a flat surface, the well-known law of specular reflection or 'the Huygens principle' determines the direction into which the light is reflected. When the beam of light is very narrow and parallel, we may speak of rays of light. The Huygens principle states that the angle between the incident ray of light with the normal on the surface equals the angle between the reflected ray of light with the normal. It should be noted that the angle of reflection does not depend on the wavelength of the light, contrary to the refraction that will be explained in a further part of this section. The reflection is called the regular reflection or perfect specular reflection. In real life surfaces, however, the theoretical strict parallelism is lost to some extent. In the following, 'specular reflection' means a mode of reflection with properties that are quite near to the perfect specular reflection as occurs at the surface of a perfect mirror. The surface on which the light is reflected, is called the specular surface or the mirror.

As said before, in specular reflection the angle of incidence of and the angle of reflection of the light beam are equal. When an observer looks at a lighted point on the mirror from the direction of the angle of reflection in the dark, the observer sees a clear and sharp image of the small lamp behind the surface, while the other part of the mirror is seen as perfect black. As the specularity of the surface is less perfect, which means that the light is slightly diffused, the spread of the light after reflection increases, and, consequently, the size of the reflected image of the light source increases and the contour of the reflected image is blurred.

In the design of outdoor lighting luminaires, several standard shapes of mirrors are used, each reflecting the light in a specific way. They are the parabolic mirror, the ellipsoid mirror and the spherical mirror. These mirrors are symmetrical for the axis of the mirror and in many cases the cross sections of the mirrors on the surfaces perpendicular to the axis are circles. The parabolic mirror reflects the light from a special point on the axis of the mirror toward the direction parallel to the axis. The special point is called as the focal point. An ellipsoid has two focal points and the ellipsoid mirror reflects the light from one focal point to another focal point. The spherical mirror reflects back all the light from the focal point toward the focal point again. Here, the focal point coincides with the centre of the sphere. Further details of the mirror optics can be found in the textbooks dealing with optics.

The optical system of the luminaires for outdoor lighting is constructed by using parts of such mirrors alone or in combination with the lenses and prisms that are discussed in a further part of this section, in such a way that the required light distribution can be obtained efficiently, simply and compactly to make the cost of the luminaire low.

(c) Mirror in combination with a large sized lamp

A large sized lamp is, optically, equivalent to an aggregate of many small lamps arranged in such way that they seem to fit in the shape of the light emitting area of the large sized lamp. When many narrow light beams from different small parts of a large sized lamp strike a point of a mirror, the directions of many reflected narrow light beams are diverged toward a wide spatial area, optically corresponding to the apparent size of the lamp seen from the point of the mirror, since the angle of the incident light from each small lamp is different.

Such diverged light beams cannot be concentrated by any mirror system as can be done with a narrow beam. This implies that, for any mirror system, optical control for a large sized lamp is not efficient in comparison with that for a small lamp.

(d) Diffuse reflector

If a surface illuminated has a strictly constant luminance, irrespective of the angle of the light incidence and/or the angle of observation, the surface is called a perfect diffuse surface. Also terms like Lambertian reflector, diffusor and diffuse reflector are used. Reflection of such a perfect diffuse surface is called as the perfect diffuse reflection. Real life surfaces, however, do not perform like perfect diffusors. For short, we will call a surface which has a reflection close to the perfect diffuse reflection, a diffuse reflection surface as well.

A surface, which eliminates light emission to the unnecessary directions by its geometric shape and the spatial size with respect to the lamp, and controls the distribution of light from the lamp by diffuse reflection, is called a diffuse reflector.

This means that a perfect diffuse reflector scatters the incident lights from any direction, or irrespective of the direction of the incident light, or irrespective of the size of lamp combined, to all semi-spherical angular region on the lighted surface so that an equal luminance is produced. This does not mean, however, that the luminous intensity distribution of reflected light for different directions in the semi-spherical region is uniform, because the luminance measured from a direction is the ratio of the luminous intensity to the measuring direction to the orthogonal projection of the relevant light-reflecting surface.

In the past, diffuse reflectors were used on a large scale in luminaires for outdoor lighting. In more recent installations, where a precise control of the light distribution is required, they are not used any more. Their use is restricted to special purposes, like e.g. the luminaires for flower gardens, suspended at a very low mounting height below the normal eye level.

(e) Refraction properties of the lens and prisms

As is well known, the optical principles of lenses and of prisms are the same. The path of the light that strikes the boundary surface of two optical media in which the refractive index is different, is broken. The optical phenomenon is called refraction. The angle over which the light rays are broken depends on the ratio between the refractive indices of the two media. Theoretically one can prove that the speed of light is different in the two media. It should be noted that the refractive index of all material substances – except the vacuum – is different for different wavelengths. Thus, the angle of refraction does depend on the wavelength of the light, contrary to the reflection that has been explained in an earlier part of this section. The similarity of the refraction phenomena in lenses and prisms can be easily seen when the lens is thought to be split up in prisms. In optical instruments like microscopes or telescopes, lenses and mirrors usually have a rotation symmetry. The optical elements that are used in luminaires are either elongated (ellipsoid) or even straight like true prisms. Such lenses and such mirrors are called prismatic lenses or prismatic mirrors.

Prisms refract the light in a direction perpendicular to their straight edges. A prism arranged in a vertical positions, for example, refracts the light passing through it into a horizontal direction. If a parabolic mirror, which reflects the light from the small lamp equipped in the direction parallel to the axis of the mirror, is combined with vertical prisms, a light beam, narrow for the vertical directions and wide for horizontal directions can efficiently be obtained. Such a light beam is used for the lighting of large sports stadiums.

For luminaires for outdoor lighting, lenses are used only for special cases, like e.g. for motorcar headlights and for traffic signals. Some road lighting luminaires contain prismatic lenses in combination with prisms.

(f) The general shape of luminaires for outdoor lighting

In principle, mirrors or reflectors are equivalent as means to control the light emitted from the luminaire. In practice, however, the difference between the two methods of light control is considerable. For obvious reasons, normal mirrors are opaque: the light is always reflected backwards. This means that, as seen from the area to be illuminated, the mirrors must be placed always behind the light source. Thus, reflector luminaires can be covered with a flat glass or even be left open. The contribution to light pollution can therefore be very small or even absent. See also secs. 12.4.3 and 12.4.4. For reasons that are just as obvious, lenses or prisms are transparent. This means that, as seen from the area to be illuminated, the lenses or prisms must be placed always in front of the light source. A very important exception to this rule are the retroreflectors that are discussed in detail in sec. 14.1.9. For obvious reasons, retroreflectors have no place in luminaires for outdoor lighting. Usually, the cover of reflector luminaires contains the optical elements. They cannot be covered with a flat glass. The implication is that the contribution to light pollution usually is considerable; so is the contribution to glare. In spite of this, refractor luminaires are used on large scale, particularly in road lighting.

11.4.3 Types of luminaires

(a) Classification of luminaires (transportable or stationary)

There are two types of outdoor lighting luminaires, which are the transportable type and the stationary type. The transportable type is used only for provisional purposes or for very small lighting installation. The stationary type is permanently secured to the supporting structure. This is normal for almost all outdoor lighting installations. In this section, only the stationary type of luminaires will be discussed.

(b) Classification of luminaires (direction of light emission)

The stationary type of the luminaires are again categorised into two sub-groups, according to the changeability of the direction of the light emission. The first group is the luminaires, which direction of light emission is fixed or unchangeable. The second group, on the other hand, is the luminaires, where the direction of the light emission can be changed by turning the luminaire around the horizontal axis and/or the vertical axis. The fixed type of the luminaires are divided into two kinds, depends on the burning positions of the lamp equipped; the vertical burning and the horizontal burning, with respect to the normal mounting position of the luminaire. The luminaire which direction of the light emission is changeable is called a 'projector'.

(c) Luminaire for vertical burning lamps

This type of the luminaires is widely used on low posts for the lighting of small streets in the towns, of residential areas, of small bridges, of small parking area, of parks and gardens, of small plaza and squares, and of the premises around buildings. Usually, this type of luminaire is mounted on the top of a straight vertical mast or pole at a mounting height between about 4 m and 6 m. Usually, the spacing along the road or street is between about 20 m and 30 m. They are commonly designated as post-top luminaires.

Generally, the light distribution is symmetrical for the vertical axis of the luminaire. Sometimes, two or even more than two luminaires are mounted at the top of the post or pole by means or brackets. When a long lamp is used, the precise light control in the vertical plane parallel to the axis of the lamp is difficult. A relatively large amount of light is emitted in the directions unnecessary to the lighting purpose and is therefore lost. These directions usually are toward the sky (upward), directions in the areas where glare is likely to occur (near the horizontal) and directions toward the surroundings (downward but still too high over the normal lighting zone). All these light emissions represent waste and are often the cause for severe light pollution.

Some luminaires for vertical burning have no optical system. In these luminaires, the lamp is enclosed in a transparent bowl or globe made of glass or plastics, or in a simple classical lantern like a gaslight. In these lanterns, usually the complete lamp is directly visible from the normal viewing directions of pedestrians, car drivers, etc. Due to a lack of optical control, such a type of luminaires waste a considerable portion of the luminous flux toward unnecessary or disturbing directions, and the luminous flux reaching the necessary area is only a small part, implying a low overall system efficiency (Pasariello, 2003; Stroppa, 2003). Many globe lights have an ULR of over 50%! (Pollard, 1993, 1997). To eliminate waste of light and the light pollution and consequent loss in electric energy and money, the electrical efficiency and visual efficiency of these lighting systems have to be checked by lighting experts with great care. The reason that globe lights, in spite of all this, are used on a very large scale in all sorts of lighting installations – even sometimes on major traffic routes – is a mystery. It is often said that architects like them, but it does not seem likely that modern architects have so little knowledge about lighting and energy conservation and so little regard for the human visual system. Also, many architects complain that the lighting industry does not provide other luminaires than globe lights. Another point is, of course, that it is undesirable that architects have such a large influence on the nighttime scene. The fact that some lighting engineers consider themselves as a special group, even to the degree that they claim to belong to the special discipline of lighting designers, does not help (Pasariello, 2003). Clearly, exchange of information, and promotion of mutual respect, would be more useful. These points are discussed in sec. 15.3.1. Whatever the outcome of such exercises, it must be stressed with emphasis that the instances where diffuse globe lights can be sensibly applied in outdoor lighting projects, are strictly limited.

This does not imply, however, all the post-top or pole-top luminaires have a low efficiency and emit their light toward the unnecessary directions. By applying an optical system of good quality, in combination with a suitable small sized modern gas discharge lamp, it is possible to design a luminaire with a high efficacy at the same time a good light control. The performance of a luminaire must not be judged by its daytime appearance, but by technical data concerning light distribution.

As said before, often luminaires are used that look like simple classical lanterns such as those that were used in the past with gaslight. They are sometimes called period or vintage luminaires. These lanterns are often used in city centres of old cities, particularly in Western Europe, Latin America, Asia, and parts of Africa. Many cities and metropoles date back many centuries. Not only are the old parts of the cities still inhabited, but in may cases they are the true cultural and artistic centre of the city or metropolis. Some points are explained in sec. 2.4, where 'city beautification' is discussed. The lanterns for the cities are often especially designed to blend in with the architecture of the city. Many have the shape and size of the traditional lanterns that were originally used for gas or oil lamps. In those lanterns, as is mentioned earlier in this section, usually the complete lamp is directly visible from the normal viewing directions. To avoid the waste of energy, the glare and light pollution, often two lamps are mounted in the lantern. One is a small lamp like e.g. an 8 Watt compact fluorescent lamp that does not contribute to the actual lighting but serves only the appearance of the lantern. The other lamp is hidden from view and provides the actual lighting. There are many different types of such two-lamp lanterns available.

(d) Luminaires for horizontal burning lamps for roads and motorways

A horizontal position of the lamp – more precisely, of the discharge tube – allows the design of compact and efficient optical systems. Luminaires of this type are especially suited for the lighting of streets, roads, motorways, etc., where the lighting quality is expressed in luminance values. The reason is that the lamp can be placed with its axis perpendicular to the road axis. This means in the first place that the lamp emits a large fraction of its luminous flux in a direction parallel to the road axis. In the second place, the optical control on the vertical surfaces parallel to the road axis is easier than those on the perpendicular to the road axis. On the other hand, the road lighting luminaire needs to have a light distribution with a stronger intensity towards the direction parallel to the road axis, to light the road surface from a long distance between the two successive poles along the road, which is much longer than the mounting height of the luminaire. In addition to this, to light a uniform and sufficient road luminance efficiently, and to eliminate the possible glare from the luminaire to be experienced by the car drivers, precise and careful control of the light distribution on the vertical surfaces parallel to the road axis is necessitated. For this reason, the easiness in optical control of the horizontal burning lamp is advantageous to design good and efficient optical system for road lighting.

For this reason, the stationary luminaire for horizontal burning is used widely for lighting of streets, traffic roads, motorways and plazas. The luminaires of this type are mounted at a height of about between 10 m and 15 m with a spacing of about between 30 m and 50 m for the distance parallel to the road axis, on columns arranged along the road. The lengthwise axis of the lamp is, as discussed in the foregoing, placed perpendicular to the vertical plane parallel to the road axis. The luminaires are fixed to a horizontal bracket or an arm at the top of the column. Some types of luminaires have special housing, which can be fastened in the horizontal position directly at the head of the straight pole.

(e) Luminaire for horizontal burning lamps for catenary motorway lighting

Another type of luminaire with a horizontal lamp position is used for the so-called catenary lighting system (De Boer, ed., 1967; Van Bommel & De Boer, 1980; Schreuder, 1998). The luminaires are suspended from a span wire parallel to the road axis over the central reserve or median. Because of the suspension over the median, catenary lighting systems can be applied only on dual carriageway roads. In most cases they are used on motorways. The height is usually about 10 to 15 m with a short spacing of somewhere between 10 m and 30 m. The span wires are fixed to masts at a long interdistance of 100 m or more. For such a lighting system, where the spacing between successive luminaires is short, no accurate light distribution for the direction parallel to the road axis is necessary, except for the glare zone. Instead, a controlled light distribution on the vertical surfaces perpendicular to the road axis is needed in order to avoid that too much light falls outside the limits of the road. Such spill light may cause energy losses and light pollution. As a result of the outstanding optical guidance, this type of light distribution brings about special advantages for foggy conditions and for wet road conditions.

(f) *Luminaires for horizontal burning lamps for large area lighting*

Many large road and motorway exchanges, toll plaza, and large squares that are a part of a traffic route, are lighted by means of high masts or high towers, in which the mounting height is higher, often much higher, than about 20 m, depending on the size of the area to be lit. Normal road lighting luminaires, similar luminaires but larger in size, or projectors to be discussed under (g) are used, depending on the mounting height and the size of the area to be lit, and on the lighting requirements. The luminaires are mounted in the same way as the road lighting luminaries. Higher precision is desirable for the control of the light distribution of the luminaire to be mounted on high masts, because even a small inaccuracy in the adjustment of the luminaire may cause a large displacement of the point where the light strikes the ground.

(g) *Projectors – luminaires for large sized areas*

Projectors are a type of stationary luminaires, which allow the adjust the direction of the light emission within a designed spatial area. Normally, once the projector is installed, however, the direction is fixed.

Projectors are used for the lighting of large size areas, such as the apron of airports, bus terminals, construction sites, major road interchanges, road toll plaza, open workspaces, large parking area, railway marshalling yards, ship building docks, sports stadiums, etc. Despite these facilities occupy a large space, the places where the towers can be erected are usually strictly limited, because traffic, work and sport games, etc., have to be carried out in the area.

For this reason, it is desirable to keep the number of the supporting structures as small as possible. This implies that the size of the area to be lit by the projectors mounted on each of the supporting structures is relatively large, and, accordingly, a large luminous flux emission is necessary for the projectors on each of the supporting structures.

On the other hand, the actual size and the shape of the area to be lighted by the projectors on each of the supporting structures will usually be quite different. The required light beam of each of the luminaires mounted is not always the same for each mast in the area. Consequently, different requirements have to be fulfilled for the light distribution for each of the high masts and often even for each individual projector. If the light distribution of all projectors together is narrower than what corresponds to the extent of the area, some parts of the area cannot be lighted sufficiently. If, however, the light distribution is too wide, some light will fall outside the area. The light energy will be wasted and can cause the light pollution.

It is unrealistic, however, to design the luminaires in such a way that each has a particular and complicated shape of its light distribution. It is much more efficient to install a number of projectors, each emitting a relatively narrow and sharp, precisely controlled, beam. The required overall light distribution is synthesized by careful combination of a number of individual luminaires emitting slightly different types of beams, aimed at different places of the area to be lighted.

Such a type of the luminaires for outdoor lighting is called projectors. To synthesize the necessary light distribution in complex form by many projectors mounted on the high mast, they are constructed in such a way that the housing can be turned around the vertical axis as well as the horizontal axis, allowing the beam to be directed in the desired direction. Many projector types allow to adjust the beam spread as well.

The projectors can be classified into two types regarding the burning position of the lamp equipped. One is the type for a horizontal lamp position. The horizontal position of the lamp for this type of projector is not changed, although its orientation can be adjusted, irrespective of the vertical direction of the light beam emitted from the projector, since the lamp is fixed with the housing horizontally at the focal point (line) of the reflector. The reflector usually is facetted and parabolic in shape. This type of projector is usually equipped with tubular halogen incandescent lamps, low-pressure sodium lamps, tubular high-pressure sodium lamps and, sometimes, tubular fluorescent lamps. The wattage of the lamps depend on the importance of the installation.

It is to be noted that the light beam from a projector is consisted of two luminous components, i.e., the direct component and the reflected components emitted from the lamp equipped. The direct component is emitted for the frontward directions. Unless a second optical system precisely designed in front of the lamp, which reflect the frontward luminous flux toward the main optical control system of the luminaire behind the lamp is.provided, the frontward component is emitted without optical control directly from the lamp, irrespective of the spread angle of the beam of the projector. In most conventional projectors, however, a second optical system in front of the lamp is not provided. The reflected component is the rearward luminous flux from the lamp and it is reflected and controlled by the main optical system behind the lamp in the luminaire so as to produce a narrow light beam. This implies that roughly one half of the luminous flux is emitted from the projector without control and only one half of the luminous flux is controlled by the optical control system. Consequently, if the main axis of the projector is directed toward horizontal direction, roughly 1/4 of luminous flux, which is not controlled by any optical control system, will be lost in the upward directions. In addition to this, a considerable portion of the frontward component emitted toward downward direction without control will be lost because it shines in unnecessary directions. To eliminate the possible light pollution to be caused by the spill light from the projectors, it is advisable to direct the main axis of the projectors as close as possible to the vertical direction.

One of the important aspects of application of these projectors for large-scale lighting is the adjustment of their aiming direction. In the design of large-scale lighting installations extensive calculations have to be carried out by means of specialized computer programmes. On the basis of these calculations, the number of projectors with different light distributions to be mounted in each tower, the location of the points to which each projector is to be aimed, and the illuminance values on the points, etc. are determined. To realize the lighting conditions in the installation as designed, all projectors mounted have to be aimed correctly at the point to which the lighting is calculated. For this purpose, careful procedures for measurements of the illuminance on various surfaces relevant to the lighting, adjustment of focus and aiming of the projector have to be taken. In most cases the final adjustment is done while the installation is finished, just before it is put into use.

Modern projectors of this type are constructed in such a way that the different adjustments of aiming the light beam and of the focus that determines the size of the lit area per projector on the ground, can be done while the housing of the projector is immobile. In this way, it is possible to adjust the beams and the beam patterns while the cover glass of the projector remains exactly horizontal. Is has been found that the cover glass being not exactly horizontal is one of the major contributing factors of the light pollution that may be caused by such large-scale installations.

11.4.4 Luminous distribution curves of luminaires

The luminous intensity distribution curve of a luminaire indicates the spatial pattern of the luminous flux emitted from the luminaire (Hentschel, 1994, Schreuder 1998). The centre of the diagram corresponds to the optical centre of the luminaire. This means that the diagram is represented in polar coordinates. Hence, a diagram like that is usually called a 'polar diagram'. The vertical line through the centre gives the angle 0 degree for the downward vertical. The distance between the centre of the diagram and a point on the distribution curve shows the variations in the luminous intensity toward the directions for the downward vertical. The luminous distribution curves can be drawn on planes for various orientations around the vertical axis through the optical centre of the luminaire. Normally, however, the distribution curves are drawn on the vertical planes, parallel to and perpendicular to the axis of the luminaire. See also sec. 14.5.3d. The polar diagram is used for selection of luminaires.

11.5 Supporting structures

11.5.1 General aspect of the supporting structure

(a) Difference between outdoor and interior lighting

In interior lighting, the luminaires are almost always mounted in the ceiling. Objects in the room are lit, not only by the direct component of the luminous flux of the lamps, but also by the indirect component, which is the luminous flux being reflected by the floor, the walls, the ceiling and other objects in the room. Consequently, the location of the luminaires, nor the direction of the luminous flux emitted from them with respect to the objects to be lighted requires no strict accuracy.

In outdoor lighting, on the contrary, there are, near the objects or the surfaces to be lighted, very few objects that reflect the light from the luminaires toward the objects with a sufficient luminous intensity, except, of course, the ground surface. Consequently, the major luminous flux illuminating the objects is coming from the luminaires directly without being reflected by other surfaces. The contribution of the indirect component, reflected by other surfaces, is much smaller compared to interior lighting.

(b) Importance of precise aiming of the luminaires

This means that, in outdoor lighting, one has to count only with the direct luminous flux component from the luminaires. For this reason, the direction of the luminous flux emitted from the luminaires, hence the aiming angles of the luminaires in terms of orientation and the inclination, is of vital importance for ensuring the high efficiency of the outdoor lighting.

(c) Lost luminous flux

This also means that a considerable amount of luminous flux, which does not directly reach the objects to be lighted, will be lost in directions that are unnecessary as regards the lighting. The luminous flux lost in the unnecessary directions may increases the light pollution and may decreases the photometric efficiency of the lighting system.

(d) Distance between the luminaires and the object to be lighted

Another point to be noted is the distance between the luminaires and the objects to be lighted in the outdoor lighting installations. In most cases, the distance is much longer than in interior lighting installations. For this reason, even slight inaccuracy in aiming the luminaires, considerably increases the luminous flux lost in unnecessary directions (ILE, 1994; CIE, 1997a).

The precise aiming of the luminaires on the supporting structures, therefore, is essential for outdoor lighting installation. Higher accuracy in aiming angles is needed as the major aiming angles are close to the horizontal direction. This is because, for directions with such low aiming angles, even a slight mis-aiming will cause a large loss of the luminous flux. To ensure the highest possible efficiency of the outdoor lighting installation, while keeping the extent of the light pollution to a minimum, it is desirable to choose a high mounting height, all within the technical and economic reasonable range.

It can be concluded that the choice of the mounting height of the luminaire considerably influences the photometric efficiency, the light pollution, and the operation cost of the lighting system. In this respect, the supporting structures are important.

11.5.2 Required characteristics of the supporting structures

Supporting structure of outdoor lighting installations must comply with the following principal characteristics.

(a) *Robust construction*

The supporting structures must be robust in mechanical, physical and chemical construction, under any weather and the climate conditions for many years. Any changes in the aiming angles of and the location of the luminaires, due to deformation of the structure or to loosened fixing screws, by any chance, must be avoided. Accordingly, the foundations for the supporting structures also must be sufficiently deep.

From the view point of light pollution, even a slight deformation caused, for example, by heavy weight loads of the luminaires, of other heavy equipment, of the workers working on the platform carrying out the maintenance works, or of the snow coverage, by wind pressures, earthquakes or by deterioration of the elements of the structure, influences the aiming angles of the luminaires noticeably, thereby increasing light pollution and decreasing the efficiency of the installation.

(b) *Convenient construction for maintenance work*

The supporting structures, especially when the working platform is mounted near or at the top of the structure, have to be constructed in such a way that the works for maintenance and repairing for lighting system can be carried out safely, easily, and conveniently. These works involve the adjustment of the aiming angles, the focusing, the inspection, and the cleaning for the optical system, the lamp replacement, painting and repairing for the luminaires, their components and supporting structure.

To make the workers accessible, safely, easily, and rapidly to the working platform at or near the top, under various weathering conditions, provisions of the steps or the ladder are desirable inside or outside the supporting structure, if the height or the construction of the structure makes them necessary.

11.5.3 Types of the supporting structures

The types of the supporting structures can be categorized by the general construction and the general mounting height of the luminaire or the luminaires. They are: (a) the groundwork, (b) fences, (c) the front walls or facades of the building, (d) the top of the building construction, (e) poles, and (f) suspension wires. In the following, the features of these supporting structures for different types and the normal mounting height of the luminaires supported will briefly be described.

(a) *Groundwork*

Supporting structures are placed on a base that is at the ground level or, more frequently, buried in the ground. For lighting system mounted on the ground level or a low mounting height of less than about 1 m, such as for projection lighting for building facades, trees or advertisements, the luminaires rest directly on the groundwork. The groundwork is usually made of reinforced concrete or has a frame construction. The outer surfaces of the groundwork are sometimes decorated by stone fragments, painted tiles, etc. Also, almost all types of larger supporting structures require a similar groundwork.

The foundation of street lighting poles is usually a concrete block, the top of which is almost level with the ground. In top of it, the pole is attached – bolted – by means of a flange. This flange can be rigid, and it can be flexible. Flexible poles are called 'break-away poles' or 'slip-joint poles' (Schreuder, 1998; SWOV, 1976, 1976a). The latter is preferred on road safety grounds. A collision with a rigid pole – sometimes, strangely enough, called 'aggressive poles' – is often fatal, whereas a collision with a break-away pole often results in nothing more serious than just some material damage. For poles of a lower height, aluminium can be used. The result is a pole that can only bend at a collision. It should be noted that poles, that are broken off or bended during a collision, may end up laying on the road, where they may cause a severe road safety hazard. Apart from having a concrete block as a foundation, poles can be just stuck into the topsoil for a length of just over one meter.

In many situations, it is not possible to use flexible poles, e.g. on bridges or viaducts, on narrow high-speed roads etc. To avoid excessive damage in collisions, a guard rail – often, wrongly, called a 'crash barrier' – must be placed between the row of poles and the road itself. It may help to reduce the severity of accidents, but it must be kept in mind that guard rails are a road safety hazard as well (Schreuder, 1998).

(b) Fences

Sometimes, fences can be used as a supporting structure of small luminaires for the lighting of the adjacent narrow paths or the small areas for parking, working or storage, etc. The normal mounting height used is less than 5 m. Luminaires that require precise optical control, nor heavy luminaires, cannot be mounted on such a fence, unless it has a specially robust construction or special mounting devices.

The advantage of the fence as a supporting structure is no other supporting structures are needed, such as poles, which make the narrow path or the available space smaller. Another advantage is freedom for selection of the spacing between successive luminaires and the mounting height of the luminaires, and the easiness in carrying out the maintenance works. As a result, good longitudinal uniformity of road lighting with favourable visual comfort can easily be provided with lesser expense than with other types of the supporting structures.

(c) Front walls or facades of the building

The front walls or the facades of the buildings adjacent to the narrow streets are used as a supporting structure of the luminaires for lighting of the narrow streets or the small open spaces adjacent to or surrounded by the buildings. This is convenient for many streets in old towns. In narrow streets without pavements or sidewalks, there is no way to place lighting poles without obstructing the traffic for pedestrians, bicycles, and motor vehicles. The mounting height of the luminaires normally applied is between about 5 m and 10 m. It depends on the width of the street and the possible mounting height of the front walls.

(d) Top of the building construction

For lighting of small parking lots, small yards of materials, small gardens or playgrounds adjacent to buildings, the top of the adjacent building can be used as a part of the supporting structure, in stead of poles. This can be combined with other supporting structures like e.g. poles. By selecting an appropriate mounting height and the locations at the top of the building, the various maintenance work for the luminaires can be carried out easily from the roof.

For the lighting of large-scale sports stadiums, such as those for the Olympic Games, for soccer, for baseball, or for athletic sports, etc., many projectors are mounted on the front edges of huge steel girdered roofs over the one or both sides of the spectator seats, but not over the sports ground itself. One important advantage of these supporting structures for big sport stadiums is that no other construction for lighting are needed, such as high towers or high poles on which many projectors are placed. See e.g. Sugawara (2003).

Another advantage is, by using the catwalks provided near the rows of the projectors, or from the roofing of the building, various maintenance works for repairing and adjustment works for the lighting system can be carried out easily at any time. The works can be finished within a relatively short period, without using long mobile ladders or crane vehicles. Taking into account the lighting design, the height and the geometric arrangement of buildings or steel girdered roofs must be determined carefully taking the lighting design fully into considerations. The mounting height, normally, is several dozen metres, depending on the kind of sports and the size of the stadium in terms of number of spectators.

(e) Poles

The poles are one of the most widely used supporting structures of modern outdoor lighting. Also other terms are used, but they `mean the same, like e.g. columns of standards. Mostly, they are made of metal pipes or long thin pieces of reinforced cement concrete. At present, longer poles are made of steel; for short poles – up to about 7 m – aluminum is also used. In some developing countries, and in some remote regions, wooden poles are used, often in combination with telephone poles or poles of the overland electric network. Poles for road and street lighting usually have a bracket for the actual support of the luminaire. The bracket can be a separate unit, or an integral part of the pole. Details are given later in this section. The bracket is sometimes also called the mast arm.

(1) Holding holes of the luminaires for fixing with the pole. The body of the luminaires to be fixed to the poles has a holding hole, into which the leading end of the pole or

of the bracket is inserted and firmly fixed. The holding hole of the luminaires is usually either in an horizontal or vertical position, to suite the type of the poles or of the arm. When the luminaire is placed directly on top of the pole – the 'pole top luminaires' – the holding hole is vertical. When, as is more common, the luminaire is attached to the mast arm, the holding hole is horizontal. Some luminaire types have two holes for both horizontal and vertical mounting, or an exchangeable holding bracket.

(2) Types of poles. Depending on the type and number of the luminaires to be mounted, a variety of types of poles with or without brackets are used. The major types of the poles are:
- straight pole type without an arm;
- straight pole type with one or more arms, brackets or supporting frames;
- curved or bent poles that are bent so that the bottom part, that goes into the ground, is vertical and the end, to which the luminaire is attached, is almost horizontal. This type is sometimes called 'whip type masts'.

(3) Straight type without arms. When using straight poles without arms, the luminaire, with a vertical holding hole, is mounted directly on the top of the pole itself. They are used widely for two rather different areas of application:
- for residential areas, pedestrian precincts, shopping malls etc., with a mounting height of about 5 m. Usually, they carry post top luminaires. In sec. 11.4.3c, it is explained that globe-type luminaires often cause considerable glare, and excessive light pollution;
- for modern road lighting installations for high speed, high volume traffic. Normally, the mounting height is between about 10 m and 15 m. In some cases, a higher mounting height up to about 20 m is used. The horizontal distance between the luminaire and the centre of the straight pole is short.

(4) Straight type with arms; bent poles. The straight poles with one or more arms are widely used for street lighting installations already for a long time. The luminaires are attached on, under or at the end. The normal mounting height is between about 8 m and 15 m. In modern road lighting installations, bent poles are used. They are made by bending the upper part of the straight pole in a shape of a curve or a straight line. To provide the second arm on the bent pole, the similar shape of pipe is welded on the pole with a bended or curved arm. In cases of the street lighting installations, sometimes, a bracket or brackets are attached to the top or the upper part of the straight pole.

(5) Aesthetic appearance of lighting installations. It must be emphasised here that the colours and the shapes of mast arms, in combination with those of the luminaires or the lanterns, have a significant influence on the daytime aesthetic appearance of the lighting installation as well as the daytime scenic attraction of the landscape in which the installation is located. Any ostentatious decoration for the poles, arms, and luminaires must be restricted to those parts of cities where they have a specific function

in the cityscape. In other situations, particularly in traffic route areas, they must be carefully be avoided. For general outdoor lighting, and more in particular for road and street lighting, the principal function is to make roads or streets bright, safe, and comfortable to be here at night, and not to make the lighting installations bright in daytime and glaring at night. As is explained in sec. 2.4, where city beautification is discussed, the sole exception is to enliven the cityscape.

(6) Tilted brackets and mast arms. Usually, the arms and the brackets are made so that the end, where the luminaires are fixed, is almost horizontal. However, it has become customary to construct the poles and the arms in such a way, that the end is not perfectly horizontal, but is tilted slightly upwards. Usually, the tilt angle is about 3 to 5 degrees upwards. This is done to avoid a 'drooping' visual effect. For the usual luminaires with light distributions of the CIE types cut-off and semi-cut-off, this causes no problems because these light distributions are not critical. The different light distribution classifications are explained in sec. 7.1.4. Flat-glass luminaires, however, as well as other types of full cut-off luminaires, require a precisely horizontal position of the lower rim of the luminaire. If such luminaires are mounted on masts or mast arms with an upward tilt, the cut-off effect is almost completely lost. This point is often overlooked. Usually, one looks at the light distribution of the luminaire in isolation, and does not pay attention to the lighting installation as a whole. Even a slight deviation from the horizontal position of the lower rim of the luminaire or of its cover may result in considerable light pollution.

(7) Brackets for multiple luminaires. As was mentioned earlier, in most cases, the arms and the brackets are made so that the end, where the luminaires are fixed, is almost horizontal. Sometimes, the brackets for street lighting installations have one or several short pipe segments in a vertical position on or under the brackets. With these pipes, a number of relatively small decorative street lanterns are mounted on, or suspended under the brackets.

(8) T-shaped or Y-shaped poles. Some straight poles have two same arms on both sides of the pole. Such a type of twin arm pole is called T-shaped pole or Y-shaped pole, depending on the shape of the arms. These poles, normally, are used for lighting of wide roads with more than four lanes and a wide median. Usually, the poles are placed in the median strip, so that each of the brackets is positioned perpendicular to the road axis. These arrangements are called median arrangements. Such lighting installations allow the total road to be lit with half the number of poles that would be required in an opposite, or portal, arrangements, or in a staggered arrangement. Furthermore only one single cable is needed for the electric supply.

Poles of this type are not only used for road lighting, but also for other medium sized outdoor lighting installations, such as parking area, sports fields, factory yards, public spaces, platform of railway stations, etc.

(9) Straight pole type with a supporting frame at the top.
For medium-sized outdoor lighting installations, where projection lighting or sports lighting is used, a number of projectors are mounted on the frame carried by a pole or poles. The normal mounting height of the luminaires is between 5 m and 15 m. They are used for the projection lighting for buildings, woods, hills, advertising signs, sports fields, factory yards, parking areas, public spaces etc.

When such a type of supporting structures are used, the aiming angles have to be determined with great care, to avoid spill lights, glare and loss of the luminous flux.

(10) High masts. For complex multi-level junction of motorways, for large sports stadiums, wide public spaces, and aprons of airports, high masts or towers are used. These carry a large frame construction on which a number of luminaires are mounted. Most of the cases, the masts are made of pipes with a large diameter. Grid constructions, similar to those of overland high-power transmission lines, are also used. The mounting height of the luminaires is usually more than 25 m – often, quite considerably more. Usually, the frames include a platform with walk-ways from which the aiming of the luminaires, and all other maintenance work can de done. The ladders to reach platform are normally placed inside the pole; so is a lift for maintenance work for the frame construction and for the lighting.

Normally, the extent of the area, where high masts are used, is very large, and the earth surface is not always flat. For design of the lighting of such complex configurations, all luminaires are placed on a single hypothetical plane at a constant height from the sea level by erecting the masts with different lengths from the ground. For such cases, the pipe which diameter is constant is easy to adjust the individual length of many poles under fabricating process (De Boer, ed., 1967).

(11) Light pollution from high mast installations. A very interesting scheme to use high masts for the lighting of a large residential area is reported by Yates (1975). The aim of the lighting was primarily to assure amenity for the residents; also matters of accident and crime prevention were considered as important goals. The high mast solution was chosen on grounds of installation and running costs. Because it is a special case that deserves to be considered in many other locations, particularly in developing countries, we will give a short description of the scheme. Another reason to pay attention to this scheme is the very low light pollution it produces, compared to conventional lighting arrangements. It might be added that, in the almost 30 years of operation, the scheme is still considered as a success.

The installation is designed for new lighting for the township of Soweto – near Johannesburg, South Africa – with single-storey houses with small gardens. To light 700 km of roads according to CIE standards would require 22 000 luminaires and to light the open spaces with standard post top luminaires would require another 400 000 units. The total costs would amount to 55 million Pound Sterling (1975 value). Test had shown that 1,6 lux on a vertical plane is enough to distinguish a person at 40 m distance. This requirement is met with 700 high masts of 30 m high with 6 floodlights with one 400 W clear high pressure sodium lamp each. The costs was about 4,6 million Pound Sterling. Additional arterial road lighting with 6000 conventional street lights costs another 1,23 million Pound Sterling. In total, the scheme costs 11% of that with conventional lighting (Yates, 1975, p. 529).

The luminaires are be standard type high-quality floodlights. The beam pattern is characterized as given in Table 11.5.1.

Direction Left degrees	Right degrees	Up degrees	Down degrees	**Luminous intensity** candela per kilolumen
0	0	0	0	1550
10	10	1,5	1,5	1550
31	31	3	3	1000
50	50	16	50	100
60	60	20	55	50

Table 11.5.1: *Beam pattern of proposed high-mast lighting, Based on data from Yates, 1975, Figure 1.*

Based on the data for the original paper of Yates, we may estimate the contribution to the light pollution. For this, we make an estimate of the total luminous intensity of the installation emitted in the horizontal plane in all directions together. We disregard the fact that, from theoretical point of view, this sort of 'adding up' intensities in not fully justified. With masts for six luminaires, one might assume that the luminous intensity of a complete mast is more or less circle-symmetric. The luminous flux of a modern 400 W tubular high-pressure sodium lamp (e.g. Philips SON-T) is 48 000 (Anon., 2002, Chapter 1.5 p. 81; Anon., 2002a). In order to reduce glare, the luminaires are tilted downward for 15 degrees. According to the data if Table 11.5.1, this means a horizontal intensity of about 100 cd/klm. This is about twice the limit of a CIE semi cut-off light distribution. The luminous intensity of one mast is $6 \cdot 100 \cdot 48 = 28\,800$ cd/klm in all directions together. For 700 masts, the total luminous intensity is 20 160 kcd. For conventional luminaires one might assume 50 cd/klm with a 150 W SON lamp of 15 000 lm. (Anon., 2002, Chapter 1.5 p. 81; Anon., 2002a). With about 420 000 units, the total luminous intensity is about 315 000 kcd. This is 15,6 times the value that is found for the high masts. Evidently, the high-mast solution results in far less light pollution.

(f) Suspension wires

(1) Crosswise suspension wires. Crosswise suspension wires, stretched across the street or road, between buildings or poles on adjacent locations on both sides of street, were used as a supporting structure in early days in many countries, especially in European countries. The advantage of the wires was that, the crosswise suspension wires enables to suspend the luminaires at any lateral positions with any crosswise spacing over the street or the road, without poles erected in the traffic areas for pedestrians, bicycles or motors. A good lighting can be provided with relatively low cost.

In modern towns, however, the crosswise suspension wires are not installed any more. Disadvantages of the system are that they could not fix the luminaires rigidly in designed spatial locations with fixed aiming angles, especially in windy weather conditions, and less attractive appearance of the street in the daytime due to the existence of a great many horizontal suspension wires; furthermore, the luminaires are seen against the bright sky in daytime.

(2) Lengthwise suspension wires. In lengthwise suspension wire lighting systems, the wires are stretched between poles along the road axis. This system is often used for the lighting of traffic routes, especially for motorways, where the supporting masts can conveniently be placed in the median of double-carriageway roads. The lighting system is called the catenary lighting system (Van Bommel & De Boer, 1980).

The catenary lighting system consists of two suspension wires arranged vertically, stretched between straight poles at a height of about 15 m. The spacing between the consecutive masts is about 70 m and 100 m. The mounting height of the luminaires is about 10 m to 15 m. The general appearance of the suspension wires or the catenary lighting system is similar to the overhead electric energy supply system for trains. One of the suspension wires at higher position is stretched as a catenary cable. The lower suspension wire, under which the luminaires are mounted, is a horizontal straight wire. The horizontal wire is suspended by a number of thin vertical wires from the catenary cable so as to keep the shape of the lower suspension wire as a straight line for suspending the luminaires at a constant height from the ground or the road surface.

The lengthwise spacing between the luminaires is only about 10 m to 15 m. The short spacing between the luminaires allows for a lengthwise road luminance distributions with excellent lengthwise uniformity. The glare does not fluctuate as much as in conventional installations (Van Bommel & De Boer, 1980). The large spacing between the poles reduces the number of poles per unit length of the road and brings about a decrease in probability of possible crashes between the car and the pole, and consequently reduces the risks of traffic accidents.

11.6 Efficiency of outdoor lighting systems

11.6.1 Efficiency of elements of outdoor lighting systems

(a) *The term 'efficiency'*

The term 'efficiency' is used in wide sense, not only in the technical but also the economic, financial, commercial, social, and even in the psychological sense. The common idea of these efficiencies is a ratio of output to input, even though the input or output cannot be measured in an objective way or be expressed as numerical figures. The output and the input need to be assessed accordingly.

(b) *Efficiency of outdoor lighting system*

As discussed earlier, an outdoor lighting system is a lighting system to create a luminous environment suitable for activities to be conducted in the outdoors in the time of after dark. The lighting system consists of a number of elements through which energy flows.

The light projected onto the objects and the surrounding areas reaches finally the eyes of persons who see things in the lighted area. The eyes are the 'terminal' of this series of the elements.

(c) *Efficiency of outdoor lighting systems and visual performance*

The amount and the quality of visual information detected and perceived by the eyes of the observer is, however, not simply determined by the amount of the light that reaches the retina. It strongly depends on the perceptual performance of the eye, which is influenced by the luminance structure of the field of view, and the size, the shape and the colour of the object to be seen, etc. These aspects are discussed in detail in the Chapters 8 and 9 of this book.

The real meaning of the efficiency of the lighting system must, therefore, be a ratio of the amount of useful visual information, to the amount of electric energy consumed by the lighting system. At this moment, however, there is no objective method to measure the amount of and quality of visual information detected and perceived.

To examine the efficiency of lighting system, the relationship between the visual performance of the observer, and the luminance structure of the field of view of the observers created by the lighting system has to be fully taken into account.

The energy supplied from the electric source flows through the series of the elements of lighting system. During the flow, by means of the lamp, the electric energy is transformed into light, invisible radiation, and heat. A portion of the light strikes on surfaces of various objects in the lighted place effectively and other portion of the light is wasted in the directions to which no light is necessary. In this respect, it is to be noted that a lighting system with a low efficiency always involves waste of energy, light and money, and tends to cause light pollution. To eliminate the light pollution from the outdoor lighting system, the improvement of the efficiency of the lighting system, is therefore of vital importance.

(d) Energy flow in the outdoor lighting system

The general steps of energy flow in the outdoor lighting system are shown in Figure 11.6.1.

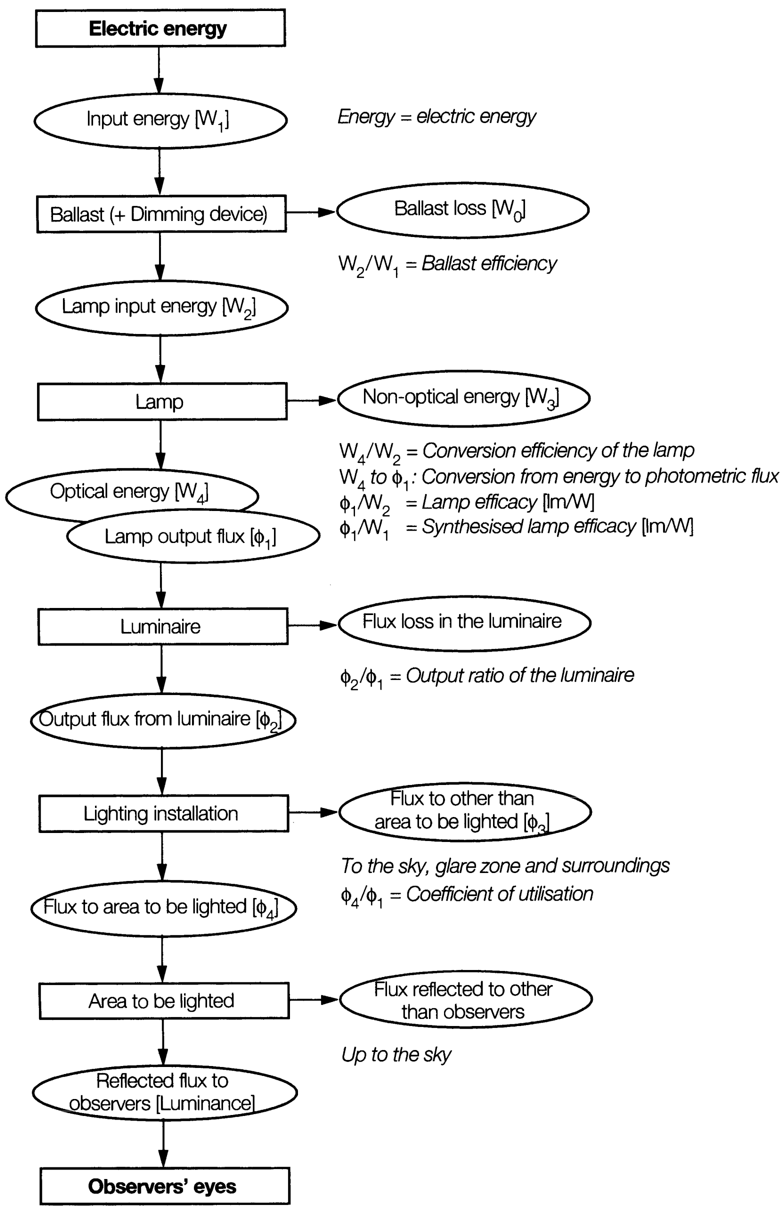

Figure 11.6.1: *General steps in outdoor lighting.*

At each step, some energy is lost. The ratio between the output energy to input energy is the efficiency of each step.

The steps can be grouped, in sequence of the energy flow, the electrical efficiency of the electric circuit consisted of a ballast, dimming device and a lamp, the electro-luminous conversion efficiency of the lamp, the luminous efficacy of the lamp, the output ratio of the luminous flux of the luminaire, the utilization factor of the luminous flux emitted from the luminaire, and the visual performance of the human eyes. In the following sections, each of these steps will be discussed separately in turn.

11.6.2 Electric efficiency of ballasts and dimming devices

The starting point of the flow of the electric energy in the lighting system is the ballast and/or the dimming device for the discharge lamps, and the dimmer for the incandescent lamps. The dimmer is connected only when the adjustment of the lighting level is necessary.

(a) Ballasts

When a discharge lamp is used, a ballast is necessary between the electric source and the lamp. The electric efficiency of the ballast is defined as a percentage ratio (%) of the output electric energy in Watts to the input electric energy in Watts. The output energy from the ballast is fed to the discharge lamp and it is equal to consumption of electric energy by the lamp.

Incandescent lamps do not require a ballast. In this case, the input electric energy is equal to the electric consumption of the lamp.

The function of the ballast for discharge lamp was discussed in sec. 11.4.1d. The electric resistance of the coils, of the semiconductors and of other wiring of the ballast, the magnetic resistance of the iron cores, and dielectric loss in the capacitances, all of which compose the ballast, consume some amount of electric energy. Normally, the amount of loss of the ballast is at an order of 10% of the energy consumption of the lamp controlled by the ballast. As shown in Figure 11.6.1, the loss of the electric energy in the ballast is indicated by a ballast loss in Watt. All lost energy is transformed into heat.

(b) Dimming devices

A dimming device is used to adjust the luminous output of the lamp to vary the lighting level of the lighting system. The electric efficiency of the dimming device is defined in the same way as the ballast.

Obviously, the dimming device brings about an increase in the electric loss of the operation of the lamp by the consumption of electric energy of the device. However it is important to note that, as discussed in the forgoing, the reduction in the lighting level by means of the dimming device, when a high lighting level is not necessary, reduces the electric consumption of the lamp and the cost of lighting. An appropriate use of the dimming device reduces electric consumption and improves the operation efficiency of lighting system. This is a way to reduced the light pollution in a reasonable way. The colour and colour rendering of the lamp usually deteriorate as the luminous flux is decreased.

As an example, some data are given about the possibilities for dimming for high-pressure sodium lamps with a rating between 70 W and 400 W. As regards the luminous flux, the dimming range is between 20%-100%. See Table 11.6.1.

Luminous flux (%)	Power (%)
10	30
20	42
30	50
40	59
50	66
60	70
70	80
80	87
90	92
100	100

Table 11.6.1: *Dimming characteristics of SON lamps from 70 W to 400 W. After Anon., 1996a.*

(c) *Electric loss and temperature rise of the ballast and dimmer*

Electric energy lost in the ballast and the dimmer is transformed into heat. The heat raises the temperature of the ballast and the dimmer, and finally the lamp equipped in the luminaire. If the ballast or the dimming device are improperly designed or constructed with materials of low quality, then the loss of the energy of and the consequent temperature rise of the ballast and the dimmer increases. To save energy and to avoid excessive temperature rise, high quality ballast and the dimming device have to be selected.

When the ballast and the dimming device are housed with insufficient cooling, the temperature may raise too much. This may lead to a risk of fire, particularly when the ambient temperature is high in the hot season. The quality and the use of the ballast and the dimmer has to comply with the international safety standards.

11.6.3 Electro-luminous conversion efficiency of lamps

The lamp is a device to convert electric energy into visible radiation, or light. As shown in Figure 11.6.1, the energy efficiency of the lamp is defined as the percentage ratio of the energy converted into visible radiation (in Watt) to the energy consumed by the lamp (in Watt). The electro-luminous conversion efficiency of lamps is dimensionless and may be expressed in %. In sec. 11.3.2, examples of the electric efficiency of typical lamps for outdoor lighting. See Table 11.3.2. For easy reference, that table is repeated here as Table 11.6.2.

Lamp type	Efficiency (%)
Incandescent lamps (gas filled)	10,0*
Tubular fluorescent lamps	28,0
Compact fluorescent lamps	19,5
Low-pressure sodium lamps	40,5
High-pressure mercury lamps	16,5
Metal halide lamps	24
High-pressure sodium lamps	31,0

Table 11.6.2: *Examples of conversion efficiency of lamps. After Meyer & Nienhuis, 1988. *) after Anon., 1987.*

As it is shown in that table, the electric efficiency of an incandescent lamps with the rating of 100 W for general – i.e. interior – lighting is about 10%. The conversion efficiency of the modern high-pressure sodium lamps is still about 30%. It is interesting to note, that even the modern discharge lamps have an electric efficiency, excluding the energy losses of the ballast is only about 3 times that of the incandescent lamps, despite the fact that the luminous flux, in lumens, generated by the modern high-pressure lamps is about 8 times that of an incandescent lamp of the same wattage.

As is explained earlier, this is due to the fact that the sensitivity of human retina depends on the wavelength of the incoming radiation. The radiation generated by incandescent lamps contains a larger amount of visible radiation to which the sensitivities of the human retina is low or even absent, compared to high-pressure sodium lamps.

The implication is that the electro-luminous conversion efficiency of lamps should not be confused with the luminous efficacy of the lamps to be discussed below.

11.6.4 The luminous efficacy of lamps

As is explained in sec. 11.3.2, the luminous efficacy of a lamp is the ratio of the amount of the output luminous flux in lumens (lm) to the electric energy consumed by the lamp in Watts (W). See Figure 11.6.1. The luminous flux is measured with a device which spectral sensitivity is corresponding to that of the eye for visible radiation. As is explained in sec. 14.1.2, all photometric quantities are defined for photopic vision, which means that the spectral sensitivity curve for day vision, the V_λ-curve, is used. The ratio is called luminous efficacy. This is because, as discussed in the foregoing, the units of the two quantities in the ratio, the luminous flux and the Watts, are not the same. In sec. 11.3.2, examples of the luminous efficacy of typical lamps for outdoor lighting. See Table 11.3.3. For easy reference, that table is repeated here as Table 11.6.3.

Lamp category	Type	Watt	Efficacy (lm/W)
Incandescent lamp	Krypton filled 100 Volt	90	17
Incandescent halogen lamp	110 Volt	130	18,5
Fluorescent tube	white	40	77,5
Fluorescent tube	triple bands	32	105
Metal halide lamp	Scandium*)	400	100
Low-pressure sodium		180	175
High-pressure sodium		360	132

Table 11.6.3: *Examples of the efficacy of typical lamps for outdoor lighting. After Anon., 2003.*
**) other metals are added as well.*

As shown in Figure 11.6.1, the real amount of the electric energy required for the operation of a discharge lamp is a sum of the energy consumed by the ballast, dimming device and the lamp itself. The actual efficacy of lamp has to be calculated as a ratio of the output luminous flux to the sum of the energy consumption. Such an efficacy is called the synthesised lamp efficacy.

As mentioned in sec. 11.3.2, it must be noted that most lamp catalogues give the efficacy of the lamps under the standard test conditions, where the energy losses of the ballast are not included. In many cases, the consumption of electric energy by the ballast and by dimming device is given in the separate parts of the product catalogues of lamp manufacturers.

It is to be noted that the electric energy consumption and the luminous flux of a lamp is not static. It may change according to the environmental conditions of the lamp, such as the ambient temperature and wind velocity, the burning position (vertical, horizontal or inclined) of the lamp, and the type of the ballast connected, the frequency of the electric current fed to the lamp from the ballast and the supply voltage, etc. Strictly speaking, the nominal energy consumption and the luminous flux output of the lamps shown in the lamp catalogues of the lamp manufacturers are valid only for the specified testing conditions of new lamps, or, as is usually specified, for lamps that have been burning for 100 hours.

To improve the efficiency of lamps, and in this way to reduce the cost of large-scale lighting, one must consider the actual luminous flux and the electric energy consumption of the lamps in question carefully under practical operating conditions equipped in the luminaire.

11.6.5 The output ratio of luminaires

(a) *Light Output Ratio (LOR) and Optical Light Output Ratio*

The Light Output Ratio (LOR) is defined as a ratio between the total lamp output luminous flux under standard conditions and the output luminous flux from the luminaire under actual operating conditions. The Optical Light Output Ratio (OLOR), on the other hand, is the ratio between the lamp output luminous flux under actual operating conditions and the luminaire output luminous flux under actual operating conditions. The difference in these two output ratios is caused by the operating conditions of the lamps. The difference between the output flux from the luminaire and the output flux of the lamp equipped in the luminaire is the luminous flux lost in the luminaire, due to absorption by various components of the luminaire.

Under actual operating conditions, the temperature in the luminaire increases and the output luminous flux of the gas discharge lamps are influenced by the ambient temperature of the lamp. The importance of the influence depends on the thermal design of the luminaire, the ambient temperature of the luminaire, and the time interval since the lamp is switched on. For this reason, for gas discharge lamps, OLOR differs from LOR, whereas for incandescent lamps they are almost the same because their light output does not depend on temperature.

The higher the OLOR, the larger the amount of the output luminous flux emitted from the luminaire. From this, one might guess that the OLOR indicates the energy efficiency of the luminaire and the luminaire with a higher OLOR is better than that with a lower OLOR. It, however, is not correct, because, not all the luminous flux emitted from the luminaire reaches the area to be lit. See also Kawakami (1996).

In figure 11.6.1, for the sake of simplicity, only the Output Ratio is indicated, without making a distinction between LOR and OLOR. It is shown in Figure 11.6.1. that a part of the output luminous flux from the luminaire is lost in directions other than the area to be lit. The proportion of the lost luminous flux strongly depends on the luminous intensity distribution of, the spatial location of and the aiming direction of the luminaires installed in the lighting installation.

(b) *Optical Output Light Ratio of and the lighting efficiency of luminaires*

An example will be used to explain the relationship between the OLOR (Optical Output Light Ratio) and the lighting efficiency of luminaires. Suppose, a small lamp with a diffuse bulb fixed to a small socket is suspended above the ground surface to be lighted, by the thin wires, through which electric current is fed to the lamp. In this case, the bare lamp is also functioning as a luminaire. The luminaire emits almost all the luminous flux generated from the lamp almost uniformly in all directions without the losses that normally are caused by the luminaire. Since, around the bare lamp, there is nothing obstructing the flow of the luminous flux, such as mirrors, reflectors, diffusing panels or other construction elements of the luminaire, except the socket, and almost all luminous flux emitted by the lamp is flowing out from the lamp. From the definition, this means that the Optical Output Light Ratio of such a bare lamp suspended by thin wires is almost 100%.

Not all the output luminous flux from the bare lamp with an OLOR of 100%, however, reaches the area to be lighted. Of the luminous flux emitted by the lamp, about 50% will be emitted above the horizon. This light is lost in the dark sky, without any contribution to the actual illumination. The remaining 50% or so of the total luminous flux is emitted downward, in the lower hemisphere. However, not all the downward luminous flux reaches the area to be lighted on the ground surface. The downward luminous flux is uniformly emitted to all the directions. Part of it is lost in the directions where no lighting is necessary or even lighting is disturbing. For example, the downward luminous flux in horizontal directions causes glare for pedestrians and car drivers, without brightening the objects to be lit. As a result, only a small portion of the downward flux reaches the area to be lit, depending on the size of the area to be lit.

From this it is obvious that the lighting efficiency of this bare lamp-luminaire, which emits the luminous flux uniformly for all spatial directions is low, even the OLOR or LOR is 100%. The OLOR or LOR therefore is not directly relevant to the energy efficiency of the luminaires for outdoor lighting.

11.6.6 The Upward Light Ratio

(a) Upward luminous flux as a cause of light pollution

One of the adverse effects of outdoor lighting is the upward luminous flux. The upward luminous flux is scattered by air molecules, small particles or droplets floating in the atmosphere. This increases the luminance of the night sky (sec. 1.2). The increased luminance of the sky reduces the luminance contrast between stars and other sky objects and the sky, against which the stars are seen. The reduction in the luminance contrast makes the astronomical observations or star watching difficult (sec. 5.1.1). To eliminate the adverse effects, the amount of the upward luminous flux from the outdoor lighting installations must be limited as small as possible.

In order to quantify.the upward flux, the upward light ratio, which give proportion of upward luminous flux to the luminous flux emitted by the luminaires or that by the lamps equipped in the luminaire have been introduced (CIE, 1997; 2003).

The Upward Light Ratio (ULR) is defined as the proportion of the output luminous flux of a luminaire and/or an installation that is emitted at and above the horizontal, when luminaires are mounted in their installed position (CIE, 2003). In an earlier document, a different abbreviation was used: 'ULOR-inst' (CIE, 1997). However, the definitions of ULR and ULOR-inst are the same (CIE, 2003). Therefore, the term 'Upward Light Ratio' (ULR) will be used, instead of ULOR-inst.

The Upward Light Ratio (ULR), should, however, not be confused with the Upward Light Output Ratio (ULOR). ULOR is defined as the proportion of the luminous flux of the lamps equipped in a luminaire that is emitted above the horizontal when the luminaire is mounted in its normal designed position (CIE, 1997; 2003). The different is that ULOR refers to standard test conditions, whereas ULR refers to the practical lighting installation.

When the Upward Light Output Ratio of a luminaire increases, the relative amount of the luminous flux directed towards the upper hemisphere increases. This automatically means that the photometric efficiency of a luminaire with a large ULOR is low. When ULR is high, it could mean that the luminaire is poor, or that the luminaires are aimed and adjusted incorrectly. ULOR can be provided in the product documentation, whereas ULR can only be assessed by measurements in the field. In still other words, ULOR is a characteristic of the luminaire, whereas ULR is a characteristic of a lighting installation.

11.6.7 Relationship between OLOR and ULOR and the Upward Luminous Flux

As mentioned earlier in this section, to eliminate the light pollution for the astronomical observations, it is essential to reduce the upward flux from the lighting installation as a whole. As discussed in sec. 11.6.6, the Upward Light Ratio (ULR) and the Upward Light Output Ratio (ULOR) give the ratio of the upward luminous flux to the output luminous flux of the luminaire, and that of the lamps equipped in the luminaire output, respectively.

From the definition of OLOR (Optical Light Output Ratio of the luminaire), the output luminous flux Φ_a from the luminaire can be calculated as:

$$\Phi_a = \mathrm{OLOR} \cdot \Phi_b \qquad [11.6.1]$$

with: Φ_b the luminous flux of the lamp equipped in the luminaire (in lumens).

The upward luminous flux Φ_u (in lumens) from the luminaire is therefore:

$$\Phi_u = \mathrm{ULR} \cdot \Phi_a = \mathrm{URL} \cdot \mathrm{OLOR} \cdot \Phi_b = \mathrm{ULOR} \cdot \Phi_b \qquad [11.6.2]$$

with: Φ_u the upward luminous flux of the luminaire (in lumens).

From the equations [11.6.1] and [11.6.2], it is clear that the upward luminous flux output of the luminaire (Φ_u), which must be limited, is in proportion to the luminous flux output of the lamp or lamps (Φ_b) in the luminaire.

11.6.8 Utilization factor and required lamp luminous flux

(a) *Utilization factor as the photometric efficiency of the lighting installation*
From its definition, the illuminance on an area is calculated as:

$$\Phi_c = E \cdot S$$

with:
E: the illuminace of the area (lux);
S: the area (m^2);
Φ_c: the luminous flux from the luminaire that reaches the area (lumen).

As mentioned earlier in this section, not all the downward luminous flux reaches the area to be lighted. The proportion of the lamp luminous flux that reaches the area to be lit, is called the utilization factor η of the lighting installation. Hence:

$$\eta = \frac{\Phi_c}{\Phi_b} \qquad [11.6.3]$$

The utilization factor is one of the most important parameters concerning the efficiency of any lighting installation, which has a strong relevance to the electric energy consumed by the lighting installation.

The utilization factor of a lighting installation is determined, amongst others, by the shape and the size of the area to be lighted, the luminous distribution, the orientation, the inclination, and the spatial arrangement of the luminaires in the installation, taking into account the area to be lit. In other words, the utilization is determined by the luminous intensity distribution of the luminaires and the geometric and the photometric design of the installation.

(b) Required lamp luminous flux

Based on the above formulae, the required luminous flux needed to illuminate a specific area of S m^2, with an illuminance of E lux, can be calculated as follows:

$$\Phi_b = \frac{\Phi_c}{\eta} = \frac{E \cdot S}{\eta}$$

(c) The upward luminous flux and the utilization factor

Based the definitions, the amount of the upward luminous flux can be calculated as follows:

$$\Phi_u = ULR \cdot \Phi_a = ULR \cdot OLOR \cdot \Phi_b = ULOR \cdot \Phi_b = ULOR \cdot \frac{E \cdot S}{\eta}$$

The above calculations clearly show that the amount of the upward luminous flux from an outdoor lighting installation cannot be limited only by ULOR, but that a high utilization factor η is of vital importance (Kawakami, 2002).

11.6.9 Lamps and luminaires combined; the efficiency of the lighting system

(a) *The combination of a lamp and a luminaire*

A combination of a lamp with a high efficacy and a luminaire with a high LOR does not automatically mean a high efficiency luminaire. Although such combinations emit larger amounts of luminous flux from the luminaire, in comparison with other combinations, not all the luminous flux emitted reaches the area to be lit, as is discussed above. To increase the luminous flux reaching the area, the luminous flux generated by the lamp must be controlled precisely and effectively, and be concentrated into the directions towards the area to be lit. The light control efficiency of the optical system of the luminaire is decisively influenced by the luminance and the size of the flashed area of the lamps, and the design and construction of the optical system.

Principally, when the luminance of the flashed area of the lamp and the optical size of the optical control system is increased, and when the optical size of the flashed area of the lamp is decreases, the control efficiency is improved.

This is why the halogen incandescent lamps, whose luminous efficacy is not much more than some 20 lm/W, are used for car headlights, instead of the compact fluorescent lamps, whose efficacy is at an order of 50 lm/W. The compact fluorescent lamp is unable to concentrate the luminous flux in the narrow spatial area needed by the headlamps. The optical characteristics of vehicle headlights are discussed in sec. 12.2.

(b) *The overall electro-photometric efficiency of the luminaire*

The product of the efficacy of lamps (lm/W) and the utilization factor of the lighting installation is the total electro-photometric efficiency of the lighting system, which determines the consumption of the electric energy for the lighting installation to light the area to the required lighting level.

(c) *Deterioration due to age of lamps and optical systems*

The optical, photometric and physical properties and the consequent performance of the lamps and the luminaires deteriorate gradually as the time of operation of the lighting installation elapsed. To keep the performance of the lighting installation as high as possible, cleaning, replacement and adjustment of various components, such as lamps, reflectors, refractors, etc. are of essential importance.

11.7 Elements of outdoor lighting design.

11.7.1 Traditional and low-pollution lighting design

(a) *Traditional CIE-based design methods for outdoor lighting*

As is explained in sec. 11.2, there is a fundamental difference between the design methods for indoor and outdoor lighting installations. The difference is, that in indoor lighting, the reflected light plays a dominant role. In outdoor situations, there is no ceiling and there are usually no walls, so there is hardly any interreflection, or none at all.

The similarity between indoor and outdoor lighting is, that almost all design is based on the fulfillment of the requirements about the level and the uniformity of the illuminance, with some additional requirements on glare restriction and sometimes on colour aspects. The only noteworthy exception is the design of the lighting for traffic routes, that is based on the fulfillment of the requirements about the level and the uniformity of the road surface luminance, again with some additional requirements on glare restriction.

The most striking similarity between the traditional CIE-based design methods for indoor and outdoor lighting installations is, that the designs are always based on the requirements for the 'user' of the installation. For indoor installations, the users are the people working, living, or relaxing in the indoor areas, or the people who look at theatre productions etc. For outdoor installations, the users are the people working outdoors, the road users, the visitors of shopping centres etc., people involved in sportive or cultural performances, and their onlookers. In some cases, sporadic attention is devoted to the interests of people living nearby. Environmental aspects, and, more in particular, aspects of light pollution are not taken into account.

(b) Low-pollution design methods for outdoor lighting

At present, there are no design methods that are expressly aimed at low-pollution lighting installations. In the following parts of this section, a first outline of such low-pollution design methods for outdoor lighting is presented. Because there are no worked-out proposals yet, the outline gives only a number of fundamental ideas about how such methods would look. In order to explain these ideas, some details are given on the design of street lighting. Most ideas can be applied, with the required amendments to other areas of outdoor lighting. In this example, traditional road lighting and a simplified method, aimed at low-pollution lighting installations, are compared. This simplified method is included for another reason as well. It is particularly suited for the design of road lighting in cases where more complex, computer aided, methods are not considered because of the costs involved, or, more important, the computers and competent computer operators are scarce. This is, of course, often the case in developing countries.

(c) A systematic approach to low-pollution lighting design

Any lighting design method must be based on the function of the installation. So, the requirements of light level, uniformity, glare and, if relevant, of colour must be fulfilled. This applies equally to traditional and to low-pollution lighting design. However, any low-pollution design method must, obviously, be based primarily on the light pollution issues. The primary issue is the environmental zone of the location where the lighting will be installed. The first step that must therefore be taken, even before the start of the lighting design, is to ascertain that the project, to which the lighting installation belongs, does fit into the area planning of the region.

In this way, an outline of low-pollution design methods for outdoor lighting would at least involve the following steps, and in the following sequence:

(1) Define the function of the project and of the lighting installation;
(2) Determine, on the basis of the relevant standards or recommendations, the light level in relation to function of the area to be lit;
(3) Determine the environmental zone in which the location falls;
(4) Ascertain whether the project fits the zone;
(5) From the environmental zone, determine the limiting values of the ULR;
(6) On the basis of ULR, select the appropriate luminaires and lamps, in order to minimize the direct upward flux;
(7) Select the appropriate materials and the installation geometry, in order to minimize the indirect upward flux;
(8) Make the actual lighting design, based on light levels and uniformity, either illuminance or luminance, in order to maximize the visibility;
(9) Adapt the design to minimum glare, either discomfort or disability, including light immission;
(10) Maximize the light-to-energy relation over the full life of the installation, including switching and dimming;
(11) Maximize the cost-benefit relation over the full life of the installation, including maintenance.

For most steps, current assessment systems are available. The low-pollution approach to outdoor lighting design is more a matter of improving the priorities, rather than of inventing clever, new tools!

11.7.2 CIE-based design methods for road lighting

(a) Overhead lighting

Road traffic at night requires artificial light to promote safely. Often, it suffices that motor vehicles use their own lights. When traffic is dense, and in particular when slow traffic is a major contributor, fixed overhead road lighting is necessary. As is explained in sec. 12.1.1, fixed road lighting is an effective accident countermeasure. It also serves well to prevent many crimes (sec. 12.1.2). In sec. 10.3.3b, when explaining the warrants for lighting, the criteria for installing fixed road lighting are discussed.

Before any fixed road lighting installation is considered, one has to determine whether a particular road requires fixed road lighting. As is explained in secs. 10.3.3 and 12.3.5, the decision of lighting a road must be made on the basis of a cost-benefit analysis.

(b) The current road lighting design methods

Road lighting is installed for visibility, more in particular to allow road users to see the run of the road and to detect obstacles. The traditional approach is based on the concept of the road surface luminance. The average road surface luminance determines the adaptation level, and thus the level of visual performance (De Boer, 1951, 1967).

Furthermore, the road surface is in most cases the background unto which visually critical objects can be seen. The determination of the average road surface luminance is the cornerstone of the road lighting design. The traditional method does include other parameters as well, more in particular the restriction of disability glare and the non-uniformity of the luminance pattern.

A more careful consideration of the driving task and the related cognitive aspects involved, suggest, however, that the visual guidance, followed by the non-uniformity are the most important design parameters (Schreuder, 1998, p. 150). There are, however, no lighting design methods, based on the driving task concepts.

Since long, it is suggested that the visibility itself should be taken as the basis for the design. Usually, the revealing power was considered as providing the most appropriate description. The revealing power and its use in road lighting is discussed in detail in secs. 9.1.3c, 10.3.1b and 11.8

(c) The CIE-approach to road lighting design

The lighting design method that is recommended by CIE allows the assessment of the average road surface luminance, the non-uniformity, the restriction of disability glare and the vertical illuminance of objects (CIE, 1976). It is based on the fundamental work of De Boer in the 1950s and 1960s, involving 'equivalent position diagrams' (De Boer et al., 1952; see also Hentschel, 1994, p. 189-190 and Schreuder, 1998, sec. 13.1.3). Almost all computer-aided design methods for road lighting are based on this principle, the first being the CIE Programme LUCY. The CIE method is complicated and can be used only when the luminous intensity distribution of the luminaires (I-table) and the reflection properties of the road surface (R-table) are precisely known – which is not always the case. Furthermore, the method can be used only for straight, level, flat, and uniform roads, and finally they can compare the results of a known installation with the requirements, and not the other way around. Essentially, it is a check and not a design tool. What is really lacking in the CIE method, is an 'expert system', where the requirements are formulated and the design parameters follow. Some attempts to construct such experts systems have been made for interior lighting, but for road lighting, they are not available yet in a easily accessible way. See Di Fraia (1993a); Schreuder (1998, p. 218). However, the most severe restriction of the CIE method is that it can be used only by designers who are expert lighting engineers as well as expert computer operators at the same time. Particularly the last restriction is extremely serious for developing countries as well as for the lower level road authorities on the municipality level in all countries.

With this in mind, simplified design methods have been introduced, that can be used by anyone with a good technical background (Schreuder, 1996, 1997, 1998b, 1999; Van der Lugt & Albers, 1996). Similar methods are described in some detail in CIE (2000) and in Van Bommel & De Boer (1980, sec. 13.3; p. 198). It should be noted that these method are based on the CIE recommendations, so it will essentially lead to roads that in general will obey the CIE requirements (CIE, 1995).

(d) Methods based on illuminance

Before road lighting design was based on the concept of visibility, and on the related concept of road luminance, it was customary to base road lighting design on the illuminance on the road surface. This concept is in line with what today is the most common design approach for almost all lighting, except the lighting of traffic routes – more in particular, the design of all functional interior lighting installations. See for details e.g. De Boer & Fischer (1981). More in particular, illuminance-based design is still the only practical design method that can be used for residential streets, pedestrian precincts, shopping malls, etc., as well as for roads that have an irregular layout, like e.g. roundabouts. The calculation methods are described in detail in De Graaff (1967, sec. 7.4.4 and sec. 7.4.5); Van Bommel & De Boer (1980, sec. 13.2.1); Hentschel (1994, sec. 7.2): Schreuder (1998, sec. 10.5). The requirements and recommendations are given in e.g. CIE (1976, 1992a, 1995); NSVV (1957, 1990).

When the design is based on illuminances, the utilization-factor methods may be used. See Van Bommel (1978) and Van Bommel & De Boer (1980). In the past, utilization curves were used in lighting design; since personal computers are used, these curves are often considered obsolete and are not included in the manufacturer's documentation any more. For a simplified design method, however, they are still useful. We will come back to this method lateron in this section, where we will propose to use the illuminance as a criterion for the quality of road lighting in developing countries.

The utilization curve is a graphical representation of the percentage of the lamp lumens that fall on the road, where the road width – for road side and curb side separately – is a variable. The road width is expressed in the mounting height. For obvious reasons, the utilization increases when the roads are wider in relation to the mounting height – more light falls on the road. As a first approximation, the factors for lanterns using advanced optical systems are similar; so are those for lanterns with simple optics as well as those for diffuse reflectors.

(e) The CIE Recommendations for road lighting

In the past, CIE did publish a series of documents, in which the recommendations for road lighting were given. The subsequent documents are CIE (1965, 1973, 1976, 1977, 1979, 1992a, 1995). The CIE documents were rather straight-forward. All roads were subdivided in a small number of classes, and for each class the light level, the uniformity and the glare were specified. The CIE recommendations, when first published in 1965, differed in two important ways from all earlier national and international guides. In the first place, the light level was, at least for all roads that were in use for motor traffic, expressed in luminance values, and not, as was until then customary, in illuminance values. And secondly, the recommendations were functional, which means that only the end result was specified. It was left to the designer of the equipment and of the installations to select the ways to reach the required values. There were no 'receipts' given. The traditional CIE recommendations were the basis for almost all national codes-of-good-practice, recommendations, standards and the like. Some nations did, however, slightly adapt the values for the different photometric requirements.

Over the years, the values were adapted to the increasing complexity of traffic situations and to the increase of the overall driving speeds. However, it was gradually felt that the CIE recommendations were not specific enough to allow their use for all road types.

A new set of CIE recommendations is going to be published soon. The drafting of the new CIE recommendations was more or less synchronous with the drafting of the European standards, as well as with several national codes, such as those of the Netherlands (CEN, 2002; NSVV, 2002). As a result, the three documents are essentially very similar. The discussion of the recommendations in this section is based on the guide for the Netherlands (NSVV, 2002). There are small insignificant differences between the documents, that will be disregarded here.

The main difference between the old and the new recommendation is the degree of detail in which the road type can be described. Actually, it is not the road classes but the lighting classes that are discerned, but the lighting classes are described in terms of road and traffic characteristics. In the new recommendations, four major classes are discerned:
(1) ME-classes for drivers of cars and relevant for roads with a traffic or 'flow' function only;
(2) CE-classes for drivers of cars and relevant for roads with a mixed or a residential function;
(3) S-classes for cyclists and pedestrians and relevant for residential streets, side-walks, cycle tracks and parts of roads adjacent to roads with traffic functions;
(4) ES-classes relevant for locations where the recognition of people is important.

The lighting requirements for ME-class roads are expressed in luminances, for CE- and S-class roads in illuminances, whereas for ES-class roads, the semi-cylindrical illuminance is added as a criterion. The luminance values for different ME-class roads can vary between 0,3 and 2,0 cd/m^2, with additional requirements as regards the non-uniformity and glare. The illuminance values for different CE-class roads can vary between 7,5 and 30 lux, with additional requirements as regards the non-uniformity. The illuminance values for different S-class roads can vary between 2 and 15 lux, with additional requirements as regards the minimum illuminance and the non-uniformity.

Further, the recommendations contain a complicated but comprehensive determination system to find out to which road class any specific road does belong. Finally, many details are given to make corrections to the road class for specific situations, like e.g. high-crime locations or complicated traffic situations. These details are not reproduced here, as they are heavily influenced by local and national situations and customs. We mention only that it is very likely that, in practice, only a few of the many possible variations will be used for the majority of cases. It is too early to estimate which variations that will be, as the system is still new, and not tested out on a large scale and over a long time, in a large number of different countries. Undoubtedly, however, the new recommendation will be an important step forward toward finding the optimal road lighting situations for a variety of conditions.

It should be stressed that a separate section is added as regards the restriction of spill light and of light pollution. Presently, however, the section contains mainly qualitative recommendations.

11.7.3 Low light pollution design methods

(a) *Outline of the method for road lighting*

In the CIE design approach to road lighting that is discussed in sec. 12.5.1, not only the road luminance and its non-uniformity are assessed, but also glare. Glare is an aspect of near-horizontal flux. Glare and light pollution are closely correlated. See also Crawford (1991, 1992, 1994). The short-cut, simplified methods that are also discussed in sec. 12.5.1, are based on the same CIE design approach to road lighting. However, the main part of the simplification is the fact that glare considerations are disregarded. The methods refer only to road illuminance or road luminance. Therefore, the CIE-based simplified design methods are not useful at all when light pollution issues have to be considered. For this reason, a new simplified design method is proposed here, that could be termed a 'low light pollution design method'. The fundamental aspects of this method is discussed in an earlier part of this section. Its main feature is, that it focusses on the upward flux from the luminaires. Contrary to many other simplified design methods for road lighting, the method proposed here is not only based on the illuminance. The luminance is taken into account, in view of the contribution of the reflected light to the upward flux, as is explained in sec. 12.4.

As usual in lighting design, all calculations involved in the design method regarding the illuminace levels, are based on new conditions. For actual operation conditions, the Maintenance Factor must be taken into account (sec. 11.2.5).

It should be stressed that road lighting has a peculiar place in all outdoor lighting, in so far that it is focussed on traffic flow, or 'throughput', and accident and crime prevention. Road lighting is purely functional. This means, that road lighting must never be considered as a luxury, nor as an aesthetic feature, like many outdoor lighting systems that are discussed in sec. 2.4, when dealing with city beautification. Also, road lighting should not be considered as serving only a very limited section of society, like the lighting of sports facilities, or security lighting. The need for a road to be lit depends only on the outcome of a cost-benefit analysis, where the benefits are the 'prevented' accidents or crimes (sec. 12.3.5).

On the basis of these considerations, for road lighting the first four steps of the systematic approach to low-pollution lighting design, that is outlined earlier in this section, can be omitted, because of the special safety nature of road lighting.

The outline of the method, adapted to road lighting, is as follows:

(1) Determine the Environmental Zone of the location. This process is described in sec. 3.4.1;
(2) Select the appropriate luminaire type on the basis of its ULR for that zone. This process is described in sec. 12.4.1;
(3) Determine the road class on the basis of the rule-of-thumb that is explained later in this section;
(4) Determine the required light level for the relevant traffic and speed conditions. This process is described in sec. 11.7.2e;
(5) Make a first estimate of the luminous flux, needed on the basis of the rule-of-thumb that is explained further on in this section. Select provisionally the lamp type and wattage;
(6) Use the efficiency diagrams in order to estimate the illuminance. These diagrams and their use are described in sec 11.6.9;
(7) If needed for more precision, repeat the procedure in an iterative process;
(8) Include the assessment of the road surface luminance on the basis of the rule-of-thumb that is explained further on in this section. Select provisionally the lamp type and wattage;
(9) If needed for more precision, repeat the procedure in an iterative process.

(b) Determination of the Environmental Zone and the related ULR

In sec. 7.1.1, details are given of the environmental zones that are introduced by CIE (CIE, 1997, 2003a) as well as the sub-zones that are recommended for use (See Murdin, 1997; Schreuder, 1994, 1997a) See Tables 7.1.1 and 7.1.2. The sub-zones are repeated here, in summary form, in Table 11.7.1.

Sub-zone	Examples
E1a	nature preserves
E1b	national parks
E1c	protected landscapes
E2	village residential areas
E3a	suburban residential areas
E3b	urban residential areas
E4a	urban areas, considerable nighttime activity.
E4b	city-centre.areas, high nighttime activity

Table 11.7.1: *Summary description of the environmental sub-zones. (See Table 7.1.2).*

In sec. 7.1.4c, the recommended luminaire classes are given for each sub-zone. See Table 7.1.7. The maximum value of the Upward Light Ratio (ULR; in %) as well as the recommendations for pre-curfew and post-curfew regimes as well as those for urban and rural conditions are added. These recommendations are repeated here in Table 11.7.2.

Sub-zone	Maximum ULR (%) pre-curfew urban	rural	post-curfew	Light distribution (road and area lighting)
E1a	–	–	–	no lighting
E1b	+	1	0	full cut-off
E1c	+	3	0	full cut-off
E2	5	3	1	full cut-off
E3a	5	3	2	cut-off
E3b	10	5	5	cut-off
E4a	15	+	10	semi-cut-off
E4b	25	+	15	semi-cut-off

Table 11.7.2: *Recommendations for installations for general area lighting (See Table 7.1.7)*

Notes: '–' means 'no lighting'; '+' means 'not relevant'; urban and rural refer to the general degree of urbanization (only relevant for zones E2 and E3 because E1 is always rural and E4 is always urban).

For the simplified design method, that will be discussed in the further parts of this section, we may assume that ULR-values of 0%, 1%, 3%, 5%, 10%, and 25% are relevant, or FCO, CO, and SCO light distributions. Lateron, we will come back to these distributions.

(c) *A simplified road classification*

In the simplified road lighting design method, that is described in this section, roads are classified along traffic volume and road width. These two parameters have been selected, because they are usually not open for changes as the design of the lighting installation progresses. They are fixed ahead of time by considerations of urban planning, economic necessities etc. The method uses five classes regarding the traffic volume and also five classes in road width.

These two are highly correlated so a 'matrix' can be established. See Table 11.7.3.

Road width	Traffic high	=	medium	=	low
wide	A	(nr)			
||	(nr)	B	(nr)		
medium		(nr)	C	(nr)	
||			(nr)	D	(nr)
narrow				(nr)	E

Table 11.7.3: *Road classification. 'nr': not recommended. Explanation: see text.*

The table is expressed in qualitative terms. In order to have an impression of the order of magnitude we are talking about, the following values might be attached to the concepts in the table. The traffic is expressed in the rush-hour number of vehicles per lane per hour, or, more precisely, in passenger car equivalents per lane per hour for the annual average rush-hour. The road width is expressed in metres for the total road for both directions together. For dual carriage-way roads, the two carriage-ways are added, irrespective of the width of the median. Shoulders are not included. For traffic, high means >1000; medium means around 100 and low means < 10. For the road width, wide means 15 m or more; medium means 7-12 m and narrow means 5 m or less. In the case of driving lanes being marked, these widths correspond usually for wide with 4 lanes or more; for medium 2-3 lanes and for narrow 1 or maybe 2 lanes. In Table 11.7.3, the letters A, B, C, D and E respectively, are used to designate the most common combination of traffic and road width. They also represent the combination that are to be preferred. The design method is based on these letters. The combinations which can be found in practice, but should not be recommended, are designated with (nr). The letters indicate both traffic volume and road width. Usually, roads with predominantly a traffic function belong to the classes A, B, or sometimes C; roads with a mixed function to classes B, C, or D and residential streets to classes D and E.

Table 11.7.3 is valid for rural and urban roads alike. The way the different road types are distributed is, obviously, not equal.

An even further simplification is given in Table 11.7.4. It is felt, although experience is lacking so far, that the remaining three classes are sufficient for most applications in developing countries.

Road width		**Traffic (rush-hour vehicles per hour, whole road)**		
	no. lanes	**high** >1000	**medium** about 100	**low** <10
wide	>4	A	–	–
medium	2-3	–	C	–
narrow	1	–	–	E

Table 11.7.4: *Abbreviated road classification*

(d) The required light level

It is difficult to indicate in general terms, the required light level for the three remaining road classes A, C and E. One can assume that class A is well within the highest classes of common road lighting recommendations. As an example, such roads would require in the Netherlands an average road surface luminance of about 1,5 cd/m^2 (NSVV, 1990). The recommendations of such roads are usually expressed in luminance values alone, but for an average asphalt road surface, the illuminance would probably be about

15-22 lux. Class C will be in the range of the simple streets that are still covered by most national recommendations. Again as an example, such streets would require in the Netherlands an average illuminance of some 3-5 lux (NSVV, 1990). Road of class E will usually be left unlit in industrialized countries. Therefore, national codes of these countries will not be much of a guide. In developing countries, however, many roads of this class will have an important social function, and therefore require overhead fixed lighting (Schreuder, 1998b, 1999). As the traffic is both low and slow, a low illumination level of about 1-2 lux usually will suffice (Schreuder, 1995; 1998, section 13.4., Table 13.4.2).

So, in summary, the required illuminance levels for the three remaining road classes will be as given in Table 11.7.5.

Road class after Table 12.5.4	Minimum illuminance average (lux)
A	15
C	3
E	1

Table 11.7.5: *Required illuminance levels for the road classes of Table 11.7.3.*

(e) *Road lighting parameters: The effective road width*

The first step in the design method is the assessment of the effective road width. Basically, this is the geometric road width minus the overhang of the luminaire, the overhang being the distance between the road edge and the (projection of) the luminaire. The 'overhang' should not be confused with the 'outreach', the length of the horizontal part of the support. Common practice in most countries is that the overhang is about 20% of the road width for single-sided arrangements and 10% for double-sided arrangements. The carriageways of dual-carriageway roads are considered separately. It should be noted that some median-mounted installations on dual-carriageway roads show a negative overhang, e.g. in catenary suspension installations. As these installations require an expert handling in design and construction, they are disregarded here. Summing up, we conclude that the effective road width is 80% of the geometric road width, which means 12 m for class A; 8 m for class C, and 4 m for Class E.

(f) *Road lighting parameters: The mounting height*

The next step is the assessment of the mounting height of the luminaires. Based on practice, the mounting height of the luminaires is chosen in relation to the traffic and the effective road width. For major roads (e.g. class A), the mounting height is 1,3 times the effective road width. For roads with a mixed function (e.g. class C), the mounting height is about 0,9 to 1,1 times the effective road width, and for residential roads (e.g. class E) the mounting height is about 0,5 to 0,8 times the effective road width. Summing up, we conclude that the mounting height is about 15 m for class A; 8 m for class C, and about 3 m for Class E.

(g) Road lighting parameters: The spacing

The spacing is the distance between two consecutive light points, irrespective at which side of the road they are located. Increasing the spacing – with the same light level – reduces costs but decreases the effects of optical guidance and increases the non-uniformity of the lighting pattern, both as regards luminance as well as illuminance. More in particular, the luminance pattern on wet roads deteriorates rapidly with increasing spacing. Practice in many European countries indicates that the conditions usually are still acceptable when the spacing on major roads (e.g. class A) is about 4 times the mounting height, on roads with a mixed function (e.g. class C) about 6, and on residential roads about 10 times. In some countries it is customary to use longer spacings. Summing up, we conclude that the spacing between the luminaires is about 60 m for class A, about 50 m for class C, and about 30 m for Class E. It should be noted, that the spacing as such will follow from the calculations that have to be made for the design. The vales of the spacing given in this part of this section, may be regarded as the practical maximum – and therefore, at the same time, as the optimum. If the design process does yield values for the spacing that are greatly different, a further iterative cycle must be made.

(h) The light level

The lighting requirements for major roads with a traffic or a mixed function is expressed in luminance values, those for residential roads in illuminance values (CIE, 1992a, 1995, NSVV, 1990, 2002). This holds for the level as well as for the lighting pattern. As the different recommendations show, the actual level depends on a number of parameters. In the simplified design method, an average of the values given in the recommendations is used. For major roads with a traffic function (e.g. class A) an average road surface luminance of 1 cd/m^2 is proposed, for major roads with a mixed function (e.g. class C) an average road surface luminance of 0,5-0,7 cd/m^2 is proposed, and for residential streets an average illuminance on the road of 2-4 lux is proposed. As the road luminance is difficult to assess in the design stage (because reflection data usually are lacking) as well as difficult to measure, the average illuminance is often used in stead. It is proposed to assume that a rather light coloured road surface is used with Eav / Lav = 15 (corresponding approximatively with a q_0-value of about 0,8). This implies an illuminance of about 15 lux for class A and about 7-10 lux for class C.

(i) Estimate of the required luminous flux; a rule-of-thumb

The estimation of the required luminous flux follows from the formula that can be used to assess the average road surface luminance. For this, a well-known simple formula to assess the average illuminance is used:

$$E_r = \frac{e_1 \cdot e_2 \cdot F}{s \cdot W} \qquad [11.7.1]$$

in which:
E_r: the average illuminance (lux);
F: the lamp flux (lm);
e_1: the luminaire efficiency;
e_2: the installation efficiency;
s: the spacing;
W: the road width.

As an example, we will take a SON lamp of 250 Watt, producing 23 000 lumen, a road with of 10 m and a spacing of 50 m, the illuminance E is:

$$E = \frac{0{,}7 \cdot 0{,}7 \cdot 23000}{50 \cdot 10} = 22{,}54 \text{ lux}$$

To find the luminance, the overall factor Q is used, which is the ratio between the average illuminance E_r and the average luminance L_r:

$$Q = \frac{E_r}{L_r} \qquad [11.7.2]$$

It should be noted that Q is not dimensionless, because E and L have different dimensions (Schreuder, 1967). It follows:

$$L = \frac{1}{Q} \cdot \frac{e_1 \cdot e_2 \cdot F}{s \cdot W} \qquad [11.7.3]$$

In the example given earlier, the average road surface luminance for an asphalt road is about 1,33 cd/m^2; for a concrete road about 1,88 cd/m^2.

When all parameters are known, the luminous flux per lamp can be assessed:

$$F = \frac{L \cdot Q \cdot s \cdot W}{e_1 \cdot e_2} \qquad [11.7.4]$$

The rule-of-thumb works as follows:
(1) L: Decide on the value of L;
(2) Q: Decide on the road type. For an asphalt road, Q usually is between 15 and 20, that is to say about 17; for a concrete road, Q is between 9 and 15 – that is to say about 12.
(3) $s \cdot W$: Assess the area that is to be lit. This is the spacing s times the road width W;
(4) e_1: Estimate the amount of light that is emitted from the luminaire. Usually, this is about 0,7. That means that about 0,3 is absorbed somewhere in the luminaire;
(5) e_2: Estimate the amount of light that hits the area to be lit. Usually, this is about 0,7. That means that about 0,3 is falling outside the area, e.g. in the verges;

(j) The use of the utilization factor diagrams

Earlier in this section, we suggested, referring to Tables 11.7.2 and 7.1.7, that for the simplified design method, it is sufficient to look at luminaires with a FCO, CO or SCO light distribution. Three luminaire types can be defined that can be used as examples of these three light distributions. In the old Philips terminology, we refer to:
(1) The FCO-open diffuse reflector HRD;
(2) The CO-closed mirror type reflector HRP;
(3) The SCO-refractor SRM.

It should be noted that we have to use these ancient luminaires, because some of them have no counterpart in modern production types, in spite of the fact that open luminaires have specific advantages. In Figures 11.7.1, 11.7.2, and 11.7.3, the utilization factor diagrams are given for these three luminaire types. The terminology is somewhat confusing. The term 'utilization factor diagram' is used by Van Bommel & De Boer (1980, p. 111-113). The term 'τ-curve' is used by Schreuder (1967, p. 132), and the term 'luminance-yield diagram' by De Graaff (1967).

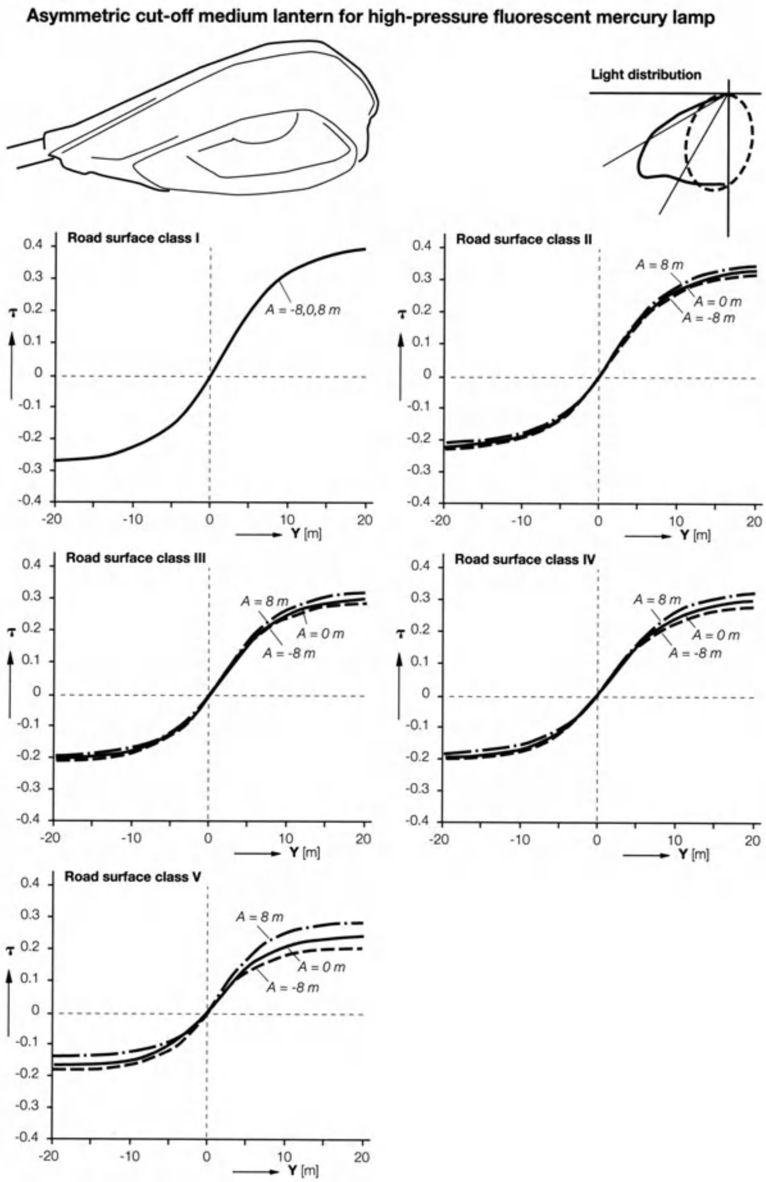

Figure 11.7.1: The utilization factor curve (or τ-curve) for the FCO luminaire type HRD. After Schreuder, 1967, p. 136.

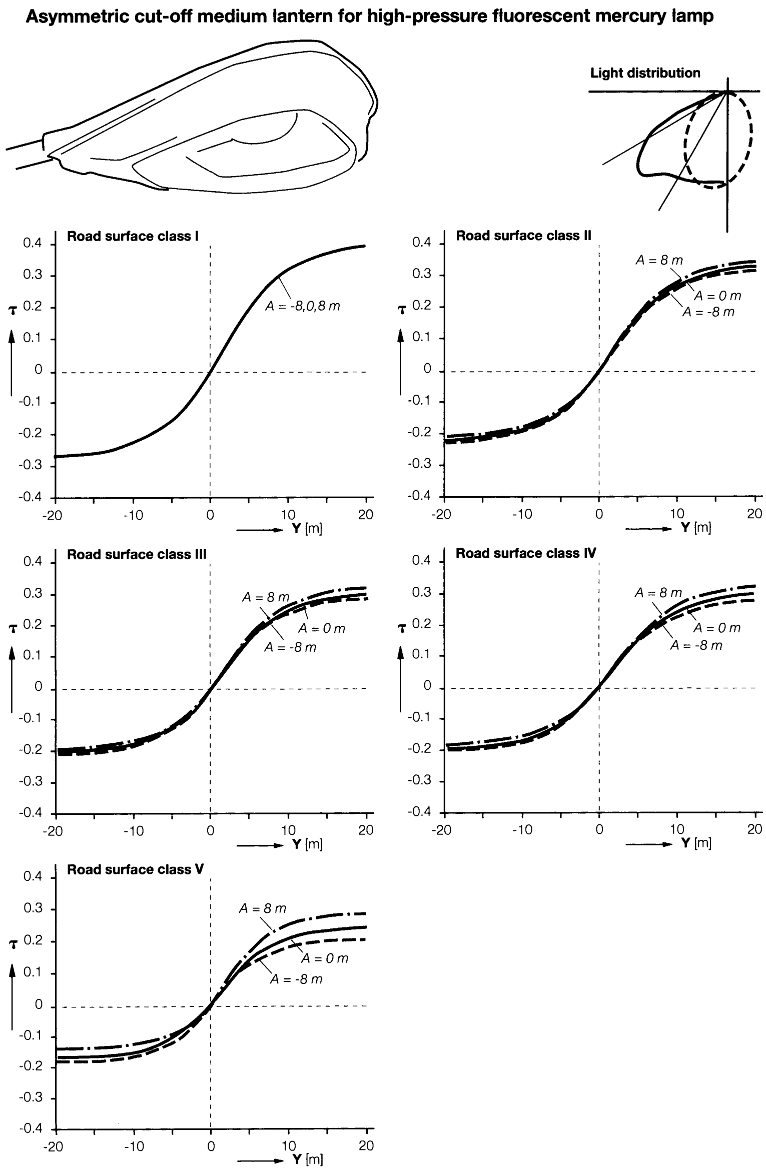

Figure 11.7.2: *The utilization factor curve (or τ-curve) for the CO luminaire type HRP. After Schreuder, 1967, p. 138.*

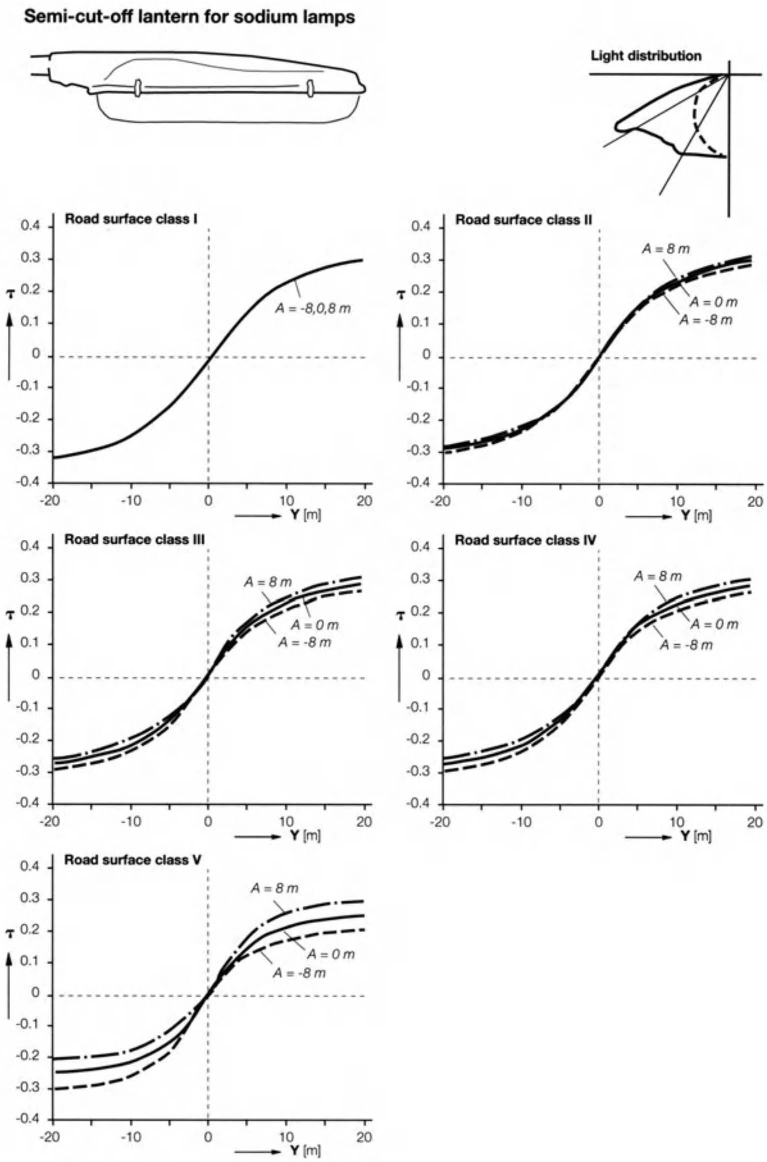

Figure 11.7.3: *The utilization factor curve (or τ-curve) for the SCO luminaire SRM. After Schreuder, 1967, p. 137.*

In each case, five utilization factor curves are given. The first (class I) refers to a perfect diffusor and represents the illuminance. The second is for a concrete road surface, and the forth is for an asphalt road of the type that is currently in use. Classes III and V represent road surfaces that are not common anymore.

Working with an utilization factor curve is illustrated in Figure 11.7.4.

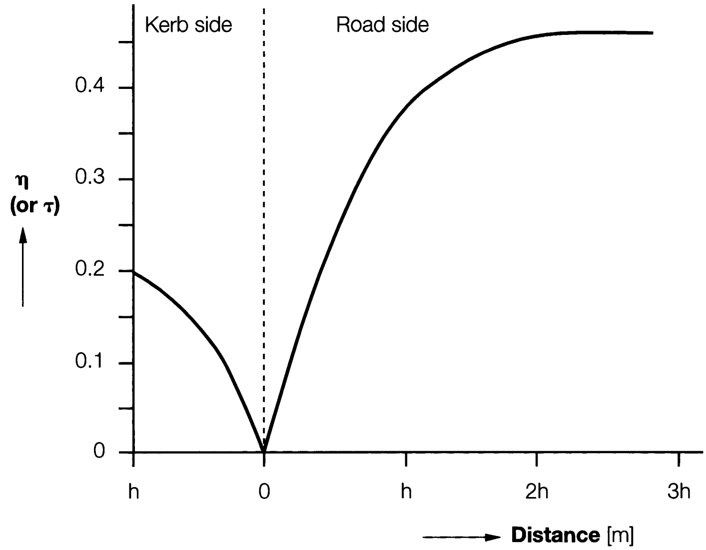

Figure 11.7.4: *Working with an utilization factor curve. Based on Van Bommel & De Boer, 1980, Figure 7.11.*

The utilization factor curves are normalized to the mounting height h. First, one inserts the two curbsides in the figure, where the projection of the luminaire is placed at h = 0. Then, the values of the utilization factor for the two curbs are read off from the η (or the τ)-scale. The differences between the two values is the utilization factor for that luminaire on that installation. It should be noted that the factor e_2, that is introduced in the discussion about the 'rule-of-thumb' estimation of the light level in relation [11.7.4] is, in fact, an estimate of the utilization factor.

11.7.5 Examples of the simplified low light pollution design method

A simplified design method for road lighting can be based on a small number of road types, each having a special function and, based on that function, a specific type of lighting installation that is its optimum. When a low light pollution design is needed, the environmental zone and the corresponding ULR must be taken into account. In the foregoing, a method is proposed, that allows to make such simplified lighting designs. In this section, several examples will be given, one for each of the road types. The examples are tabulated in Table 11.7.6.

	Road class		
	A	C	E
Road width (m)	12	8	4
Mounting height (m)	15	8	3
Spacing (m)	60	50	30
ULR (%)	FCO	CO	SCO
Required Illuminance (lux)	15	3	1
Required flux (lm; after [12.5.2]	22 000	2450	240

***Table 11.7.6:** Luminous flux values required for different road classes.*

Of course, one never can be certain that the exact lumen value is available. As an example, some lamps are quoted that come, at least, near the required lumen values. See Table 11.7.7. The lamp data and their designations are from the Philips Lighting Catalogue (Anon., 1997b).

	Road class		
	A	C	E
Required flux (lm)	22 000	2450	240
lamp type	SON 250 W	TLD 30 W	PLE 9 W
lumen	27 000	2450	400
lamp type	SON 150 W		PLE 5 W
lumen	14 500		200
data Anon., 1997b; p.:	1-179	1-101	1-140

***Table 11.7.7:** Lamp types, close to the required flux values*

If the discrepancy between 'supply' and 'demand' is felt to be too large, the installation needs to be adapted, and the calculations need to be made again in a next iterative step. If higher precision is needed, or if the luminance is required, it is recommended to use the method of the utilization factor curves, that is described in an earlier part of this section.

In conclusion, it is possible to make a crude design, in a first approximation, for a low-pollution road lighting installation in a simple way.

11.8 Visibility based design method for road lighting

11.8.1 General aspects

(a) *CIE method and CIE Recommendations for road lighting*

Since 1965, when the first version of the CIE recommendations (CIE, 1965) was published, the CIE method, with revisions, has a long successful history of almost 40 years, and is still valid. See also sec. 11.7.2c.

The CIE method for road lighting (CIE, 1965, 1977, 1995), is based on the recommendations for the lighting criteria, such as the average road surface luminance (L_r), the overall uniformity of the road surface luminance (U_0), and the admissible limit of the threshold increment due to glare (TI). The recommendations have been specified for visibility and for visual comfort. The CIE design method, however, does not directly depend on visibility but on the recommended quality criteria for the lighting parameters of road lighting, derived on the basis of investigations concerning visibility (Dunbar, 1938; De Boer, 1951: De Boer et al., 1959). It has been understood, therefore, that the recommended levels of the luminance are indirect indications of visibility.

In this section, a new approach to road lighting design is discussed, based on visibility. This approach is based on the research of Narisada and his collaborators, that has extended over several decades, but came to fruition only recently.

(b) *New demands for road lighting*

Over the last decades, however, the social demands for road lighting have rapidly and greatly increased. The increase has been brought about by the global issues, in addition to the principal demands for safety on the roads, security on the streets and the city beatification of after dark, into the field of the atmospheric temperature rises and the light pollution, about which the details have been discussed in the Chapters 1 and 13 of this book. These situations lead to a conclusion that the road lighting, by improving the physical, the photometric and the visual efficiency, needs to minimize the waste on the luminous flux and on the electric energy for road lighting, while keeping or improving the visibility conditions. This requires development of a new design method for road lighting more closely related with visibility.

(c) *Present situations of road lighting design*

Concerning the recommendations, there is general agreement that, in road lighting complying with the recommendations, none of the lighting parameters for quality criteria should fall outside the recommended ranges for the relevant criterion (Narisada, 1999, 2000). However, due to various technical reasons, it is not always possible to determine precisely, for all the lighting parameters, the figures recommended and/or calculated. One of the technical reasons can be explained that the luminous flux emitted by a type of the lamps available, for example, is provided in steps, according to a series of the wattages of the lamps. To maintain the relevant lighting parameter in a recommended range, the designers have, in most cases, to select a lamp whose luminous flux is greater than the calculated value.

For this reason, there was a trend to design the road lighting to a higher quality than specified in the recommendations. Every lighting parameter, except for glare, is higher than the recommended value. This means that the lighting installations consume more energy than needed to fulfill precisely the recommendations; it is, however, on the safe side. Consequently, it increases atmospheric temperature rises brought about by the excessive energy generation required, and the light pollution by the luminous flux reflected by the surfaces excessively lit. To solve the problems, at least partly, it is desirable either:

- to use a dimming system;
- to establish a trade-off relationship between the lighting parameters;
- or to develop a road lighting design method for a synthesised general quality criterion (Narisada, 1999, 2000).

A trade-off relationship means that, in order to maintain a necessary level of an overall the lighting quality, one lighting parameter that exceeds the relevant criterion is combined with another lighting parameter, which is less than that recommended value, so as to cancel the exceeding quality (Narisada, 1995). The overall lighting quality is called the 'synthesised lighting quality'.In this respect, dimming systems cannot solve the problem completely, because this does not include any trade-off relationship.

(d) Trade-off between average road surface luminance and overall uniformity

In Japan, investigations have been carried out to find the trade-off relationships between the average road surface luminance (L_r) and the overall uniformity (L_{min} / L_r) to ensure perception of object against the darkest part of the road surface, on a road lighting simulator in the laboratory (Narisada, 1971; Narisada & Inoue, 1973). The investigations have been repeated on two lit stretches of considerable lengths of two motorways, using cars cruising with a constant speed of 60 km/h (Narisada & Inoue, 1973, 1981). In the investigation, it was assumed that the darkest part of the road surface was the point where the perception of the object was the most difficult, and that, if sufficient visibility was provided at the darkest part, the necessary visibility conditions can be provided over the whole road surface area.

As a result, for various luminance contrasts, a simple trade-off relationship was established between the overall luminance uniformity (U_0) and the average road surface luminance (L_r), in order to perceive objects with a constant luminance contrasts against the darkest part of the road surface. It was shown that, irrespective of the luminance contrast to be perceived, the average road surface luminance (L_r) must be increased by a factor in proportion to the inverse square of the overall uniformity (U_0), in order to ensure a constant luminance contrast threshold at the darkest part of the road surface. The relationship can be expressed as:

$$L_r = \frac{L_u}{(U_0)^2} \qquad [11.8.1]$$

where L_u is the road surface luminance necessary to perceive a luminance contrast under perfectly uniform conditions ($U_0 = 1$). This implies that, if a road lighting installation is able to provide an overall uniformity of 0,5, instead of that recommended by CIE of 0,4, for example, to maintain visibility at the darkest part of the road surface, the average road surface luminance can be reduced to a value to 64% = $(0{,}4 / 0{,}5)^2$.

11.8.2 Luminance contrast under road lighting conditions

(a) Luminance contrast for non-uniform road surface luminance

Under actual road lighting conditions, however, the distribution of the luminance contrast of an object with a given reflection factor over whole road surface area is not constant. Instead, as to be discussed later in this section, it varies from one point to another on the road surface according to the combinations of the distribution of the vertical illuminance on the objects, the reflection factor of the visible surfaces of the object, and the distribution of the luminance on the road surface which constitute their background. As a consequence, the darkest part is not necessarily the point where the perception of the object is the most difficult, in spite of the assumption for the overall uniformity made in sec. 11.8.1d. The distribution of the luminance contrast threshold or of the luminance difference threshold over the whole road surface area is needed in order to determine the location of the point, where the perception of the object is the most difficult. At the time of the investigations, however, there was no method to derive the detailed distributions of the luminance contrast threshold over the non-uniform road surface luminance distribution (Narisada, 1999, 2000).

(b) Luminance contrast threshold or the luminance difference threshold?

Generally speaking, the visibility problems in relation to lighting can be examined either by the luminance contrast threshold or by the luminance difference threshold (Narisada, 1999, 2000). As is well-known, the difference between these two is only in the mathematical forms for the expression of the experimental results: they are reciprocal to each other.

In interior lighting, the principal objects to be seen are the characters or the drawings printed or written on paper. The paper constitutes the background, against which the objects are seen. For such objects, the difference in the distance between the observer and the object as well as the background is very short – almost zero – and the illuminance on the visible surface of the object and on the background paper are the same. For this reason, the luminance contrast between the object and the background is constant, irrespective of the lighting level. The luminance contrast, therefore, is a convenient tool for dealing with visual problems for lighting for interior works in relation to the lighting level (Narisada, 1999, 2000).

In cases of road lighting, on the contrary, the principal objects to be seen are pedestrians, bicycles, other vehicles, and obstacles on and around the road. They are seen against various backgrounds, such as the road surface, building facades, other vehicles, trees, bushes, walls, mountains, dark sky, etc. in the three-dimensional perspective view of the road and its surroundings a very long way ahead. The visible surfaces of most of them are illuminated differently by different light sources with different illuminance levels. As a result, variations in the luminance of these backgrounds are not always relevant to the changes in the lighting level of the road surface.

According to the CIE recommendations, the level of road lighting means the average luminance of a part of the road surface between about 60 m and 160 m ahead of the observer (CIE, 1965, 1977, 1995). The ways in which the lighting level changes in road lighting are not simple, compared to interior lighting. They are changed individually or in combination of:
(1) The luminous flux of the lamps;
(2) The number of lamps in each luminaire;
(3) The number of luminaires on each supporting structure;
(4) The reflection properties of the road surface;
(5) The arrangements of the luminaires;
(6) The spacing between the successive luminaires;
(7) The mounting height of the luminaires;
(8) The luminous intensity distribution of the luminaires.

Variations (1), (2) and (3) vary the lighting level without changing the distribution of the road surface luminance and the vertical illuminance on the visible surfaces of the objects on the road. Variation (4) happens only when the road authorities change the road surface, e.g. resurfacing it, for reasons other than the lighting.

Variations of the other points will result in changes in the lighting level, in the distribution of the road surface luminance and in the vertical illuminance on the visible surfaces of the objects. As a consequence, the luminance contrast of the object changes in a complex manner and the luminance contrast under road lighting for various points on the road surface is not constant for the changes in the lighting level. For these reasons, it is apparent that the luminance contrast is complicated to handle, for variations of visibility, and for the changes in the lighting level in comparison with the luminance difference threshold (Narisada, 1999, 2000). In the following, therefore, the luminance difference threshold will be used, in stead of the luminance contrast threshold that was used in the past.

(c) The luminance difference threshold

In this section, for the sake of simplicity, the minimum luminance difference between the object and the background, necessary to perceive the object under road lighting conditions, will be called 'the luminance difference threshold (for road lighting conditions)'. The threshold is larger than the theoretical threshold. The theoretical difference threshold corresponds to the luminance difference threshold calculated from the Visibility Reference Function for luminance contrast given in CIE (1981). The luminance difference threshold for road lighting conditions corresponds closely to the thresholds, calculated from the CIE data by Narisada (2001) and Narisada & Karasawa (2001, 2003) as well as those assessed from the results for uniform conditions for vehicle headlighting by Dunbar (1938); for road lighting by De Boer (1951), De Boer et al. (1959) and Ostrovsky (1962), as all are synthesised in one curve by Knudsen (1968); and also from the measurements for road lighting obtained with driving experiments on motorways by Narisada & Inoue (1973, 1981).

11.8.3 Visibility based methods for road lighting design in the past

(a) *The need for visibility based design methods for road lighting*

As described earlier in this chapter, road lighting is installed for visibility, more in particular to allow road users to see the run of the road and to detect obstacles. Taking the increase in the social demands as mentioned earlier in this section, and the recent progress in the field of road lighting engineering into account, development of a new design method, which is directly based on visibility, is desirable in the near future.

(b) *Historical background of visibility based design methods*

For about 65 years, attempts have been made to develop a method to design road lighting more directly on the basis of visibility. The first idea was the concept of 'revealing power' proposed by Waldram about 65 years ago (Waldram 1938). The revealing power was usually defined as the percentage of objects, a square foot in size, placed arbitrarily on the road, which can still be seen, where the diffuse reflection factor of objects follows the statistical distribution of the clothes of pedestrians (Schreuder, 1998).

Since the time of Waldram, the concept have been expanded (Harris & Christie, 1951), and used for analysis of the potential visibility of road lighting installation, by a number of investigators (Hentschel, 1971, Lambert et al., 1973, Van Bommel & De Boer, 1980). In spite of the efforts by these investigators, however, practical applications of their results are still limited.

In this section, the term 'potential visibility' will be used in stead of 'visibility of road lighting installation' which has been used before (Narisada, 1995), because the terms 'visibility of objects' and 'visibility of a lighting installation' may sometimes be confused. The term potential visibility is introduced by Lecocq (2002) in the considerations of a CIE Committee TC 4-36 on VL design parameters. See also Lecocq (1991, 1999, 2003).

(c) *Recent design method for road lighting on the basis of Visibility Level*

In the last decades of the 20th Century, in North America another attempt has been made to base road lighting design on a 'metric' for the visibility. This metric is the Visibility Level (see IES, 1988 and LRI, 1993). The Visibility Level (VL) is defined as a ratio between two luminance differences. At the one hand ($\delta L / \delta L_{min}$), the actual luminance difference between the object (L_o) and its background (L_b), or $\delta L = L_o - L_b$. At the other hand, the luminance difference between the object just perceptible and its background associated with the adaptation condition in question (CIE 1981). The concept of the Visibility Level stems originally from Holladay more than 75 years ago (Holladay, 1926).

The method is based on the research on the luminance contrast threshold by Blackwell (1946) for uniform background. The weighted average of the Visibility Level of an array of targets on the road surface is calculated. The weighted average is used as a synthesised criterion for visibility of road lighting (ANSI/IESNA, 2000). It is called 'Small Target Visibility', or SVT.

On the basis of the concept of the Visibility Level, and on studies by Janoff (1993), a method for the design of road lighting has been developed (ANSI/IESNA, 2000). The method is to calculate the Visibility Levels for a small square object of 18 cm × 18 cm with a reflection factor of 50% at a number of grid points on the road surface. The reason why a reflection factor of 50% was chosen, was mentioned in the Appendix of the American National Standard Practice for Roadway Lighting (ANSI/IESNA, 2000). It said that: "A design whose geometry is optimised for 50 % target yields higher weighted average VL for all other target reflectance than does a design optimised for any other target reflectance" (Keck, 1993).

11.8.4 Experimental background of the visibility based design method

(a) *Experiments for uniform luminance field*

In early days, the function of the luminance difference threshold for the background luminance was obtained with experiments for uniform background. Under the experimental conditions, the object to be perceived was presented against the uniform background, to the luminance of which the observer's eyes were fully adapted (Blackwell, 1946). Under the experimental conditions, the adaptation luminance of the observer's eyes and the background luminance were always the same.

This does not imply, however, that the influence of the adaptation luminance and the background luminance on the luminance contrast threshold or the luminance difference thresholds is the same. Since the adaptation luminance concerns the physiological state of the sensitivity of the retina, whereas the background luminance is a photometric stimuli to the retina (Narisada & Karasawa, 2001, 2003).

Under practical conditions, the distribution of the luminance in the driver's field of view is not uniform and, as the car proceeds, the distribution of and the general level of the luminance in the field of view of the driver are rapidly and intricately changing. The adaptation luminance of the drivers' eyes, however, due to slowness in the photochemical process in the retina for changes in the state of adaptation, cannot follow the rapid and intricate variations in the luminances in the view of view at any moment (sec. 8.2.3). Instead, the driver's eyes are adapted fairly steadily to a dynamic average luminance, which stimulated the fovea for some length of time in the immediate past (Narisada, 1999, 2000).

In practice, however, it is generally accepted to assume that the driver's eyes are adapted to the average road surface luminance (Narisada et al., 1997). Because the lit road surface, on which important visual information regarding the run of the road and dangerous obstacles may be unexpectedly appearing, has a dominant areal effect on the perspective view of the road relevant to driving and easily captures the driver's visual attention.

The drivers have to perceive the objects, which are appearing randomly in various parts of rapidly changing non-uniform field of view, against the background, at the moment when the driver momentarily focuses his or her visual attention onto one of the objects for only 0,1 or 0,2 seconds (Watanabe, 1965, Narisada & Yoshikawa, 1974). This means that the drivers have to perceive the objects against the momentarily presented background which luminance is extensively and momentarily changing, with their eyes adapted to a dynamic average of the luminances fairly steady. From this it is obvious that the results of the experiments for uniform background cannot apply to non-uniform dynamic conditions, under which the observer's eyes are not adapted to the luminance of the background, which is considerably different from the adaptation luminance (Narisada, 1995; Narisada & Yoshimura. 1977, 1977a).

(b) Investigation on the influence of the momentarily presented background luminance

The first systematic investigation concerning the influence of the adaptation luminance and the background luminance to perceive various luminance contrasts, has been carried out by Schreuder (1964) concerning the black hole effect, which occurs during tunnel approach in daytime (sec. 9.1.3).

During the tunnel approach in daytime, the driver's eyes are adapted to the general level of the luminance in the access zone lit by intensive daylight to a luminance level of several thousands candelas per square metre. On the other hand, due to technical and economic limitations, the luminance in the tunnel interior, against which the driver has to perceive obstacles, is limited to a value less than 10 cd/m^2. Under such extremely different conditions between the adaptation luminance and the background luminance, the tunnel is seen by approaching drivers as a black hole. This is the cause of the black hole effect (Schreuder, 1964).

To solve the black hole effect, an intensified lighting section has to be provided at the first stretch of the tunnel, called the threshold zone (Schreuder, 1964, CIE, 1984). Schreuder (1964) has investigated the necessary luminance in the threshold zone to perceive the luminance contrast against the luminance in the threshold zone. Before each observation run, the observer's eyes were adapted fully to the luminance of a uniform screen. During the period of the pre-adaptation, the tunnel mouth was closed and practically no tunnel mouth was visible to the observer. After a sufficient period of the pre-adaptation, at the centre of the uniform screen, a small rectangular tunnel was momentarily opened for 0,1 seconds, against the luminance in the tunnel. The object was presented simultaneously, while keeping the high luminance of the uniform screen constant except the portion of the tunnel opened. As a result, a group of curves, necessary to perceive a variety of the luminance contrasts against the background, while keeping the adaptation luminance constant, was obtained. Consequently, from the experiments, an important fact was found that momentarily changes in the background luminance varies the luminance contrast threshold instantaneously and considerably, while the observer's eyes adapted steady to a luminance considerably higher than the background luminance.

Schreuder's results, however, could not apply directly to the visual problems for road lighting. This was because the aims of the experiments by Schreuder was to investigate visual problems of the black hole effect during tunnel approach and over the background luminance in the momentarily presented tunnel, a considerable amount of veiling luminance caused by the bright uniform screen was superimposed.

(c) *Experiments on the luminance difference threshold under dynamic conditions*

Two series of experiments were made to investigate the luminance difference threshold under dynamic conditions, under which the adaptation luminance and the background are different (Narisada & Yoshimura, 1977, 1977a).

In the first series, the luminance difference threshold was measured for a small sized uniform field, to the luminance of which the observers' eyes were fully adapted (Narisada, 1995). A small object exposed momentarily for 0,125 seconds against the uniform field was perceived. The luminance difference threshold thus obtained was determined by the adaptation luminance and the background luminance in combination.

In the second series, after a sufficient period of the adaptation to the luminance of the uniform field, as in the first series, the uniform field suddenly disappeared immediately before the object was presented momentarily. The object, then, was presented against the dark background again momentarily for 0,125 seconds. The adaptation did not change by the momentarily variations in the background luminance. Figure 11.8.1 shows the difference in the field of view of the observer in two series during the period of pre-adaptation and at the moment when the object is perceived.

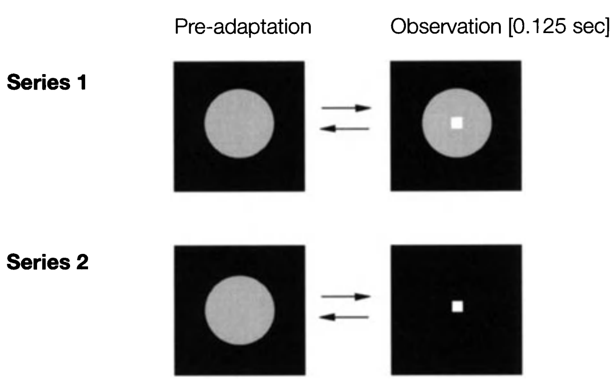

Figure 11.8.1: *Variations in the field of view in the two series of the experiments. After Narisada, 1995.*

Because of the disappearing of the background at the moment when the object was perceived, the luminance difference threshold obtained with the second series was not influenced by the background luminance, but only by the adaptation luminance. This means that the difference in the luminance difference thresholds for the same adaptation luminance between Series 1 and 2 was the luminance difference threshold determined by the background luminance.

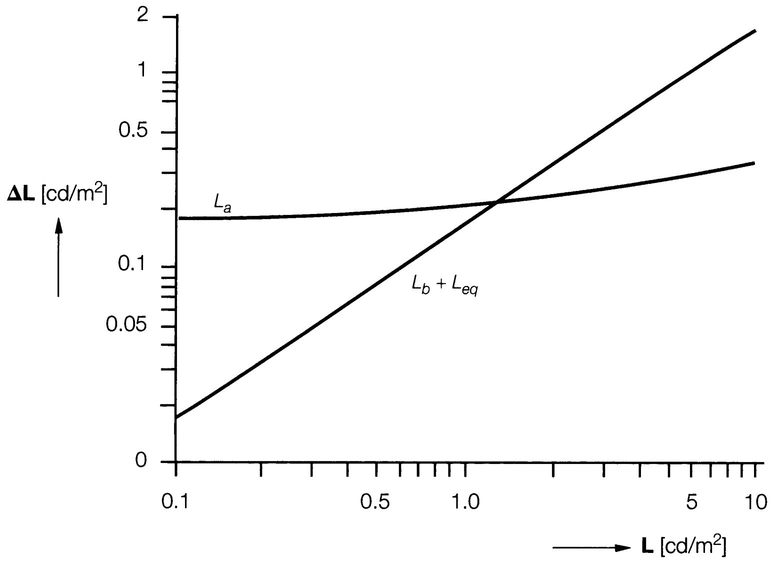

Figure 11.8.2: *The luminance difference thresholds for the adaptation luminance and the background luminance for road lighting. After Narisada, 1995.*

The curve in Figure 11.8.2 shows the luminance difference threshold for the adaptation luminance and the straight line gives that for the background luminance thus calculated. (Narisada, 1995; Narisada & Yoshimura, 1977, 1977a). Further details are found in the original paper (Narisada, 1995). In this way, two independent relationships of the luminance difference threshold, one for the adaptation luminance and another for the background luminance have been obtained.

Adding the luminance difference threshold determined by the adaptation luminance and that by the background luminance, the luminance difference threshold for any combination of the adaptation luminance and the background luminance for any non-uniform luminance field can be derived. The additivity of the two luminance difference thresholds has experimentally been conformed (Takeuchi & Narisada, 1996). If necessary, the luminance difference threshold for a uniform luminance field can be obtained as the sum of the two luminance difference thresholds for the same values of the adaptation luminance and the background luminance.

(d) *Influence of the equivalent veiling luminance caused by the disability glare*

From the experimental procedure employed, it was apparent that when an amount of the equivalent veiling luminance caused by the disability glare is superimposing over the field of view, the increase in the luminance difference threshold can easily be included in the luminance difference threshold derived by adding the amount to the veiling luminance to the background luminance (Takeuchi & Narisada, 1996).

11.8.5 Theoretical background of Revealing Power based design for road lighting

(a) *Visibility level and potential visibility of road lighting*

From the definition as given in sec. 11.8.3c, it follows that the Visibility Level ($VL = \delta L / \delta L_{min}$) at a point of the road surface varies according to the reflection factor of the object, as the luminance of the object changes accordingly. As mentioned earlier, δL is the photometric difference in the luminance ($L_b - L_o$) actually existing between the object and the background, and δL_{min} is the luminance difference threshold of the observer's eyes looking at the point.

This shows clearly that the numerical figures of the Visibility Level are not relevant to the potential visibility at a point on the road, but to only the visibility of an arbitrarily chosen object at that point on the road. Even if the VL at a point on the road is high, this does not imply that the potential visibility at that point is also good. Similarly, even if the VL at a point on the road is zero, it does not mean that nothing is visible at that point. Other objects, whose reflection factor is considerably different from that of the standard object, may be seen with a high Visibility Level (Narisada & Karasawa, 2001, 2003, Narisada et al., 2003).

The Visibility Level is technically meaningful for the potential visibility of road lighting, only when an appropriate reflection factor is chosen for the object and it is seen in an appropriate polarity to be discussed later in this section.

(b) *Reference Reflection Factor and Reference Object*

As mentioned above, the potential visibility of road lighting depends on the reflection factor used for calculations for the Visibility Level and the polarity of the luminance difference ($L_b - L_o$) between the background and the object to be seen. In this section, the reflection factor used for calculations for Visibility Level is called the 'Reference Reflection Factor' and the object, whose reflection factor is equal to the Reference Reflection Factor is called the 'Reference Object' (Narisada & Karasawa, 2001, 2003, Narisada et al., 2003).

(c) *Polarity of the luminance difference and visible reflection factors*

If the Reference Object is just visible (with a Visibility Level of 1), and if it is darker than the background at a point on the road surface, i.e. the luminance difference is positive, then all the objects, whose reflection factor is lower than the Reference

Reflection Factor, are visible, if they are sufficiently large. The Visibility Level of these objects increases as the reflection factor decreases, since the luminance difference increases accordingly. Similarly, if a Reference Object is just visibly lighter than the background, then all the objects, whose reflection factor is higher than the Reference Reflection Factor are visible. The Visibility Level of these objects increases as the reflection factor increases. The potential visibility at a point of a road lighting installation is better if the number of objects whose reflection factors are perceptible increases. It should be noted that there is no lighting under which all the objects are perceptible with the same polarity of the luminance difference, either positive or negative. Always the range of luminance differences is less than the luminance difference threshold in either polarity, in which no object is visible (Narisada & Karasawa, 2001, 2003, Narisada et al., 2003).

(d) Critical object

On actual roads, there will be a variety of obstacles, small, large, short, long, thin, blocky, hard, soft, light, and dark, etc. Of all, the principal factors relevant to perception are the reflection factor, concerning light and dark, and the size and shape. It is hardly possible to examine separately the visibility of all those different obstacles in relation to lighting. To examine the visual requirements of road lighting, in this section, a square object will be used, with a size 0,2 m × 0,2 m, which is an object the most difficult to perceive but still dangerous for traffic is used (CIE, 1984; De Boer et al., 1959; Narisada, 1971, 1999, 2000; Narisada & Inoue, 1973, 1981; Schreuder, 1964). This is not a representative of various obstacles. Instead, the object is used as the 'metric' of visibility needed for safe driving.

Such small critical objects must be visible in order to drive a car safely, to make correct judgments for differences in speed with other vehicles and for the lateral position with respect to the driving lane in curved stretches, or to judge the behaviour of pedestrians crossing the street, etc. To make correct judgments, the driver needs to perceive the points at which the rear wheels of a large car are in contact with the road surface; also, the motion of the legs, the arms, the head of pedestrians have to be clearly visible (Narisada, 2001). These objects – or rather, parts of objects – are really very small. To perceive the points correctly, visibility conditions that enables to perceive the small metric object long ahead is essentially necessary. Such a small metric object will be called here as the 'critical object'. See also sec. 10.3.1e. In the following parts of this section, the visibility of the critical object will be discussed.

(e) Spherical object

Lecocq (1991) has suggested using a spherical object, instead the flat target, taking into account of the direction of observation and visibility. He has investigated the advantages of the spherical object for visibility study (Lecocq, 1991, 1999, 2003). In this section, however, to make the calculation simple, a flat object has been used.

(f) Reference Reflection Factor and statistical distribution of reflection factors

If a Reference Object (Reference object with a Reference Reflection Factor) just visible is darker than the background at point A and lighter at point B, and if the number of possible objects, whose reflection factor is lower than the Reference Reflection Factor, is larger than those having a higher reflection factor, then the potential visibility at point A is better than point B.

This means that the polarity of the luminance difference between the luminance of the Reference Object just visible and that of the background, and the statistical distribution of reflection factor of object are decisive factors for the calculated potential visibility of road lighting (Narisada & Karasawa, 2001, 2003, Narisada et al., 2003).

(g) Statistical distribution of reflection factor of possible objects

Waldram used for his study of the Revealing Power, the statistical distribution of reflection factor of pedestrian's clothing as in Figure 11.8.3 synthesised by Smith (1938). The curve shows about 90% of pedestrian's clothing has a reflection factor less than 20%. Similar field studies conducted in the Netherlands and Japan about 30 years later, showed no marked difference with those of Smith (Serizawa, 1967, Van Bommel, 1970). This means that, if a small flat object (the critical object) with a reflection factor of 20% is just visible at a point on the road surface, being darker than the background road surface, then about 90% of the objects are perceptible at that point and the corresponding Revealing Power is about 90%.

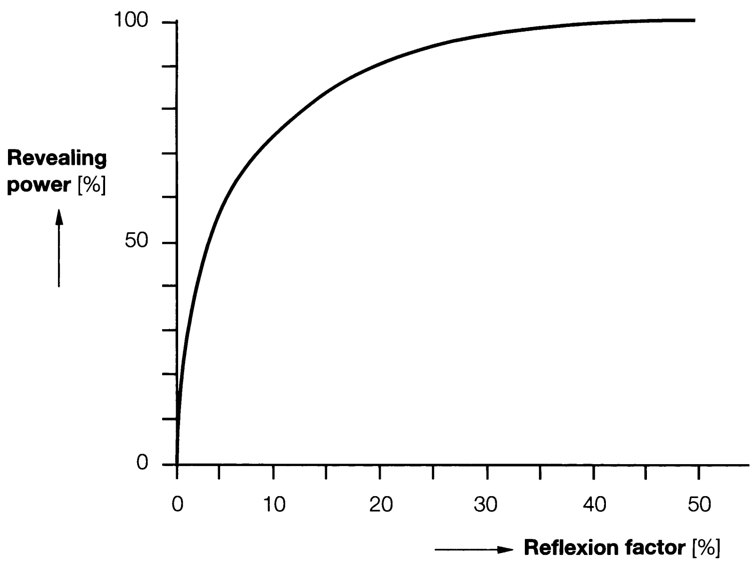

Figure 11.8.3: *Statistical distribution of reflection factor of pedestrian's clothing. After Smith, 1938.*

On the contrary, if the object that is just visible at a point on the road, is lighter than the background, then the Revealing Power at that point is only 10%. This obviously shows that the polarity of the luminance difference between an object perceived at a point under the road lighting or the tunnel lighting and the background, against which the object is seen, is essential relevance and importance for the potential visibility at the point of lighting.

(h) Reflection factors and the sensory lightness

Obstacles to be perceived under modern road lighting, however, are not only pedestrians but also a variety of objects on and around the road. Smith's results can sometimes be questioned in that his results concern only for pedestrians' clothing and lay too much emphasise on dark colours even though colours used at present are much lighter. The question may be caused, perhaps, by the impression that an object with a colour with a reflection factor of 20% looks very dark, since the object reflects only 1/5 of the incident light (Narisada & Karasawa, 2001, 2003).

Generally speaking, people choose the lightness of colours they like to have on various things, such as clothing, interior decoration, electronic equipments, furniture, other various household apparatus, paintings and toys, etc, not by their reflection factors but by the sensory lightness and colour itself. The sensory lightness, which human eyes perceive, has no linear relation with the reflection factor. One of the examples of linear scale of the lightness of colours is the Munsell Value scale (Newhall et al., 1943). In the Munsell Value scale, the Value 0 corresponds to a completely black surface with a reflection factor of 0%. In practice, it is not possible to produce either a completely black, or a completely white surface. The Value scale between 1 and 9 are divided in equal steps of sensory lightness. See also sec. 8.3.7h. The relationship between the reflection factors and the sensory lightness is analogical to the relationship between the frequency of tones and the musical scale.

Below, a number of examples of reflection factors and their corresponding Munsell Values will be given. The colour whose reflection factor is 20%, corresponds to a Munsell Value of about 5, is just the middle of the Value scale. On the other hand, the Munsell Value of pure chocolate, which colour is relatively dark has a reflection factor of about 5%, with a Value of about 2,5 (still a lightness about a half of that of the neutral grey). An asphalt concrete road surface, whose reflection factor is about 15% has a Value of about 4,5 (slightly darker than the neutral grey). In addition, that of a used cement concrete road surface, whose reflection factor is about 25% has a Value of about 5,5, and that of a new cement concrete, whose reflection factor is about only 50% has a Munsell Value of about 7,5. The Munsell value of the Caucasian female complexion, whose reflection factor is about only 60% has a Value of about 8 (Narisada & Karasawa, 2001, 2003).

It must to be noted that the colours with higher lightness do not have a vivid colours but subtle colours. Instead, many people at present like to have vivid colours and their consequent Munsell Values, normally, are less than 6, and the reflection factor is less than about 30%.

These examples show that the Smith survey does not lay too much emphasise on dark colours and pedestrians in Smith survey did not choose especially dark colours for their clothing and other things. For these reasons, it can be concluded that the results of Smith on the statistical distribution of the reflection factor can still be used for analysis of the potential visibility of modern road lighting installations, unless scientific and reliable surveys reveal any obvious other tendency.

One further remark should be made. On the one hand, people living in countries with strong traditions, will select their clothes, both in the degree of cover as in the material and colour, in agreement with these traditions. Some are white or almost white, whereas others are black or almost black, depending on the customs – as well as on the climate – of the country or region. Personal preference, nor nighttime visibility seem to be a major consideration. On the other hand, people in most industrialized countries select their clothes as regards the degree of cover, but also the material and colour, in agreement with season and fashion. It is easy to observe, that most people prefer light coloured clothing during the day in summer, whereas in the winter, and more in particular at night, most people wear dark clothing. So, in the end, when considering the lit streets at night, the Smith figures still seem to be relevant, at least for the industrialized countries. For other parts of the world, where about 85% of the total world population lives, there are no quantitative data.

(i) Conversion Visibility Level into Revealing Power

The conversiof Visibility Level into Revealing Power was studied by Narisada & Karasawa (2001, 2003) and Narisada et al. (2003). The distribution of the Revealing Power can be obtained from the distribution curves for Visibility Level =1 in the same polarity of the luminance difference for various Reference Reflection Factors. As discussed in the preceding part of this section, and as shown in Figure 11.8.3, for example, if a Reference Object with a Reference Reflection Factor of 20% just visible at a point on the road surface with a Visibility Level of 1 is darker than the background, then the potential visibility at that point corresponds to a Revealing Power of 90%. If the Reference Object just visible is lighter than the background, then the corresponding Revealing Power is 10% (the difference between 100% and the Revealing Power for darker objects). By repeating the procedure, the distribution of the Visibility Level of one for various Reference Reflection Factors can easily be converted into the distribution of the Revealing Power. The Reference Reflection Factor and the corresponding Revealing Power are given in Table 11.8.1.

Revealing Power (%)	Reference Reflection Factor (%)
90	20
80	17
75	11
70	8
60	5

Table 11.8.1: *Revealing Power and Reference Reflection Factor*

(j) Area Ratio for Revealing Power

To express the general level of Revealing Power as a synthesised quality criterion, an Area Ratio has been suggested. It is defined as the percentage of area making up the whole road surface area over which the Revealing Power is higher than 90%. An Area Ratio of 70% may be one of the acceptable levels of visibility of road lighting for important roads (Narisada & Karasawa, 2001, 2003, Narisada et al., 2003).

11.8.6 Procedure for deriving distribution of Revealing Power

To develop a new visibility based design method for road lighting, it is necessary to calculate necessary basic distributions of the Revealing Power for each type of the luminaire for each type of road surface. The is the basis of Revealing Power method.

The distribution of Revealing Power for this purpose can be derived in the following procedures. Further details are to be referred to the original papers (Narisada & Karasawa, 2001, 2003, Narisada et al., 1997, 2003).

(1) By applying the widely used calculation method (CIE, 2000), calculate the luminance for a type of the luminance, at many points on the road surface for a type of the road surface;
(2) Calculate the average road surface luminance of the luminance at the many points;
(3) Utilising the experimental results in Figure 11.8.2, for a value of the average road surface luminance to which the driver's eyes are assumed to adapt, obtain the luminance difference threshold (δ Lmin) against the background road surface luminance at the many points on the whole road surface area. The location of the point of the road surface is tentatively assumed at 7 m behind the object. The point on the road surface 7 m behind the object 100 m is located just vertical centre of the Critical Object at 100 m ahead seen by a driver, whose eye height is about 1,5 m;
(4) By applying the widely used calculation method (CIE, 2000), calculate the vertical illuminance on the visible surface of the object at many points on the road surface area;
(5) Referring to Table 11.8.1, select a reflection factor of object, which corresponds to a Revealing Power (for example, a Revealing Power of 90%), of which distribution is to be calculated;
(6) Calculate the luminance of the Reference Object, whose reflection factor, for instance, is 20%, corresponding to a Revealing Power of 90% at many points on the road surface;
(7) Calculate the difference ($\delta L = L_b - L_o$) between the background luminance (L_b) and that of the object (L_o) at the many points on the road surface, on the basis of calculated results in (1) and (6);
(8) Calculate the Visibility Level as a ratio ($\delta L / \delta L_{min}$) of the luminance difference (δL) to the luminance different threshold (δ Lmin) at all relevant points on the road surface. The difference in different polarities must not be confused. Only those in the same polarity are relevant;

(9) Derive distribution curves for Visibility Level = 1, for the Reference Reflection Factor (For example a reflection factor of 20%);
(10) The distribution curve for Visibility Level 1 shows the distribution curve of the corresponding Revealing Power (of 90% as the example);
(11) By calculating for the percentage areal extent making up the whole road surface area, in which the Revealing Power is higher than, 90%, the Area Ratio can be obtained.

11.8.7 Relations between the Area Ratio and the lighting parameters

(a) Calculation of the relationship between the Area Ratio and the lighting parameters

The relations between the Area Ratio and the lighting parameters has been studied by Narisada et al. (2003). To examine the influence of the design parameters on the Area Ratio, and repeating the procedures in the forgoing, calculations for the relationships between the Area Ratio and lighting parameters for a combination of a semi-cut off luminaire and an asphalt concrete road surface are necessary. The lighting parameters subjects of calculations are:
(1) The road surface luminance;
(2) The luminaire arrangement;
(3) The mounting height;
(4) The spacing-to-height ratio;
(5) The overall uniformity.

As a result, it has been made apparent that (1) the average road surface luminance, (2) the luminaire arrangements, and (3) the mounting height have a remarkable influence on the Area Ratio or the potential visibility (Narisada et al. 2003). The spacing-to-height ratio (4), when smaller than 3,5, as well as the overall uniformity (5) have a minor influence.

The Area Ratio for the opposite arrangement is higher than that for the single sided arrangement. The Area Ratio increases as the average road surface luminance and/or the mounting height are increased. These results can be given in the graphic forms.

(b) Revealing Power method – 1

The synthesised recommendations for quality criteria for this design method are the percentage of the Area Ratio for different categories of roads. The luminaire manufacturers can provide the curves for the relationships between the necessary Area Ratio and the lighting parameters, for a combination of the luminaire and the typical road surfaces. The designer selects, taking various associating factors of roads into account, the best combinations of the luminaire, the luminaire arrangement, the mounting height and determine the road surface luminance. The validity of the computer program and the accuracy of the basic data must carefully be checked. The method to verify the results of the design is still a subject of future development.

(c) Revealing Power method – 2

The recommendations for quality criteria for this design method are the average road surface luminances for different categories of roads, in combination with mounting height or a ratio of the mounting height to the width of the road. The recommended luminance, to ensure an Area Ratio of 70%, for example, is derived by the procedures in the foregoing for a typical luminaire and for a road surface, which are a subject of the international agreement. The method to verify the results of the design can be made by the measurement of the average road surface luminance. Even in such a simple way, the relevance of the lighting to visibility will be made much closer.

(d) Advantages of the Revealing Power method for road lighting design

The Revealing Power method mentioned above has a number of advantages, such as:

(1) Lighting is designed for one single synthesised requirement for visibility, the Area Ratio of the Revealing Power. By using the design method, the problems concerning the over lighting, due to the lack of trade-off relationships between the lighting parameters and the visibility can be solved;
(2) The lighting designers are able to improve the visibility conditions, by calculating appropriate geometric dimensions of the lighting installation in relation to the Area Ratio;
(3) By using the Revealing Power method, light pollution caused by the reflection from the illuminated surfaces can be reduced, while keeping the potential visibility of road lighting unchanged, by combining appropriate geometric dimensions of the lighting installation.

The Revealing Power method is one of the promising methods for road lighting under discussions. To reach the final goal, the method needs still some years to come.

11.8.8 Road surface luminance for other than visibility

As discussed earlier, by selecting an appropriate lighting parameters, similar levels for Area Ratio can be obtained for road lighting with a lower road surface luminance. However, this does not imply automatically that lower average road surface luminances are applicable or advisable by ensuring a high level of the Area Ratio. The Area Ratio is the minimum requirement for road lighting. It is not advisable to provide a very low average road surface luminance, even if an acceptable Area Ratio is ensured (Narisada & Karasawa, 2001, 2003).

The first reason is that under low road surface luminance conditions, the relative influence of the vertical illuminance from the headlights of one's own car and increases in the luminance of the object and of the disability glare caused by the headlights of on-coming traffic, are large and consequently the Area Ratio deteriorates considerably, far more than that expected.

The second reason is that drivers driving on a dark road feel anxiety about safety, irrespective of the potential visibility provided, as no one can judge the level of the Revealing Power visually. Such psychological stress reduces the task performance of the drivers. Therefore, the luminance level in order to ensure visual comfort, investigated by a number of investigators must fully be taken into account.

The reason is visibility of the road surface ahead. To ensure visibility of the run of the road for considerably distance ahead, for fast safe driving, a sufficient brightness is necessary to provide over the whole road surface areas. The matter will also be a subject of future discussions.

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12 Effects of outdoor lighting on society and on the environment

The effects of outdoor lighting are related to the direct influence on society, more in particular on road accident and street crime reduction as well on the environment. This chapter deals with the methodological aspects of these. Several other influences on society, aimed at making the visual surroundings more effective or more agreeable, are discussed in detail in other chapters. The influence of outdoor lighting on living creatures, on the climate as well as other environmental effects are discussed in Chapter 4.

The major priorities for installing road and street lighting are the reduction of accidents and crime. This relates to the objective measure of the reduction, but the subjective aspects like e.g. the feeling of security are at least as important. Surveys show that the objective road accident risk is world-wide one of the major causes for premature death, whereas subjectively the fear of road crime is much greater than the fear of road accidents.

Vehicle headlighting has been an area of intensive research for many decades now. In the past, most research was carried out by road safety institutes, but in the last two decades or so, the research is almost completely done by the car lighting industry. New ideas and new products focus on the improvement of the visibility for the car driver. They all, invariably, increase glare for other road users. The influence on light pollution has not been studied at all. One may expect a considerable influence, because glare and light pollution increase when the light above, and close to, the horizon increases. Furthermore, the major astronomical observatories are almost all located in sparsely populated regions, where vehicle lighting usually is the predominant, and often the only, form of nighttime outdoor lighting. For these reasons, the car headlighting is discussed in detail in this chapter, concluding with an estimate of the quantitative effects of vehicle headlighting on light pollution. The conclusion is that vehicle headlighting may cause severe light pollution, particularly in directions close to, and above the horizon. In most cases, the headlighting will cause considerably more light pollution than a regular road lighting installation.

Many measures that would diminish the impact of light pollution have not been implemented simply because the costs are high, irrespective of the benefits. A wise government, however, decides to take any policy measure when the benefits exceeds the costs. For this, cost/benefit evaluations are needed, in which all advantages and all disadvantages of a measure are expressed in the same unit, usually in money-value. When a number of alternative measures are compared, a list of priorities can be established. Such lists are helpful to develop any sort of policy, e.g. for the reduction of accidents and crime, but also for the reduction of light pollution.

The total light that is emitted upwards by outdoor lighting, is more than the light emitted upwards by the luminaires. There is always light reflected upwards by the surface of the lit area. Some misunderstanding of the physics of light propagation as well as a lack of understanding of the technical and optical restrictions of outdoor luminaire design, did give rise to the 'flat glass controversy'. Some people believe that using a flat cover glass will reduce the upward flux, and thus the light pollution drastically, whereas other believe that a shallow bowl is better, because the luminaires can be placed further apart. When installations with luminaires with different cover shapes are compared, it seems that there may be considerable differences as regards the split-up between the direct and the indirect – or reflected – component of the upward flux. However, when luminaires were compared where only the shape of the cover was different, the differences proved to be marginal. There seem to be no serious grounds to keep the 'flat glass controversy' alive.

12.1 Road lighting

12.1.1 Accident prevention

(a) *Introduction to accident and crime studies*

It has already been explained in detail on several occasions in this book, that, when considering light pollution from outdoor lighting, it is, obviously, essential to know the need for lighting, as well as its effect. More in particular, the crucial questions are, on the one hand, what the relation is between outdoor lighting and traffic accidents, and, on the other hand, what the relation is between outdoor lighting and crime.

As is explained in great detail in several chapters of this book, extensive research has been done on these two relationships. Unfortunately, most research is tinted heavily by the interest – often the commercial interest – of the parties involved in the research activities, and, more in particular, in the reporting of the results. Additionally, it must be stated that in both areas of research, most studies suffer from methodological flaws. Unfortunately, in many cases the flaws are so severe, that it is difficult to estimate what is the significance, if any at all, of such studies. As mentioned earlier, the interest of some parties involved did lead, not only to the publication of such studies, but to quote them with a lot of emphasis, as long as they seem to support the case of that party. One does not have to search deeply to find the two parties we have in mind: on the one hand the astronomical community, that pursues a real dark surrounding to favour astronomical observations, and on the other hand, the lighting and energy communities, that advocate generous light. It is noteworthy, that the parties, that would benefit most from the reduced accidents and restricted crime, viz. the law enforcement agencies and the civilian protection organizations, are not particularly active in this area.

The relations between outdoor lighting and traffic accidents, and the relation between outdoor lighting and crime are, as indicated earlier, essential in all considerations about light pollution. The reason is that accident reduction and crime restriction are the two main objectives to install outdoor lighting in the first place. Other reasons to install outdoor lighting – other functions of outdoor lighting – are important for special groups within the community, or for specific locations, like e.g. the lighting for city beautification, the lighting of sports facilities, or the lighting of industrial and commercial sites. As stated earlier, these are essential in all considerations about light pollution. Accident reduction and crime restriction relate, however, to everybody, and to almost all locations, in society. If there was no need to reduce traffic accidents, or to restrict crime, there would be hardly any problem of light pollution.

The two items have much in common. The problems that are indicated here, stem from the fact that the research in these fields often did yield ambiguous results. The promotion of the results is often slanted into a direction that is favourable for one of the parties involved. Over the years, the lighting and energy communities maintained that it has been 'proved' that outdoor lighting reduces road accidents and restricts crime. At the same time, the astronomical community, in some small way supported by environmental protectionists, are adamant that more lighting causes more road accidents and more criminal acts. Both assertions are, of course, very crude, and mostly rhetorical.

In a section called '2.2. Researchers and bias', in relation to "the organization that controls, funds, or otherwise supports the research", it is written: "Unfortunately, such situations appear to influence authors far more than might be expected. There are known cases in which scientific papers and reports have been markedly compromised by this kind of bias" (Clark, 2002, p. 9). It might be added, that the pressure is by no means always financial.

As far as they are based on data, the main sources were statistical studies, often of the before-and-after type, where the number of accidents or the number of criminal acts in the 'before' period were compared to the correponding number in the 'after' period, that is, after some 'improvement' of the lighting was introduced. Both in principle as well as in practice, it is impossible to deduct any causal relationship whatsoever from statistical data. Now, in order to invent or to assess any accident or crime countermeasure, it is essential to know the causal relation between the measure and the accidents or the crimes.

At this point, there arises a difference between the studies regarding the relation between outdoor lighting and traffic accidents, and those regarding the relation between outdoor lighting and crime.

The relation between outdoor lighting and traffic accidents is not only based on the results of statistical investigations. As is mentioned in part (e) of this section, meta-analysis did support in broad lines the findings of the individual statistical studies (Elvik, 1995; Welsh & Farrington, 2002). There are many indications from analytical research, that more adequate lighting promotes better visual performance, whereas other studies show clearly that many accidents, particularly nighttime accidents, are closely related to poor visual performance (Schreuder, 1967, 1970, 1970a,b, 1971, 1975, 1981, 1991). Some aspects of the functional approach are briefly discussed in sec. 2.1. It should be noted, that here the term 'adequate' is used, and not the term 'generous' that was used in earlier days. What this implies, is that the quality of light counts, and not quantity. In conclusion, it seems to be justified to assert, that adequate outdoor lighting on roads and streets is an effective road traffic accidents countermeasure. Only seldom one will meet the opinion anymore that 'more lighting causes more road accidents'.

The end result of all this is, that there is a controversy between the astronomical community, supported by environmental protectionists at the one hand, and the lighting and energy communities at the other hand. The controversy sometimes grows to ugly proportions. The solution is, of course, to do better research, or, at least, study the available research very carefully. This has been done in recent years in several occasions. Some of the results are discussed in sec. 15.1, when stressing the need that astronomers and lighting engineers to respect each other, rather than fight each other.

To conclude this summary introduction to accident and crime studies, we will briefly mention two reports that are well-known and considered often as the 'final word' concerning the relation between lighting and crime. The main reason of this brief discussion is, that there is some doubt in how far they deserve this description of the 'final word'.

Both are restricted in scope in the way that was explained earlier. Fear of crime is covered only in a summary way, if at all. No attempts have been made to discern in different types of crime or different types of criminal. Post-crime aspects and not included. And finally, both are almost completely restricted to US and UK sources.

The first study we want to mention, is a report to the United States Congress (Sherman et al., 1997). It should be pointed out that the report is a policy paper and not a programme for research. As is mentioned in sec. 12.1.2c, a study of the 1970s from the USA recommended that: "That a single project evaluation design be developed, implemented, refined and promulgated as a model evaluation study" (Tien, 1979, p. 30). However, the suggestion that lighting is no good for crime reduction, had a negative effect on the motivation to do any further research. The study of Sherman et al. (1997) still comes to the same conclusions. This may be illustrated by a quote from Chapter 7 of that report

'Preventing crime at places': "Lighting has received considerable attention. We can have very little confidence that improved lighting prevents crime, particularly since we do not know if offenders use lighting to their advantage. In short, the effectiveness of lighting is unknown." However, the report concludes, that the effort in crime prevention should be focussed on urban areas of concentrated poverty, where the homicide rate is 20 times the national average; there is a need for rigorous testing of innovative programmes (After Sherman et al., 1997). The first shortcoming of the report is that no attention is devoted to studies from outside the USA. However, almost all US-efforts stopped with the work of Tien that was quoted earlier. Subjective safety and criminal prosecution are not taken into account. As regards the profiles of criminals, the quote given earlier suggests that the authors feel that this is an essential aspect, of which not enough is known. It seems therefore, that this report, objective as it may be, is not particularly suitable as a support for the opinion that 'more lighting causes more criminal acts'.

The second study we want to mention, is from Australia (Clark, 2002). It is interesting to start with a few quotes from the Executive Summary: "It is common experience that artificial light at night tends to allay the fear of crime, and this has been confirmed by scientific studies" (Clark, 2002, p. 2). Those who have the well-being of society in mind, would be satisfied with this. Fear of crime is a major obstruction for people to maintain social contacts, particularly for the vulnerable members of society: the elderly, the women and the children. Measures that reduce these obstructions, that agree with common experience, and that are supported by scientific evidence, deserve to be taken.

"It is also commonly believed that outdoor lighting helps to prevent crime at night but the evidence is equivocal. Crime-reducing, nil, uncertain, and increasing effects have been reported" (Clark, 2002, p. 2). As long as no distinction is made between types of crime and types of criminal, one should expect conflicting evidence. Nevertheless, the report admits that in some, or maybe even in many, cases, lighting helps to prevent crime. In this light, it is impossible to understand the demands that are made by the author on governments and lighting institutions. These demands will be described later in this section.

"Thorough scientific reviews published in 1977 and 1997 in the USA concluded that the effects of lighting on crime were unknown" (Clark, 2002, p. 2). The 'thorough scientific reviews' are, first, the old and rather inadequate study of Tien et al. (1977), that is discussed in some more detail in 12.1.2c, together with the negative analysis of it, given by Painter (1999). The second is the report by Sherman et al. (1997), that is mentioned earlier in this section, where a quote is given with a somewhat different angle. Both reports suggest that the knowledge is inadequate to reach a firm conclusion, and that further research is needed. If this is the case, the research should be undertaken, as is mentioned earlier in this section. Again, it is impossible to understand the demands that are made by the author on governments and lighting institutions.

It has been mentioned earlier in this section, that many believe that a major contribution of lighting is, that it enables the police to pursue and apprehend criminals after the act, as well that it allows witnesses to give trustworthy statements. It seems that none of the quoted studies did include this 'post-crime effect'. Therefore, it is, at present, just an opinion of law-enforcement agents.

"Governments should ensure that resources are not wasted by the installation of any more security lighting or other outdoor lighting at all where the justification includes or implies crime prevention. National lighting standards should not contain any statement or implication that outdoor lighting will prevent or deter crime" (Clark, 2002, p. 2, 3).

It is mentioned several times, that it is impossible to understand how these strict demands that are made on governments and lighting institutions, follow from the results of the studies that are quoted in the report of Clark (2002). Contrary to this, it should be recommended that lighting should be installed or improved in those situations where fear of crime is considered an important issue. Also, it can be suggested that lighting might be useful in cases where specific types of crime are often committed. A much better recommendation is, of course, to solve the problem once and for all with a large-scale, international, comprehensive study that is both scientifically sound and methodologically correct. In sec. 12.1.3, some indications are given concerning the social costs of crime. With these figures in mind, it seems likely that the costs of such – be it expensive – research would be earned back rapidly. This is, of course, only conjecture, as long as nobody seriously considers such research.

In summary, it seems to be a pity that this amount of useful work did end in still one more 'cut out the stupid lamps'-reports, of which there are far too many already. They all use the same – lack of – material, and quote the 'results' from each other. The report of Clark, in spite of its 'scientific' semblance, lacks the level of objectivity that is essential for it to be useful to help to solve the controversy we have indicated earlier in this section. As has been explained in the Introduction, it is precisely the objective of this book to avoid such pitfalls, and put the efforts to reduce light pollution on a basis that is a firm as possible. Reports like that of Clark do not help; they only increase the confusion.

(b) Accident study methodology

World wide, road accidents represent the third most frequent cause of death. Heart diseases and depression, with or without suicide, rank as number one and number two respectively. These results are reported by the Federation Internatinale d'Automobile FIA and summarized in Anon. (2003c). It is interesting to note that the subjective appraisal of the accident risk is much lower than that of crime. In one of the many surveys it was found that, in the Netherlands in 2002, 84% of respondents feared crime, whereas only 11% feared road accidents (Anon., 2002b). Although the total number of road accidents is staggering, the 'density' of them is relatively small. For the Netherlands, the number of accidents of all types, including small dents in the fenders that are hardly worth-while repairing, is about one million a year; the number of fatalities is about 1100 per year. There are about 7 million vehicles that each drive about 15 000 km per year (Gross data over 2001, CBS 2002). So the 'density' of fatal accidents is about 0,0095 fatalities per million vehicle·km, whereas for all accidents the 'density' is about 11 accidents per million vehicle·km. The trends in road accidents in the Netherlands are published in Koornstra et al., eds., 1992. For each individual car driver or pedestrian, being involved in a serious accident is very rare; most people will never experience this. In a further part of this section, some data on road accidents in other countries are given. The Netherlands belong to the more 'safe' countries as regards road accidents.

The consequence of the low accident density is that road safety measures must be based on statistical accident studies; individual accidents ('case studies') are useful for legal purposes, but they offer only anecdotic information. The statistical approach has, however, two severe draw-backs:
(1) Statistical studies cannot ever give information about the causes; they cannot provide causal relations.
(2) There is a need for very large numbers of 'occurrences' before statistical conclusions of any use may be drawn ('statistical significance').

Referring to road lighting, suppose we want to know the effect of raising the light level. It is not sufficient to take a 10 km stretch road, change the lighting, count accidents for a week and come to a conclusion. The sample size one needs varies very much for the purpose of the study, the requirements of accuracy and the properties that are investigated. Most statistical investigations deal with differences between conditions. For each condition, data are collected; such sub-collections are sometimes called 'cells'. A useful rule-of-thumb is that a cell-size smaller than 100 usually leads to nothing useful at all. In many cases the sample size must be 10 000 or more! In general, the larger the sample, the smaller the 'spread' – the more accurate the results. Getting a larger sample can be done in two ways: taking more streets, or observing the accidents a longer period. Evidently, there is a price to pay in this. If one takes 10 000 streets, raising the level just for the experiments is very costly, and there are no 10 000 identical streets to be found in a country. And observing for 10 years means that in that time cars have changed, legislation has been adapted, the weather is a variable etc. All this is done when one has a very large 'pool' to draw from, and very much money to do the experiments. The theory of statistical analyzes is discussed in detail in Buijs, 1995; Clarke & Cooke, 1994; Dixon & Massey, 1957; Moroney, 1990 and Wijvekate, 1971, 1975. Details on the methodology and numerical examples, are given in Schreuder (1998).

In road safety studies, usually 'relation studies' are used: one looks for a large number of similar streets with different light levels, collect all nighttime accidents, and assess the relation. In order to be able to compensate (at least to some extent) for the variability between the streets in the sample, one may use the daytime accidents as a 'control'. The well-known 'before-and-after studies' are often used in other aspects of road safety, but the samples we may get when studying road lighting are usually not big enough.

In secs. 12.1.2 to 12.1.5, many aspects of studies about crime and fear of crime are discussed. Often, the same, or at least similar, methods to study the effects of lighting on these two aspects are used as in accident studies. Just as with accidents, the occurrences are rare. This means that statistical methods are preferred. However, statistical studies present a number of pitfalls. Many are dealt with in some detail in sec. 12.1.3f. Some of them will be indicated briefly here, because they are relevant for accident studies as well. The first has been mentioned already.

(1) Statistical analyzes cannot give anything but correlations. There is no way to find any sort of causal relation with statistical methods. This need not to worry us; there are plenty of other methods to investigate causal relations.
(2) Many investigators seem not understand the difference between the following three sentences: "There is no proof that a relation exists"; "There is proof that the relation does not exists" and "There is proof that the complementary relation exists". In relation to the relation to crime, the three sentences would run: "There is no proof that lighting reduces crime"; "There is proof that lighting does not reduce crime" and "There is proof that lighting promotes crime". It is, of course, a basic flaw in (Aristotelian) logic.
(3) It is not always realized that criminals form a very varied bunch of people. It is essential to realize this. As is explained in sec. 12.1.2g, lighting as a deterrent works only if the would-be criminals are deterred; that means, that they are afraid of the consequences of being seen and apprehended. Now, this is the case only for a specific type of criminal: the traditional burglar, the exhibitionist, the rapist. Many criminals do not care to be recognised, because either they are drunk or they know that the penal system is so full of holes that there is no risk of punishment when seen. This is the case for hooligans, vandals, gangs of non-european youth, etc. Then there is the modern criminal, the terrorist. They want to be seen, they want to be noticed, because that is an essential part of their terrorist action. And many commit suicide, anyway. So dumping all crimes and all criminals on one big heap is a major source of error. This misconception may be found in some studies by people who are not accustomed to think in terms of psychology – one is tempted to say, in terms of psychotherapy (Marchant, 2003, Wainwright, 2003).

There are many ways in which statistical studies regarding rare incidents can go wrong. Probably the major source is, as mentioned earlier, the 'rare' incidence. This means that is a great exception the sample in the study is large enough to apply rigorous statistical methods. Some investigators stop here; they proclaim – correctly – that they did not find any proof of a relation. As indicated, this statement can be transformed all too easily into the statement that there is proof that the opposite it true. Other investigators are more inventive and start working. Some do not do anything themselves, but they are satisfied by quoting other studies, in the naive belief that, if it is printed, it is true.

There is more to it, of course. Most statistical studies deal with a variable that can have two possible values. These studies can be described with a discrete distribution where the two possible values have different probabilities. A statistical distribution having these characteristics is called a 'binomial distribution' (Clarke & Cooke, 1994, sec. 7.6, p. 106-109). A binomial distribution will show r successes in n trails, and thus (n – r) misses. That is the binomial character of the distribution. The total probability of r successes in n trails is:

$$\frac{n!}{r!\cdot(n-r)!} \qquad [12.1.1]$$

This is Theorem 5.4.9 of Clarke & Cooke (1994, p. 72).
For short, usually this is written as:

$$\binom{n}{r} \qquad [12.1.1a]$$

One may specify the probability distribution of a random variable as:

$$P_r(R=r)=\binom{n}{r}\pi^r\cdot(1-\pi)^{n-r} \qquad [12.1.2]$$

with: r = 0, 1, 2... n;
and $0 < \pi < 1$. (After Clarke & Cooke, 1994, p. 106).

A major prerequisite for this and similar calculations is that the trials are independent. More in particular, if they are not, it is likely to expect that the variance will increase as a result of what is called 'overdispersion' (Marchant, 2003, 2004). And it is this independence in the data of the crime studies that are summarized by Farrington & Wells (2002), that is doubted, arguing that it is "implausible in the extreme" (Marchant, 2003). This would imply that the relation between lighting and crime that is reported by Farrington & Welsh (2002), cannot be supported. It seems that a strong statement like this, would require further support, e.g. by crime repeater studies.

The major point about any possible relation between lighting and crime is still to come. Indeed, the case for a reduction of reported criminal acts as a result of increased outdoor lighting is not a strong one. The main reason to promote 'good' outdoor lighting helps to create a nighttime surrounding that make the people feel safe and agreeable outdoors. It is a major help in breaking the isolation of the vulnerable members of society – the elderly, the women, the children. These effects are shown clearly, over and over again, by many studies in different countries. It must be stressed that 'good' lighting does not automatically imply 'more' lighting – a thing many people do not seem to grasp. Details of this are given in the subsequent sections of this chapter.

(c) Risk and exposure

Hazards may lead to damage, stress, suffering, injury or death. In other words, hazards involve risk. According to the Oxford Dictionary, risk is: "A hazard, chance of bad consequences, loss etc., exposure to mischance" (as quoted by Hakkert & Brainmaister, 2002, p. 8). A more useful definition is given in Collins Dictionary: "A possibility that something unpleasant or undesirable might happen" (also as quoted by Hakkert & Brainmaister, 2002, p. 8). In the field of road accident research, risk has a much more specific meaning: "A way to quantify road safety relative to the amount of exposure, as opposed to the absolute level of safety as measured by the absolute number of accidents or casualties" (Hakkert & Brainmaister, 2002, p. 8). In other fields of incident research, a similar definition of risk could be introduced.

These quotes indicate two distinct approaches to safety. One is the absolute number. In many cases, society has decided that a certain number of incidents (casualties or fatalities) is acceptable, but not more. As an example, in space exploration, this number is zero. When, in spite of the efforts, accidents do happen, the programmes are stopped. It is interesting to note that when after a few years the memory of the disaster is worn thin, the programme will be restarted again.

In many areas of human activity, however, a completely different approach is taken. In reducing transportation accidents, as well as in fighting crime, it is assumed as just a natural fact, that incidents happen. In principle, it is left to the actors in the traffic or the crime scene, to make their own decisions to avoid unwanted incidents. The role of the authorities is nothing more that to ensure that excesses do not happen too frequent. Even major disasters, like e.g. the capsizing of a ferry, or a terrorist attack on high-rise office buildings, where many hundreds, or even thousands, of people get killed, does not change the attitude of the authorities. The automatic reaction of official spokespersons is: "Disasters cannot be completely ruled out". The same is said, over and over again, for terrorist attacks.

Many governmental decisions in risky situations are usually nothing more that a matter of avoiding responsibilities. Public opinion, however, is not always satisfied. So, absolute risk factors are quantified by estimating a severity factor that represents the product of the frequency of the incident f and the number of fatalities per incident N – the so-called fN-factor (Hakkert & Brainmaister, 2002, p. 20). As an example, a number of fN-curves is given in Figure 12.1.1. In this figure, the chance for a specific incident, with a specific death-toll, is depicted.

Because public opinion plays an important role, and thus the influence of media coverage is crucial, strange things may happen. In early 2003, a number of persons suffered from the Severe Acute Respiratory Syndrome SARS; quite a few even died. It goes without saying that the suffering for those involved is very serious indeed; that is not to say, however, that it is a disaster on world scale. Between 1 november 2002 and 11 july 2003, on a world-wide scale, 8437 cases were reported, of which 813 people died (WHO, 2003). In view of the numbers, a few hundred fatalities worldwide, and several thousand sick, it seems rather far-fetched to speak of a 'world epidemic'; particularly when these numbers are compared to those of 'ordinary' influenza or 'flu', with hundreds of millions of people suffering from it each year, and well over one million death per year. Over the years, in the USA alone, over 400 000 people died of influenza, and the yearly death toll is over 20 000 in the USA alone (Anon., 2001d). Another example is tuberculosis. Although officially it is maintained, that it is 'almost' overcome, still more than 2 000 000 people worldwide die every year from it. Still, the so-called SARS-epidemic brought the air travel to the far East almost to a halt.

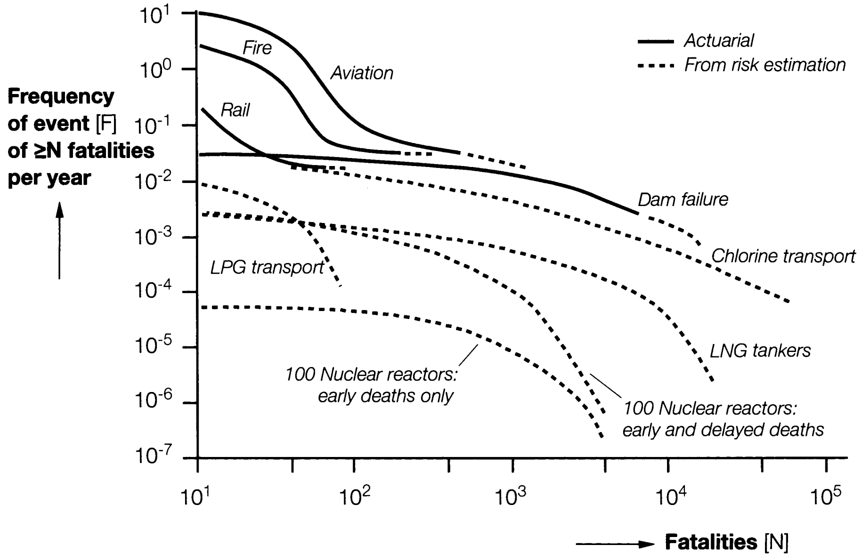

Figure 12.1.1: *Calculated fN-curves for high risks in the USA. After Hakkert & Brainmaister, 2002, figure 2, based on data from Van Poortvliet, 1999, and Cappola & Hall, 1981.*

The media attention is, as in many other cases as well, rather haphazard when assessing risks of actions or incidents. The SARS-epidemic is an example, where the influence of the media created a world-wide scare that was not founded at all. A similar thing happened, as is explained in sec. 12.1.3f, with the terrorist attack from 11 September 2001. As a result, many people will begin to believe that, whenever an incident is pushed by the media, it is automatically disqualified as a serious problem. An example of this is the AIDS problems. The media attention is overwhelming, stressing the role of drug abuse and homosexual acts in the transmission of the illness. However, contrary to SARS and terrorist attacks, the death toll of AIDS is horrendously high. Some data are given in Table 12.1.1. It may be noted that towards the end of 2003, numbers are given that are still considerably higher.

There is more to it. In the last few years, there was a shift in the attention towards AIDS. In stead of the emphasis on the dissemination of AIDS as a result of drug addiction and homosexual promiscuity, the emphasis is now on more effective – and cheaper – drugs against AIDS. In stead of the not very successful attempts to prevent people from getting AIDS, the emphasis is on curing people who are HIV-positive. This shift did some good as regards the public awareness about the problem, but it did much more good as regards the interest of politicians. AIDS is not conquered, but it seems that there are fruitful ways now.

	HIV-infected end 2002	New inf. in 2002	Died in 2002
total	42 000 000	5 000 000	3 100 000
adults	38 600 000	4 200 000	1 500 000
of which women	19 200 000	2 000 000	1 200 000
children under 15 y.	3 200 000	800 000	610 000

Table 12.1.1: *Aids worldwide. After Anon., 2003e. Based on data from UNAIDS.*

There is a lesson to be learned from this, a lesson that may be applied as well to the restriction of light pollution. Many people do not stop to point out, over and over again, that the situation is horrible and that light pollution is getting out of hand. This meets unbelief by the general public, and irritation by the politicians, simply because it is not true. It is much more effective to stress that there are many technical and organizational ways to reduce light pollution. As is explained in sec. 15.2, where public awareness is discussed, this approach seems to be more successful, both with the general public as with the politicians. One reason is, that, just as with new anti-AIDS drugs, pollution restrictions offer many possibilities for technical innovation and commercial development.

In the foregoing, a definition of risk was given, that suggested two distinct approaches to safety research. We have discussed the absolute number. The other is a way to quantify safety relative to the amount of exposure. Here, it is not the absolute number of incidents that is sought for, but the ratio of this number to another quantity. This quantity is usually called ‘exposure’. In transport safety studies, it seems logical to use the distance traveled as the measure of exposure. In this way, it is possible to compare the relative risk of different transport modes for the same trips. Also, it is possible to compare the effect of different transport safety measures. Some examples are given in Table 12.1.2a, where the fatality risk for different transport modes are compared.

Travel mode	10^8 person km	10^8 person hours
Road		
– total	1,1	3,3
– bus	0,08	2
– car	0,8	30
– foot	7,5	30
– bicycle	6,3	90
– motorcycle	16	500
Rail	0,04	2
Ferry	0,33	10,5
Air	0,08	36,5

Table 12.1.2a: *Fatality risks over distance and over time for different travel modes in the EU. After Hakkert & Brainmaister, 2002, table 2. Based on data from ETSC, 1999.*

It has been suggested to use the risk per hour in stead of the risk per km as a measure of exposure (Wesemann et al., 1998). For the comparison of widely different activities, this seems to be a good solution. As can easily be seen from Table 12.1.2a, exposure expressed in fatalities per hour is not helpful for transportation systems research. However, for activities where the costs or the profits are measured in time units, expressing exposure in fatalities per hour can be quite useful. Such activities may include office or factory work, mountaineering and other sports, or just being at home. Some examples are given in Table 12.1.2b. Some data in that table stem from Table 12.1.2a.

Activities	**per 10^8 person hours**
Transport	
– road	3,3
– rail	2,0
– ferry	10,5
– air	36,5
Work	
– total	0,9
– banking and financing	0,17
– chemical industry	1,1
– construction work	4,9
– railway work	5,6
– ore mining	13,0
Home	
– All ages	2,6
– Under 65	1,0
– Over 65	11,5

Table 12.1.2b: *Accident fatalities per unit of time for different activities. After Hakkert & Brainmaister, 2002, table 1. Based on data from Evans, 1993 and Collins, 1990.*

It is interesting to note that sports, and particularly motor-racing, hang-gliding, ski-jumping and mountaineering, are not included in this table. In sec. 10.4.1a, it is explained that the risks that are accepted, depend heavily on the notion whether one takes the risk by free will, or whether one is forced against the free will to do so.

For all statistical studies that involve considerations of incident risk, it is essential to make the correct choice of what is to be used as a measure for exposure. In the foregoing, some examples are given, when discussing accident risk, where either travelled distance or time spent is used as a measure of exposure. The discussion about SARS and influenza is less straight-forward. It might seem that no exposure measure is used. This may be true as regards the attention of the media, and in its wake of WHO; when SARS and influenza are compared, however, in order to give an indication of the severity of the two as regards the health of the world as a whole, implicitly the total world population is used an a measure of exposure.

Choosing the right measure of exposure can be tricky. We will give a few examples, some of which might seem a little far-fetched. The aim of the examples is, however, to issue a warning against a careless selection of the measure of exposure. In sec. 10.4.1, it is mentioned that around 175 people have died while trying to climb Mount Everest. The number is small, particularly as it stretches over at last 50 years: just over 3 persons per year world-wide. Therefore, it might seem that climbing Mount Everest is about the least dangerous thing you could do, while living on Earth. The risk is 3 per 6 000 000 000, or about 5. 10^{-10}. If, however, it is taken into account that in that period only about 1000 people reached the top, the fatality risk would be 175 per 1000 or 17,5%!

A silly, but clarifying, example is the statement that being in bed is far out the most dangerous place to be in: almost all people die in bed. A similar silly example is that in some countries like China, Japan and the Netherlands, almost every-one dies after drinking tea – often even for many decades. What is more, in these three countries, pedal bicycles are an important means of transport, contrary to almost all other industrialized countries. True, the example is silly, but try and figure out the relationship between drinking tea over long periods of time and riding bicycles for different countries. The examples have been given here to point out that, if one is not careful in selecting the right measure of exposure, the result can be absolute nonsense.

(d) Road safety in the different countries

Most data given earlier in this section refer to the Netherlands. The situation as regards road safety varies very considerably for different countries, their affluence being an important factor. At the one hand, the affluent countries have more cars and consequently more road accidents; at the other hand, the less-affluent countries have a less well-developed infrastructure and a population who is not accustomed to road traffic. The number of accidents per car increases steeply with decreasing per capita Gross National Product (GNP).

Countries are the building blocks of the world. This is not only a matter of convenience, but it is justified by the fact that whatever the internal structure and organization, almost all countries are experienced by the inhabitants as 'their' country, as an essential unity.

Different countries may have different road safety problems. It cannot be stressed enough, however, that road safety is a major problem in almost all countries of the world, developing and developed alike. As the road traffic scene often is considered in isolation, the severity of the road safety problems is not always fully recognized. The severity follows from the following observations:

(1) In almost all countries road accidents cause a relatively heavy economic loss. Whatever the economic situation, the percentage of the GNP that is lost is quite appreciable;

(2) In many countries the majority of the – often scarce – medical supplies are used for road casualties. In many countries, the majority of hospital beds is occupied by victims of road accidents;
(3) Victims of road accidents are to be found mainly under the higher qualified professionals – one of the primary assets of many countries
(4) Road accidents often result in severe obstructions in the transport of essential goods.

It should be kept in mind that as a result of rapid and often non-uniform economic and industrial developments, developing countries are often, contrary to industrializsed countries, characterised by large differences in almost all aspects of life – traffic included – in different parts or regions of the countries. These differences are reinforced by the fact that many developing countries are very large and only sparsely populated, and by the pull on population of the big cities.

A comparison of the road safety situation in different countries is based on two data sets that are collected in most countries and that seem to be reasonably reliable: the number of traffic deaths in a year and the number of motor vehicles (cars and trucks) in the same year. The relation between the two might give some information about the 'danger' of the country. The ratio 'annual deaths per vehicle' turns out to be quite variable; for nearly 100 countries world-wide, it ranges between 0,000 13 (Iceland) and about 0,042 (Tajikistan). There seems to be a relation with the affluence. All 'top 10 countries' belong to the affluent countries. See Table 12.1.3. The data are from Anon. (1995; 1996). See also Schreuder (1998a).

	Number of death D	**Number of vehicles V**	**'Danger ratio' D/V**	**Per capita GNP** (ranking)
Iceland	17	131 839	0,00013	(nd)
Norway	281	1 981 990	0,00014	4
Australia	1 600	10 139 900	0,00016	20
Sweden	632	3 881 854	0,00016	6
United Kingdom	3 814	22 456 000	0,00017	18
Japan	10 942	63 000 000	0,00017	2
Netherlands	1 252	6 408 000	0,00020	12
Italy	6 645	33 456 137	0,00020	15
United States	40 115	194 063 482	0,00021	5
Switzerland	723	3 424 120	0,00021	1
average			**0,000175**	

Table 12.1.3: *The number of traffic fatalities, number of vehicles and per capita GNP for the 10 countries with the lowest 'danger ratio'. Years 1995 and 1996 combined. 'nd': no data.*

The conclusion is not difficult to draw: within the 'top 10' countries, the 'danger ratio' is almost the same. Although there are some deviations, they seem to fall within the 'rounding off' region!

(e) The relation between public lighting and accident prevention and reduction

Detailed research efforts by leading scientific institutes, spanning several decades, have established beyond any doubt that road lighting has a positive effect on the reduction of road traffic accidents. The research results have been collected by international bodies like CIE (1968; 1992), OECD (1972, 1980) as well as by national bodies of Australia (Fisher, 1973), Belgium (De Clercq, 1985, 1985a), Germany (Lamm et al., 1985; Pfundt, 1986), the Netherlands (Schreuder, 1983; 1985; 1988; 1990; 1992; 1993; 1998; Schreuder et al., 1991; Vis, 1994), UK (Hargroves & Scott, 1979; Scott, 1980), USA (Gallagher et al., 1975) and several other countries as well. See De Boer, ed. (1967) and De Boer & Schreuder (1972).

Almost all studies that were quoted in these surveys were of the 'before-and-after' type. Consequently, in may cases the experimental design showed flaws, in some cases even serious flaws. Furthermore, some studies did not show any significant results, whereas one or two even suggested that, when the lighting was improved, the accidents actually increased. In these cases, it could be surmised that the traffic situation between the before and the after periods had changed – therefore making the before-and-after method invalid. One should not be surprised, however, that the groups disagreeing with road lighting did grasp these exceptions with both hands, declaring that the benefits of road lighting were not proved or even were non-existent. Some even accused the lighting and energy industries of tampering with the data. The fact that most studies were made by independent road safety agencies did not persuade them.

These rather unscientific discussion ought to be stopped by now. New statistical methods have been applied. Recently, all available material has been re-evaluated by applying the meta-analysis approach, where the value of each individual study is evaluated and expressed in a score. The score serves as a 'figure of merit' of the particular investigation, and its results are weighted according to this figure of merit. In this way, the 'best' studies contribute most to the overall result. The value assessment is often done on the basis of a subjective appraisal of the methodological details that are published together with the results of the study. The method is described in detail by Hagenzieker & Van der Heijden (1990, 1990a) and Hagenzieker et al. (1997). It should be mentioned here, however, that even the meta-analysis method has its own pitfalls. This has been mentioned in sec. 12.1.1b, when discussing some of the finer points of accident study methodologies (Marchant, 2003; 2004). An economist of Oslo University, who had no previous knowledge of road safety nor of road lighting, applied the method to the relation between the two (Elvik, 1995). In all cases, the results were almost identical.

The results can be summarized as follows:

(1) On major urban thoroughfares, good road lighting results in a reduction of about 30% of the night time casualties. A similar effect is found on rural trunk roads and motorways.

(2) increasing the light level decreases the accident risk. Within the range of adequate road lighting, doubling the road surface luminance leads to a reduction of the nighttime risk (night/day accident ratio) of about 13%.

This value is derived from the following data (see Table 12.1.4):

Road type	Accident reduction at double level (%)	Country of study
Rural non-motorways	12,9	The Netherlands, Schreuder, 1998
Rural motorways	5,8	The Netherlands, Schreuder, 1998
Urban thoroughfares	30	UK, Hargroves & Scott, 1979; Scott, 1980
	11,9	USA, Gallagher et al, 1975
Urban roads, streets	4,4	The Netherlands, Schreuder, 1998
average (approx.)	13	

Table 12.1.4: *Accident reduction for doubling the road surface luminance.*

12.1.2. The relation between public lighting and crime prevention and reduction

(a) *Definitions and descriptions*

When considering the relation between public lighting and crime, it is necessary to discern a number of distinct aspects:

- The area of interest. When the relation with lighting is considered, it is obvious that we talk about the outdoors. The lighting has to be defined in terms of outdoor (public) lighting.
- Crime. Crimes (criminal acts) are understood to be socially unacceptable acts (socially unacceptable behaviour) that are in conflict with the law – more in particular in conflict with criminal law. There are three types of behaviour that are considered socially unacceptable in most cultures: aggressive behaviour, sexual intimidation and stealing.
- Fear for crime. In many cases the fear for crime has a more disrupting effect on the social patterns than actual crime. Fear for crime is a major obstruction for many people as regards their social contacts: one finds often that people – particularly the elderly, but also women and children, do not venture outdoors for fear of being attacked or assaulted. They stay indoors, which leads to a frustration of social contacts and to an atrophy of social skills – which in turn is often quoted as a cause for crime! This fear is particularly strong after dark; the social context is often considered is the major reason to improve outdoor lighting.

- Criminal. A person who performs a criminal act or shows socially unacceptable behaviour.
- Aggression. Aggression is defined as a complex of acts that is intended to harm other people or to cause damage. The fact of being intentional is essential to the concept of aggression.
- Non-aggressive behaviour. There is a lot of non-aggressive behaviour that is equally non-acceptable. In the outdoors, it is mainly vandalism and stealing (burglary).
- Victims. Victims are people who suffer from crimes, violence, or other socially unacceptable behaviour. In the outdoor scene, the harm and the damage usually is physical, but it may be psychological as well.
- Violence. Violence is described as physical aggressive acts, often causing injury and sometimes death.

Crime is almost universal because much goes directly down to the most basic instincts of living creatures – human and animal alike. However, what is considered criminal behaviour and what are considered acceptable countermeasures, varies very much from culture to culture, or even from sub-culture to sub-culture. This holds both for the formal legal and punitory systems as for the informal considerations and methods. As an example, in some cultures the decisions of what is acceptable and what not, as well as the type and degree of the punishment, is decreed by the king, sometimes by a judge using the legal codes, and sometimes by juries that react essentially emotional. The same holds for the type of punishments: death penalty and mutilation are common in many cultures and abhorred in others. So, it may be hard to apply the results of research and of experience from one country to other countries or other cultures; it may be done in some cases, but in other cases not at all. With this in mind, the literature that is quoted in the following sections should be assessed.

Because of the fact that crime is so widespread in all societies, it is no wonder that many efforts are made to prevent crime, or at least minimize its impact. In the political programmes of almost all governments, fighting crime is a matter of the highest priority, recently focussing on terrorist attack types of crime. The measures that are proposed, are just as varied as the types of crime; one type of measure that interests us here more in particular, is installing or improving outdoor lighting as a crime countermeasure. Obviously, outdoor lighting is effective only at night; therefore, the emphasis in the following sections will be on nighttime crime.

At this point, it is probably good to say a few words about the statistical correlations and the causal relations between lighting and crime. Many, but not all, studies in this area describe correlations between lighting and crime parameters. Usually, it is assumed that there is some sort of causal relation between them, implying at the correlations are not just random. The most common assumption is, that improving outdoor lighting will help to prevent criminal acts, or to reduce their consequences. This assumption is the basis for many outdoor lighting improvements, which may cause additional light pollution. Hence the importance for the context of this book. In sec. 12.1.2i, it is discussed in great detail, in how far this claim can be justified. Here, a report will be discussed briefly, that claims that the causal relation is inverted; improving outdoor lighting will cause additional crime (Clark, 2003). This report is a sequel to Clark (2002), that is discussed in sec. 12.1.1a. Part 2 focusses on the correlation between crime and lighting. In the Executive Summary, a number of instances is quoted where it is found that high crime rates and high lighting levels – more in particular, high values or upward flux – are found. Based on these relations, a hypothesis is founded. "The new hypothesis suggests that high rates of crime are partly a result of excessively high outdoor ambient light levels at night. This was tested by examining the crime rate in cities of Australia, Canada, England, and the USA. For England, and the USA statistically significant positive correlations were found between crime data and city upward light energy losses measured by satellites" (Clark, 2003, p. iii). It seems that this is a case of the exchange of dependent and independent variable, that is explained in some detail in sec. 9.1.1a. The data in the report support the hypothesis that there is a correlation between lighting and crime, but the report also quotes correlations, some of them statistically significant, between crime or lighting and a considerable number of socio-economic and demographic variables. This should be no surprise because almost everything people do, including installing lighting and committing crimes, depends on how many people are around. Correlations have no value when dealing with causal relations (sec .12.1.1a). Saying that lighting causes crime is just as unfounded as saying that crime causes lighting. Both may be true, but there is no way to find this out by just looking at correlations. The author seems to be aware of this. "Light at night and crime are positively correlated, whatever people say. Causality cannot be proved, but it is strongly supported by a causal connection between imposed darkness and the reduced crime observed in many small- and large-scale instances" (Clark, 2003, p. iii). The 'small- and large-scale instances' were unexpected power failures. The causal relations, suggested in the Executive Summary, are based for a large part, not on causality studies, but on the opinion of journalists, police authorities, and ordinary people around (Clark, 2003, sec. 3.2 and sec. 3.3).

The scope of the report by Clack is much wider, however. Because many socio-economic and demographic variables, including lighting and crime, show a strong correlation, an exchange of dependent and independent variables might easily suggests some casual relation that may, or may not exist: "Urbanization, urban sprawl and crime appear controllable simply by limiting the absolute level of ambient artificial light permitted outdoors. Desirable demographic changes may be achievable with lighting restrictions tailored to specific areas" (Clark, 2003, p. iii). The end of the Executive Summary seems to represent the programme of the report: "Good lighting needs to be redefined. Outcomes should include avoidance of national, corporate, individual, and natural resources on misguided and counterproductive schemes that currently require more and brighter lighting supposedly to reduce crime while actually increasing it" (Clark, 2003, p.iii). Defining 'good lighting' in such a way that the functions of it will be fulfilled, while reducing waste on all kinds, would be agreeable to all. The point is that it is assumed that all increase of lighting automatically leads to an increase of crime, as is expressed by what is termed earlier as a 'new hypothesis'.

There is another aspect of criticism to this undoubtedly well-intended report. Apart from the unwarranted exchange of dependent and independent variables, it is apparent that 'more light' is not specified with sufficient precision. More important, there is not even an outset of a definition of 'crime' or 'crime rate'. Crime appears to have increased substantially in many countries during the twentieth century. Criminological studies of long-term variations in the crime rate and its causes are hampered by factors such as:

- large shifts in what society regards as crime (e.g. drunkenness, nude bathing, homosexuality);
- the emergence of new crimes (e.g. internet fraud, aircraft hijacking);
- political and industrial influences on reporting and recording of crime and its solution rates;
- improvement in methods of detection and prosecution of offenders, and so on (Clark, 2003, sec. 2.2. Crime Data, p. 9).

In that section it is suggested that crime data with these shortcomings might be used for crime comparisons within one country. There are severe doubts in that, however, particularly if long term, longitudinal studies are made. Comparisons between countries are out of the question, as long as no sound definitions of crime, crime rate, and a number of related variables are made. As long as this is not done, the report, well-intended as it might be, has little or no value in the discussion about the influence of lighting on crime. Such reports may increase only the confusion. As is explained in the Introduction, it is precisely the objective of this book to reduce such confusion, and to put the efforts to reduce light pollution on a basis that is a firm as possible.

(b) Nighttime crime

Poor outdoor lighting is not useful for normal pedestrians, but it is for those intending street crime at night. The eyes of criminals lurking in the dark spot in the poorly lit street for a considerable time are able to adapt fully to the very low luminance of the dark spot and able to perceive necessary details of their targeted pedestrians coming to the criminal in the dark. On the contrary, the eyes of normal pedestrians in the poorly lit streets remain adapted to the relatively high luminances in the other lighted streets walking just a few seconds ago, such as the railway station, underground rail, bus, tram, restaurant, theatre, supermarket, shopping streets, or their house from which they have departed, and not to the luminance of the poorly lit street cannot identify the criminals approaching in the dark. Similarly, the eyes of the policemen whose eyes are adapted to the relatively high luminance cannot detect the criminal(s) lurking in the dark from the patrolling cars, and make it difficult to chase the criminal(s) running away. This implies that the poorly lit streets are the most dangerous spots in the town.

Crime and fear for crime are major problems in many industrialized countries. The two major reasons seem to be firstly, the very high level of the actual registered crime rate. The probability to be robbed, mugged or raped in a specific year is much higher than the probability to be involved in a traffic accident, or a domestic accident. And secondly, the crime in modern society, particularly in big cities, seems to have no preference for any person – it seems to be governed by blind fate.

Fear for crime is the largest of all obstructions for social contacts, particularly during the dark. The fear is not evenly distributed over the different groups of the society. Women and the elderly are the most subject to this fear. The question in how far this fear is justified, is not relevant as long as it is a real fear. Very few elderly people dare to leave their house at night. A study in the Netherlands by the Ministry of the Interior suggested that one in three citizens was troubled in their sleep by the fear of crime. In short, many people believe that the fear of crime is one of the major problems of our society at present.

(c) Lighting and crime, survey of the international literature

In most densely populated countries like e.g. the Netherlands and many other West-European countries, the majority of urban roads and streets are lit, contrary to rural roads, that usually are not lit. So when discussing urban road and street lighting, the question 'to light or not to light' that is a pressing one for rural areas, is hardly relevant in urban areas. However, in many other countries (e.g. the US, or South Africa) urban, and particularly suburban areas, roads are left unlit, because many feel that the road side development makes road lighting not feasible. As research in this respect is lacking, most studies relate to the 'European' situation, where unlit urban residential roads can be neglected.

Although from its beginning, public lighting was installed primarily as a crime-prevention measure, the relation between lighting and crime is not well studied. There are a number of studies that, for lack of a proper methodology, offer no more than anecdotal results. Surveys are given by Aelen & Van Oortmessen (1984) and Schreuder (1992, 1994, 1994a, 1998, 2000).

Usually, a marked reduction in crime rates is reported after the lighting is upgraded. This applies more in particular for all sorts of street violence, robbery, breaking in, etc., and more specially for sexual assault. So, street lighting is often considered as primarily a 'woman-friendly' measure – quite rightly so. In some cases, very dramatic reductions have been quoted; however, in many cases these reductions were accompanied by an increase in crime rate in another nearby location, which suggest not a prevention of crime, but rather a shift. Still, the benefits can be quite pronounced. There must be made one remark, however. Studying the results of the upgrading of the lighting is, of course, not a method that is to be recommended, primarily because the study sites are not selected 'at random'. The remarks that have been made in sec. 12.1.1b, while discussing the methodology of accidents studies, are equally valuable – and valid – for crime studies. We will come back to this point later. In sec. 12.1.5c, the 'five criteria for social safety' as suggested and implemented by the Government of the Netherlands, are discussed in some detail.

A major problem is that almost all studies are little more than opinions and anecdotes: systematic, well designed quantitative research is almost completely lacking. It is therefore difficult to justify on a cost/effectiveness basis the expenditure for crime prevention lighting. Most studies are poorly documented and do not seem to agree with standards of 'good' research.

An example is the widely quoted USA studies of Tien et al. (1977) and Tien (1979). The study included 41 lighting schemes, of which, however, only 15 could be used for further assessment. The study includes a number of earlier studies, like those of Murray (1960); Callender (1962); Hoover (1963, 1970); Berla (1965); Jones (1970) and Bennet (1976). A conclusion could not be drawn. The author recommended only further study: "Therefore, it is recommended that a single project evaluation design be developed, implemented, refined and promulgated as a model evaluation study" (Tien, 1979, p. 30). This study is often understood as showing that lighting is not an effective crime countermeasure. This is, in view of the methodological weaknesses, obviously not a sound conclusion. Tien (1979) seems to be a sequel to a large study that was published in 1977 (Tien et al., 1977). The large study is quite impressive because all sorts of details are quoted. There is some doubt whether these details are relevant. Painter (1999) points out very clearly that the conclusion of Tien (1979) can indeed not be used for setting up crime countermeasures; it had, however, a very negative effect on the motivation to do any further research. The influence can still be felt. As mentioned earlier, the more recent US study of Sherman et al (1997) still comes to the same conclusions. This may be illustrated by a quote from Chapter 7 of that report 'Preventing crime at places': "Lighting has received considerable attention. We can have very little confidence that improved lighting prevents crime, particularly since we do not know if offenders use lighting to their advantage. In short, the effectiveness of lighting is unknown." (Quote from Anon., 2000a). In contrast to this somewhat fatalistic statement is a quote from the general conclusions (somewhat summarized): "The effort in crime prevention should be focussed on urban areas of concentrated poverty, where the homicide rate is 20 times the national average" (which is by far the highest in the world; see Van Dijk & De Waard, 2000) and also "There is a need for rigorous testing of innovative programmes". In all fairness, it should be pointed out that the report of Sherman et al. is a policy paper and not a programme for research.

There have been other, be it not many, studies mainly in Europe. Surveys of the different studies are made by Aelen & Van Oortmerssen (1984), Schreuder (1994) and Painter (1999). Most studies quoted in these surveys suffer from similar defects as those from the USA.

A study that did receive considerable interest in Europe was that of Mariner (1983). In a French city (Lyon) it was found that streets with a low light level had much more crimes than streets with a high light level. As no data on the crime rates nor of the street or lighting characteristics were given, it is difficult to support any conclusion. The same holds for a small study in Eindhoven, where 'dimming' of street lighting installations was compared to the traditional switching. From this study it was concluded that one needs to avoid primarily the dark patches in order to reduce crime, rather than increasing the average level (Anon, 1987; Nohlmans, 1987). This view is supported by Simons et al. (1987; 1988). Further studies in the Netherlands did not give much additional information. Both Aelen & Van Oortmerssen (1984) and Maas (1986) mainly based their conclusions on the international literature. Van Oortmerssen (1987) presented some qualitative experience from the city of The Hague, and quoted, apart from the studies that have been mentioned above, some quantitative data. Halving the light level was reported to result in a rise in crime numbers from 20% to over 100% (depending on the type of crime; Anon, 1976), whereas an increase in the light level was reported to be followed by a reduction in crime numbers from 40% to 90% (Le Vere, 1977; Fischer, 1978). The numbers seem to be quite impressive; as no details are given, it is not possible to draw any conclusion from them.

(d) Lighting and crime; the crime studies made in the Netherlands

The Ministry of Economic Affairs of the Netherlands issued in 1981 a booklet to assist local authorities in applying savings in public lighting (SVEN, 1981). The aim was to reduce the operating costs of public lighting without harm to the quality as regards road safety and as public security. In the revision, crime reduction and crime prevention were included.

Just as the accident studies, the crime study was a relation study. The number (and the severity) of reported criminal offenses are related to the public lighting. The study is based on the assumption that the crime risk diminishes when the lighting level increases. The crime risk in the dark was expressed in the ratio between the night and day crime numbers (n/d). The study assumed that n/d was correlated to the light level, expressed in the horizontal illumination (E_{hor}). The crime data were based on the criminal offenses reported to the police. The study was focussed of two types of criminal offenses: sexual crimes, as their social and psychological consequences are severe, and breaking into cars, because these are very frequent in the Netherlands. The results are given in Table 12.1.5 and Table 12.1.6.

Light level (lux)	**Day**	**Dark**	**Dark/Day**
<1,6	14	39	2,79
1,6-2,5	186	667	3,59
2,6-3,9	143	244	1,71
4,0-6,3	260	813	3,13
6,4-9,9	252	648	2,57
10,0-15,9	128	253	1,98
>16	60	111	1,85

Table 12.1.5: *Car related crime (after Schreuder, 1993; see also Schreuder 1994, 1994a)*

Light level (lux)	Evening	Night	Day	Dark	Dark/Day
1,4-2,7	12	46	71	58	0,82
2,8-5,6	3	10	11	13	1,18
5,7-7,9	11	16	19	27	1,42
8,0-11,2	7	14	24	21	0,88
>11,3	6	20	20	26	1,3

Table 12.1.6: *Sex related crime (after Schreuder 1994, 1994a).*

The analysis shows that for the car-related crimes, the proportion of criminal offenses in the dark decreases very clearly with increasing light level. These is a shade of a suggestion that the curve levels off or even increases for light levels, more than about 10 lux (Schreuder, 1998). This suggestion, however, is the result of limited data only, and should therefore be handled with care. The number of registered sex-related crimes in the sample was too small to draw any firm conclusions. There is no clear trend to be seen.

As stated before, crime, particularly outdoor crime or street crime, is one of the major problems in most countries, developing and industrialized alike. It causes severe disruptions in the social system. It causes a lot of suffering, particularly from the part of the victims and the families of the victims. It costs a lot of money, both as result of the crime itself as well as for the law enforcement and the crime prevention. The form of street crime that causes the most concern is violence; second come sexual intimidations, closely followed by robbery. These three are the major forms of street crime, be it at day or at night. The majority of the nighttime street crime is directly drug-related. Data for the Netherlands are given in Anon., 1999; Terlouw et al., 1999. One may assume that in other countries, the picture is essentially the same.

In several countries, studies were made in this area. Most suffer from two draw-backs: first, the researchers tried to 'prove' a positive relation between lighting and crime reduction – a severe mistake in field studies. One should try and discover a relationship between the two assuming there is one, or, if one is more puristic, assuming there is none. And secondly, the research methodology itself often shows severe flaws. Most research was of the 'before-and-after' type, a type that offers little safeguards that the outcome is more the result of confounding factors than of the parameters that are investigated. There are better alternatives, e.g. like the relation studies that are explained in a further part of this section. We will quote a few of these studies. For more details see Painter (1999) and Schreuder (1998, 2000).

(e) Lighting and crime; earlier crime studies

In research, epidemiology studies are studies performed in the field, where the relation between variables is investigated, concentrating on the correlations rather than on the causal relationships between them. When they are made on a sufficiently large scale and when the samples are taken randomly, they supply the data on which the size and the type of the problems may be assessed. Most older 'lighting studies' have been surveyed by Aelen & Van Oortmerssen, 1984; Painter, 1999; Farrington & Welsh, 2002; Schreuder 1994, 1998, 2000.

Most studies are little more that opinions and anecdotes: systematic, well designed quantitative research is almost completely lacking. An example is the widely quoted USA studies of Tien et al. (1977) and Tien (1979) that have been quoted earlier. Typically, a conclusion could not be drawn. The only recommendation of the author was to do more studies: "Therefore, it is recommended that a single project evaluation design be developed, implemented, refined and promulgated as a model evaluation study" (Tien, 1979, p. 30). This study is often understood as showing that lighting is not an effective crime countermeasure. This is, in view of the methodological weaknesses, obviously not a sound conclusion. Painter (1991, 1993) points out very clearly that the conclusion of Tien (1979) can indeed not be used for setting up crime countermeasures; it had, however, a very negative effect on the motivation to do any further research. The influence is still being felt. The more recent USA study of Sherman et al (1997) that is discussed earlier, still comes to the same conclusions. One might conclude from these quotes that the first thing to do seems to set up a decent scientific investigation about the contribution of public lighting to the prevention of crime. This is the main conclusion from two recent British studies that, incidently, also fail to include non-English language research (Farrington & Welsh, 2002; Pease, 1999). Also, they do not make any differentiation according to crime type. In spite of that severe flaw, the Farrington & Welsh-study concludes that "improved street lighting could be a feasible, inexpensive and effective method of reducing crime" (Farrington & Welsh, 2002, p. 4). According to Painter & Farrington, the most conservative benefit is estimated as follows: "Cost ratios after one year were 2.4 to 1 and 1.3 to 1 in the two cases respectively" (Painter & Farrington, 1999).

In another study, it is quoted that "According to survey data, the total number of criminal offenses (excluding harassment) has been reduced by 27%. Personal offenses were reduced by 35%; property offenses by 25%". Sexual harassment against women amounts to about 14% of all incidents, and the reduction is 24% (Painter, 1991).

Two other British studies are often quoted in such a way that they are supposed to prove that lighting does not deter crime (Ramsey et al., 1991; Atkins et al., 1991). A careful re-evaluation shows that the two studies conclude that the fear of crime is reduced considerably by improved lighting, and also that people believe that better lighting helps to reduce crime. Furthermore, both studies state that the actual reduction of the crime rates is not great: an overall reduction of 6,3% is reported (See Atkins et al., 1991, Table 3).

(f) Comments regarding methodology

Painter (1999) concludes for the 15 studies, as indicated earlier, that there is some evidence that relighting can reduce crime and disorder as well as reducing fear, particulary amongst women and elderly people, and increase nighttime street use. Although the results indeed look promising, there must be some caution based on methodological considerations. The projects involved the improvement of the street lighting in distinct – often rather small – residential areas that were not selected on a 'random' base. The reason for upgrading the lighting was that the crime situation was considered poor in these areas, whereas the authorities judged that improving lighting might be a sensible thing to do to improve the situation as regards crime. Obviously, this way of reasoning might give raise to circular arguments. The data were mainly collected by pedestrian counts and household enquiries; it seems that police reports were not used at all. Furthermore, most studies were simple 'before-and-after' studies, where the lighting in the 'before'-period was considered inadequate and improved in the 'after' period.

Painter (1999) sums up a number of problems related with this type of research. The caution is based on the fact that, as mentioned earlier, it has been established firmly in the adjacent area of studies in road accidents that the problems might be more severe than Painter acknowledges. In almost all cases, before and after periods need to be long in order to acquire enough data. A major problem with before-and-after studies is that almost everything one may think of will change during time; so the time series of almost any pair of two variables will show a correlation, even if the two variables have nothing at all to do with each other. In the classical book of Moroney (1990), a number of well-known examples of 'nonsense correlations' are given. The classical before-and-after studies go even further: correlations between time series are not determined, but only the difference between the time-average of the parameters involved.

The studies lacked another essential aspect for a sound experimental methodology: the regions where the lighting was improved were not randomly taken, but selected on the basis of the notion that lighting could be beneficial in them. In this particular case the consequences are maybe not that serious as the reasons for improving the lighting as well as the ideas about the type of crime that is to be attacked, are rather diffuse.

To overcome many of these problems, it is essential to have a control area whenever before-and-after studies are performed. This means that the same data are collected, however without any changes in the parameter to be investigated. But even then, many changes over time cannot be accounted for by a simple area-wise control. In studies of the relation between street lighting and accidents, mostly the daytime accidents are used as an – additional – control. A better solution is to use relation studies, where many different situations are investigated in the same period without waiting that anything will be changed in the lighting. This can be combined with the study of daytime incidents. See for details CIE (1992); Schreuder, (1992, 1994, 1998). A further improvement may be found by applying a 'meta-analysis' where the characteristics of the different participating investigations are 'weighted' according to their relevance to the problem. The idea is explained an earlier part of this section. See Elvik (1995) and Hagenzieker et al. (1997). It may be good to repeat once more, that even the meta-analysis method has its own pitfalls. This has been mentioned in sec. 12.1.1b, when discussing some of the finer points of accident study methodologies (Marchant, 2003; 2004).

Another problem is that the data are usually not uniform nor well-spread. Many statistical methods can be used only if the parameter values are distributed according to the Gauss-law ('normally distributed'). Sometimes, data transformations may be used, like the log-normal distribution; however, taking the logarithm may cause a severe loss of data. Also, many real-life occurrences are not normally distributed. Assuming a Poisson-distribution may help; however, for most statistical analysis methods, a transformation into normally distributed data is required. This obviously will introduce systematical errors. For the theory of these statistical problems, reference may be made to the classical books of Clarke & Cooke (1994) and Dixon & Massey (1957). See also Moroney (1990). However, there are research methods that can give good results even if the data are not completely uniform and reliable (Schreuder, 1988, 1998).

Also there is the danger, as indicated above, of circular reasoning. The selection of the parameters to be investigated is usually based on 'common sense' or 'gut feeling'. Now these two may be very useful in solving practical problems, but there is a danger that the things one looks for in the results are just the things one has introduced in the data collection: the dependent and the independent variables are not independent of each other. The major pitfall is that the data found in the trial experiments where the parameters are determined and the hypotheses are formulated, are used again in the main experiment. No wonder the hypothesis is confirmed by these data, as these data are used to formulate the hypothesis. One way out is never to try to confirm a hypothesis, only to falsify it (Popper, 1959). Another is to use, as mentioned earlier, a meta-analysis where there is no preference for any particular hypothesis.

A more fundamental problem is that with all statistical studies, nothing but statistical relations, like e.g. correlations can be found. If one is interested in causal relations – and such knowledge is essential to be able to make any useful predictions of the effect of measures – other types of studies are required. Painter (1999) acknowledges this aspect.

And finally, a major pitfall in statistical studies, and more in particular if the results are used as a basis for countermeasures, is the 'regression to the mean'. In each time-series of data there is a spread. This may be the result of errors in the measurements themselves, or of the influence of random variations. This means that e.g. the year-to-year number of burglaries in a certain area fluctuates, even if the conditions are perfectly stable. The fluctuations are essentially variable as a result of the stochastic character of the input data. Now, if one considers to introduce a measure against burglaries, usually the best moment to do so, when the arguments seem to be the most pressing, is just after a year where the actual observed number of burglaries is 'exceptionally' high. So, the measure is taken. For the sake of the argument we will assume that the measure has no influence whatsoever on the number of burglaries. Nevertheless, the next year, the number of burglaries will most likely be lower, just because at the target year it was exceptionally high. It is tempting to state that the measure against burglaries was 'very successful' because the number of burglaries decreased dramatically after it was introduced. Clearly this conclusion has no ground. This effect is called, for obvious reasons, the 'regression to the mean'. When, apart from statistical data, there is also a causal relationship between the measure and the number of burglaries, this error may be avoided.

(g) Closed circuit television and crime

Many criminals may be considered as being cowards. They will do much to avoid being seen and recognized. This is, in fact, one of the major incentives to install outdoor lighting in crime-sensitive areas. As is explained in sec. 12.1.2j, there is ample proof that this indeed helps to prevent crime.

There are two important methods that can be applied for seeing and recognizing suspects and criminals:
(1) Outdoor lighting. The technical aspects of outdoor lighting as a crime deterrent are discussed in detail in sec. 12.1.2.
(2) Closed circuit television or CCTV.

Here we will discuss briefly the characteristics of the two systems. Outdoor lighting has the advantage of being directly visible; this is considered as a crime deterrent on its own. Furthermore, as is explained in sec. 12.1.5c, where the five criteria of safe surroundings are discussed, it helps to create a user-friendly atmosphere, which, in its turn, will help visitors to feel more secure and to act accordingly. Also, it promotes social control. And finally, it is of great assistance to recognize any potential criminals as well as their clothing, which helps to apprehend them if needed, and which helps witnesses to give a good description. As is explained in sec. 8.3, this requires outdoor lighting with good colour rendering properties: the use of monochromatic low-pressure sodium lamps is not recommended for outdoor lighting in crime-sensitive areas.

However, outdoor lighting has the draw-back that it works ‘real time’. The information is provided at the moment of the crime itself, or maybe some time before the actual criminal act. In this respects, CCTV has the advantage that the recordings can be kept till afterwards. This information is important for the apprehension of suspects, and even may have its uses during any juridical court procedures. Of course, it is this potential use that may lead to restrictions in applying CCTV, on the grounds of protecting the privacy of the suspects. As is often the case, the interests of suspects and of criminals are considered more important than the interest of potential victims. It should be noted that, similarly to outdoor lighting, it is very important that the CCTV-system provides good colour recognition. For this reason, the common black-and-white security TV systems are not always very useful in crime-sensitive areas. So, both systems have advantages and disadvantages, and in many countries, they are applied in combination.

The effects of CCTV have been evaluated in great detail by Welsh & Farrington (2002). In this study, a large number of reports on the crime prevention effects of CCTV have been reviewed. Based on a rigorous methodological analysis, most reports have been rejected, because they did not comply with the requirements for a sound meta-analysis. In the end, only 17 reports have been used for this research. Most were related to city centres and housing developments, a few to public transport and the rest to car parks. The overall results are depicted in Figure 12.1.2.

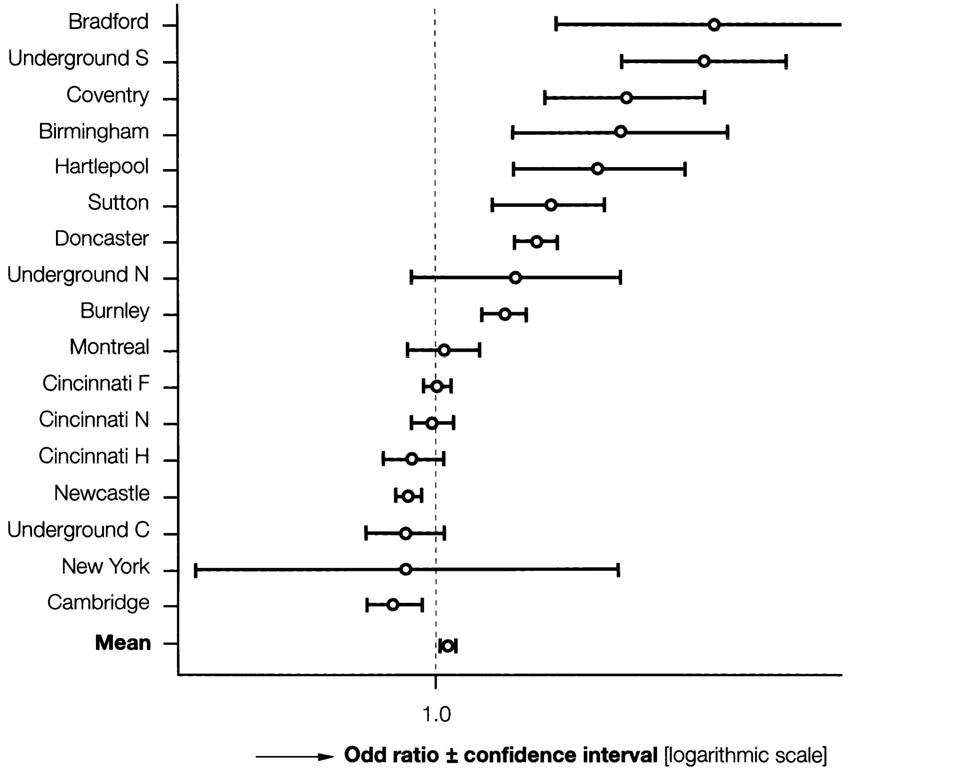

Figure 12.1.2: *The CCTV evaluations. After Welsh & Farrington, 2002, Figure 3.1. The odds ratios and the confidence intervals are given on a logarithmic scale.*

Note: In the original, no scale is added.

In this figure, the net results of the 17 schemes are given. As a criterion is used the 'odds ratio'. This ratio "indicates the proportional change in crime in the control area with the experimental area. It signifies the decrease in crime in the experimental area compared with the control area" (Welsh & Farrington, 2002, p. 26). In other words, when the odds ratio is greater than unity, CCTV helps to reduce crime; if the confidence ratio is always over unity, the help is statistically significant to the selected percentage.

From Figure 12.1.2, it can be seen that, in 8 cases, the CCTV helps in a statistically significant way. In two cases the effect is negative in a statistically significant way. The rest, 7 in all, do not permit a statistically significant statement. Most important, the mean of all studies taken into account in the meta-analysis, is marginally positive, and this in 'just' a statistically significant way. The result is about 4% (Welsh & Farrington, 2002, p. 41).

The only sub-group where a considerable, systematic, improvement in the crime scene was found, was in car parks. However, here, CCTV always had been combined with improved lighting (Welsh & Farrington, 2002, p. 42). So, as a conclusion, it seems that CCTV as such is not a very effective crime countermeasure. "Overall, it might be concluded that CCTV reduces crime to a small degree" (Welsh & Farrington, 2002, p. vii).

It should be noted, although this is not discussed by Welsh & Farrington (2002), that, in order for CCTV to work properly, the lighting level must at least be about 30 lux (corresponding to about 2 cd/m^2) for easy recognition. This figure is often used in traffic control TV for road traffic tunnels (Huijben, ed., 2003). In sec. 12.1.4d, the minimum levels needed for facial recognition under office working conditions are discussed. It is explained that, when facial features have to be recognizable without any special effort on the part of the observer, the luminance of the face must be at least 17 cd/m^2, whereas the facial features are just recognizable when the luminance of the face is about 1 cd/m^2 (De Boer & Fisher, 1981, p. 35-37). For Caucasians, these luminance would require an illuminance of about 130 lux and 8 lux respectively (De Boer & Fisher, 1981, p. 37). If these figures can be used for CCTV in crime-sensitive locations as well, it implies that the lighting usually has to be improved in the first place. So, it remains to be seen whether CCTV has any advantage over improved outdoor lighting from the point of view of the restriction of light pollution.

The report does not contain a cost/benefit analysis. The authors, however, suggest clearly that the large sum of money spent on CCTV schemes – 170 million Pound Sterling for the years 1999 through 2001 – could have been spent better (Welsh & Farrington, 2002, p. 44).

(h) Lighting and crime; crime typology

A major part of crime in modern society is street crime and particularly nighttime street crime. Beke & Van Herwijnen (1990) quote three reasons for that:

(1) The victim sees the criminal only late.
(2) Witnesses have little chance to notice the crime.
(3) Police surveillance is difficult.

In this respect, not only the actual number of criminal acts should be taken into account, but also – probably even more so – the subjective aspects of the 'fear for crime' (Painter, 1999; Schreuder, 2000). The severity of nighttime street crime holds for industrialized as well as for developing countries. Statistical data are scarce as crime data are considered as being 'sensitive' from the point of view of the protection of the privacy of citizens, particularly of criminals. It might be argued that in this way, the victims suffer even more than from the crime alone.

Because no-one can doubt the severity of the nighttime street-crime scene, it is obvious to look into road and street lighting as a crime countermeasure. The lack of valid statistical make scientific large-scale field research difficult. Studies of more detailed nature did prove, however, that often, but not always and not for all crime types, improving road lighting helps to prevent crimes and to reduce crime rates. More important still, almost always an improvement in the psychological aspects was reported. Furtheron, we will report about several of these studies.

As a conclusion it may stated that the effectiveness of public lighting as a crime countermeasure is studied widely. The results are, however, somewhat ambiguous. For one part this is probably the result of the anecdotal fashion in which most studies have been executed (non-random sampling; poor data recording etc.), but probably more importantly by the fact that crimes and criminals do not constitute homogeneous groups. In-depth psychological studies of criminal behaviour, more specifically of street violence, suggests that the typology of criminals and victims as well as the motivation and sociological background shows wide variations (Schreuder, 2000).

(i) *The influence of the light level; survey of the Japanese report*

A major set of studies have been made in Japan. The results are published in a report by the Illumination Engineering Institute of Japan (IEIJ). The following section is based on a summary translation (Narisada, 2002). The report is a set of five annual reports for activities between 1986 and 1990 made under the auspices of the Kansai Branch of the IEIJ.

The first report from 1986 concerned a statistical survey of traffic accidents and crimes. The second report of 1987 concerned a survey of recommendations for public lighting in various countries, including Japan. At that time, there was no national code in Japan. In also contained a survey of existing lighting installations in various towns e.g. Osaka, Hyogo (Kobe) and Kyoto, and the investigations carried out in the laboratory of Matsushita Electric Industries to find the lighting levels that needed for the security of pedestrians.

The third report of 1988 surveyed lighting design techniques, luminaires and lamps as well as the results of a survey sent out to municipalities about lighting. Some data are given in Table 12.1.7.

Towns	Luminous flux installed (lm/km^2)	Number of robberies per 10 000 population
Osaka	360	1,7
	470	1,85
	690	1,39
	1000	2,13
	1340	0,96
	1390	2,43
	1890	1,53
Tokyo	1340	1,25
	1540	0,7
	1600	1,22
	2100	0,51
	2310	0,86
	2500	0,65

Table 12.1.7: *The number of robberies without injury per 10 000 inhabitants for different regions in Osaka and Tokyo, in relation to the luminous flux installed per km^2*

The fourth report of 1989 contains a statistical survey of the relationship between the lighting levels and the frequency of incidence of various categories of outdoor crime. A summary of the translation of the report is given in the next section. The fifth report of 1990 surveyed the effects of improved test lighting installations. These were designed on the basis of the results of the investigation on crime incidence. These results were reported in the second report of 1987. The results were promising. It might be possible, however, that the effect would be over-estimated since the frequency of police patrols was increased after the improvement of the lighting.

The study reported in the second report of 1987 consisted of two parts: a "Comparison of street crimes in Tokyo and Osaka" and a "Survey of questionnaire for 66 suspects of street crimes".

The comparison of street crime in Tokyo and Osaka starts with a comparison of the street lighting in the different town districts in Tokyo and Osaka, expressed in the installed lumen-value per square km. The results of the comparison are given in Table 12.1.8. It should be noted that the values in the table of lm/km^2 do not reflect the actual street lighting illuminance levels, due to the differences in geography, roadside development and population in the different town districts.

Tokyo town district	**lm/km^2**	**Osaka town district**	**lm/km^2**
A	2510	G	1390
B	2100	H	1890
C	1600	I	1000
D	2310	J	464
E	1550	K	689
F	1350	L	357
		M	1340
Average	**1903**		**1019**
	(100%)		(53%)

Table 12.1.8: *Comparison of the street lighting between Tokyo and Osaka.*

Next, the report gives the number of nighttime outdoor crimes per 10 000 inhabitants for the year 1987 for Tokyo and Osaka. Most of the 'robberies' are snatch-and-runs from pedestrians by motorcyclists or bicyclists. See Table 12.1.9.

Not all outdoor crimes are street crimes. Of the robberies, about 95% occur on the streets, about 40,1% of the stealing of cars, about 53,2% of the stealing from cars and about 26,5% of the stealing of car parts. This was thought to be a part of the reason that robberies have, from the crime categories, the highest correlation with the installed luminous flux.

The Japanese reports also include a study about the correlation between crime and installed luminous flux. A correlation analysis let to the following relation between (Y) the number of robberies per 10 000 inhabitants and (X) the installed luminous flux:

$$Y = -0{,}000545\,X + 2{,}10$$

It should be noted that the correlation coefficient nor the standard deviations are given in the summary of the report. From the relation, it can be expected that for an increase of the installed luminous flux of 880 in Osaka level to the Tokyo level of 1980, the number of robberies per 10 000 inhabitants might drop from 1,62 to 1,02 – a reduction of 37%.

Town district	Robbery	Stealing cars	Stealing from cars	Stealing car parts
All Tokyo	**0,68**	**1,05**	**5,04**	**1,07**
A	0,65	0,72	3,54	0,50
B	0,52	0,77	6,57	1,46
C	1,22	1,51	5,31	1,58
D	0,86	1,06	2,45	0,93
E	0,71	0,81	3,70	0,76
F	1,25	0,58	4,72	1,11
All Osaka	**1,58**	**3,24**	**6,90**	**1,81**
G	2,43	2,86	6,77	1,69
H	1,53	4,32	10,06	2,84
I	2,14	4,84	8,37	3,02
J	1,85	3,38	3,14	0,48
K	1,39	3,51	7,26	3,05
L	1,70	2,96	5,17	1,08
M	0,96	3,88	8,80	2,64
Tokyo/Osaka	**2,3**	**3,1**	**1,4**	**1,7**

Table 12.1.9: *Nighttime outdoor crimes per 10 000 inhabitants (1987).*

An enquiry under crime suspects was part of the research. A multiple-question type of questionnaire relating to their views about street crimes at night were distributed under 66 suspects who were arrested for street crimes committed between February 1987 and August 1988 The following results were found:

- From the 66 suspects, 63 were male. About 62% were teenagers and 23% were in their twenties. Of all crimes, 31 (47%) were robberies and 23 (34,8%) were stealing cars. 97% of robberies were committed on the street, but only 35% of the car thefts. The rest was committed on open parking places.
- Between 65% and 70% of the suspects stated that the crimes were committed regardless of lighting. About 1/4 to 1/3 of the suspects took easy escape into consideration. For

most robberies (84%) and stealing cars (74%) the suspects selected locations with little pedestrian traffic.

- For general crimes, between 33% and 39% of the suspects mentioned that they gave up the intended crimes if there was lighting installed.

(j) Influence of lighting on burglaries

A recent study in the Netherlands suggests that, over the years, there is a remarkable shift for breaking into homes from the nighttime towards the daytime (Anon., 2003). The study relates to 16 116 burglaries in 2002 and 4146 burglaries in 1989. The main results are:

(1) There is a clear shift from the nighttime towards the daytime. This is depicted in Figure 12.1.3.

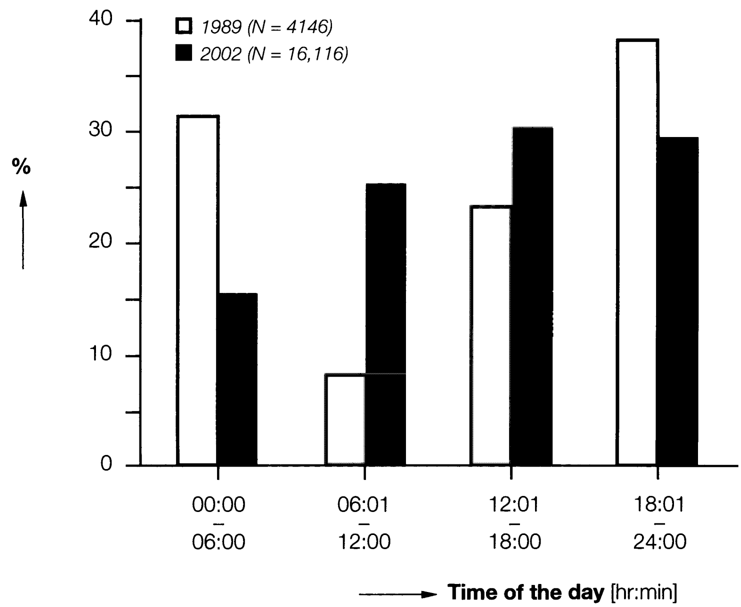

Figure 12.1.3: *Percentage of burglaries in homes for different times of the day. (a) 1989; (b) 2002. After Anon., 2003.*

(2) There is a shift in the day of the week. In 1989, Friday and Saturday were most frequent, in 2002 it was Tuesday and Friday.

(3) There is a shift from row-houses towards separate houses. Row-houses decreased from 49% in 1989 to 21% in 2002; separate houses increased from 22% in 1989 to 30% in 2002.

(4) There is a shift from doors to windows as the means of ingress. The door decreased from 57% in 1989 to 49% in 2002. The window increased from 27% in 1989 to 41% in 2002.

(5) There is a shift from the rear towards the front of the house as the means of ingress. The rear decreased from 73% in 1989 to 60% in 2002. The front increased from 24% in 1989 to 34% in 2002.

These date suggest the following changes in the surrounding of the burglar while breaking in:
(1) The improved road lighting and security lighting might contribute to the shift from the nighttime to the daytime. When one is quite visible, it is just as easy to break in during the day. This would also explain the shift to the front of the house.
(2) The changes in housing development might explain the shift from row-houses towards separate houses, as the latter are much more popular nowadays.
(3) The shift for doors to windows might be the result of a marked improvement, over the last decade, in securing doors.
(4) Many changes might relate to a marked shift towards two-person households where both partners work during the weekdays.

In summary, the study suggests that, amongst other causes, the improvement of road and security lighting is noted by burglars, who did change some of their habits accordingly.

(k) The influence of the light level; the study in the Netherlands

In the Netherlands, a small-scale study was made, using the well-established methodological principles that are common in road accident studies (Schreuder, 1992). The method used is a 'relation study', where the number of reported criminal offenses (of different types) are related directly to the public lighting. For each street in a certain city, all data regarding the crime situation and regarding the lighting are collected. Appropriate statistical analysis methods (meta-analysis amongst them) give the results. The advantages and the disadvantages of this type of studies are well-known (See for this CIE, 1992). In this study, the relation between the light level and criminal acts of different kinds were investigated. The results are summarized in Table 12.1.10 (After Schreuder, 2000a).

From these two tables is may be seen that in general, the crime rate (day/night ratio) decreases when the light level increases. This seems to be the case for a number of different crime types. There is a slight suggestion (mainly for the stealing from cars, Table 12.1.10), that at road lighting levels that are high compared to common road lighting standards, crime rates may again increase.

Crime type	Time	Light level (lux) <1,6	1,6	2,6 2,5	4,0 3,9	6,4 6,3	10,0 9,9	>16 15,9
bag stolen	day	1	2	3	2	1	4	0
	night	0	2	5	2	1	1	1
burglary front	day	0	2	4	5	1	1	0
	night	0	8	10	6	0	0	1
burglary side	day	0	6	5	6	1	2	0
	night	5	31	37	30	3	8	4
sexual crime	day	0	4	3	1	2	1	0
	night	0	1	1	2	2	1	2
theft from car	day	2	27	50	61	36	69	20
	night	20	119	158	90	30	82	27
	night/day	10	4,4	3,16	1,48	0,83	1,19	1,35
total	**day**	**3**	**41**	**65**	**74**	**41**	**77**	**20**
	night	**25**	**169**	**211**	**130**	**36**	**92**	**34**
	night/day	**8,3**	**4,12**	**3,25**	**1,75**	**0,88**	**1,19**	**1,7**

Table 12.1.10: *The relation between the light level and criminal acts of different kinds (After Schreuder, 2000a; based on data from Schreuder, 1992).*

Notes:
– 'burglary front' means breaking into a house etc. from the front;
– 'burglary side' means breaking into a house etc. from the side.

(l) Conclusions concerning lighting studies

The results can be summarized as follows:

- in the words of Farrington & Welsh: "Improved street lighting could be a feasible, inexpensive and effective method of reducing crime";
- increasing the road lighting level deceased in general the nighttime crime, as the night/day crime rates drop;
- there is a suggestion that a high road lighting may result in an increase in crime rates.

There is one thing to remark here, however. Because the results are not very well in line with each other, and because in some cases, conflicting evidence is presented, it seems not to be fully justified to say that road and street lighting is, in all cases, an effective crime countermeasure. There are reasons to believe that different crimes are committed by different types of criminals. So, one should not take for granted that all criminals react to the presence or absence of lighting in the same way.

12.1.3 Non-lighting studies about crime

(a) Accidents in general

To put things in perspective: in the Netherlands, violence is not at all the most common cause for victimization. For the whole country, with a population of about 16 million, the following data are given for 1995 (Table 12.1.11).

Cause	**Number of victims** (rounded off) **female**	**male**	**sum**
traffic	60	80	140
home	280	300	580
sport	60	120	180
occupational	20	90	110
violence	10	30	40
self inflicted	4	3	7
unknown	6	10	16
total	440	633	1073

Table 12.1.11: *Numbers of victims (*1000 in 1995). source: Consument en veiligheid, quoted from Metro, 26 October 1999. (Anon., 1999a).*

In 2003, similar numbers have been reported. See Table 12.1.11a

Victims (% of total population)	**Year** **2002**	**2003**
theft/burglary	46	50
traffic accident	33	34
sexual offence	5	5
violent robbery	3	4

Table 12.1.11a: *Crime victims in the Netherlands. Source: TNS NIPO. After Anon, 2003h.*

It seems that the crime numbers are increasing over the years. It is not known precisely in how far this reflects the actual crime situation, because, the willingness to report incidents to the police, and the policy of the police to make official reports, is not constant over the years. This is a well-known fact for other incidents, like e.g. road accidents (Harris 1989, 1989a; Flury 1990).

(b) Police Monitor study

The Police Monitor is a major enquiry held in the Netherlands sine 1993 every two years under contract of the Ministries of the Interior and of Justice. The police force resorts in the Netherlands under those two Ministries. The actual research is done by means of telephone enquiries by a special consortium, called: "Uitvoeringsconsortium Projectbureau Politieminitor". The enquiries cover three major aspects of crime: the feeling of being insecure and the victimization (subjective and objective safety); the relation between police and citizens; the measures taken by citizens to prevent crime. The reports of the Police Monitor cover several volumes: first a national report with an appendix and, in addition, 25 regional reports. We will discuss briefly the relevant passages of the 1999 national report (Anon., 1999b). References are given in relation to the report. In the tables given here, many data are rounded off. Reports from more recent years present the same overall picture.

Within the context of the Police Monitor, a number of studies are directed towards the problems arising in the neighbourhood. The reason for this approach is that it is a part of the crime prevention policy in the Netherlands to achieve that, at least the neighbourhoods were the general population lives, are free of excessive crime, so that there is less chance that the 'innocent bystander' becomes a crime victim. We will not discuss here the ethical aspects of this policy, where certain neighbourhoods are stigmatized as 'criminal' with all the well-known problems of stigmatization, one being that this is a self-fulfilling prophecy. It might be added that the most recent discussions in the Government of the Netherlands show clearly that the problems are still far from solved!

The first question relates to the opinions that a specific aspect concerning material damage and/or loss occurs 'often' in the view of the respondents. See Table 12.1.12.

	Reported as occurring 'often'
damage to/theft from cars	18%
burglary	23%
theft of bicycle	25%
theft of cars	18%

Table 12.1.12: *Opinions on material damage over 1999 (Anon., 1999b, p. 19, fig. 1.1).*

In all cases, the numbers are significantly lower than those of 1995 and 1997.

The second question relates to the opinions that a specific aspect of disturbance by traffic occurs 'often' in the view of the respondents. See Table 12.1.13.

	Reported as occurring 'often'
noise	14%
collisions	13%
speeding	48%
aggressive behaviour	20%

Table 12.1.13: *Opinions on disturbance over 1999 (Anon., 1999b, p. 21, fig. 1.4).*

The data do not differ much from those of 1995 and 1997.

The third question relates to the opinions that a specific aspect of threat occurs 'often' in the view of the respondents. See Table 12.1.14

	Reported as occurring 'often'
drunks on the street	8%
actual threat	2%
violent crimes	6%
disturbing people on the street	4%
drug addicts on the street	7%

Table 12.1.14: *Specific aspects of threat over 1999 (Anon., 1999b, p. 23, fig. 1.7).*

The data do differ from those of 1995 and 1997 but not systematically.

The fourth question relates to the opinions that a specific aspect neighbourhood neglect and deterioration occurs 'often' in the view of the respondents. See Table 12.1.15.

	Reported as occurring 'often'
disturbance by neighbours	5%
disturbance by juvenile groups	12%
vandalism	20%
dog's droppings on the street	50%
trash on the street	26%
graffiti	17%
noise	8%

Table 12.1.15: *Neighbourhood neglect over 1999 (Anon., 1999b, p. 25, fig. 1.10).*

The data do differ from those of 1995 and 1997 but not systematically.

Within the context of the Police Monitor, a number of studies are directed towards the feelings of being insecure – the subjective safety. The first part was a study about the general feelings of being insecure. In 1999, 31% of the respondents felt insecure 'occasionally'; 6% of the respondents felt insecure 'often'. The percentages are very similar to those of 1993, 1995 and 1997 (Anon., 1999b, p. 29, figures 2.1. and 2.2).

The next study was about the changes in behaviour as a result of feeling insecure. Table 12.1.16 shows the percentages of respondents showed certain types of avoidance behaviour 'often':

	Reported as occurring 'often'
avoid locations in the residential area	11
do not open door at night	17
do not take valuables along	16
make detours to avoid dangerous locations	10
forbid children to play at specific locations	26

Table 12.1.16: *Specific behaviour over 1999 (Anon., 1999b, p. 30-31, fig. 2.3).*

Leaving valuables at home did decrease in the last few years, forbidding children to play at specific locations did increase considerably. The other aspects were almost constant over the years.

A major aspect of the Police Monitor are studies about victimization. The first is about victimization in relation to objects. The victimization in relation to objects is expressed in the percentages of objects that were the aim ('victim') of criminal acts. The data are given for 1999 and represent the victimization in one year only. See Table 12.1.17.

	Reported victimization
theft of bicycle	7
damage to cars	25
theft from cars	7
theft of cars	1
attempted burglary	5
burglary	3

Table 12.1.17: *Victimization over 1999 (Anon., 1999b, p. 34, fig. 3.1).*

In all cases, the percentages dropped considerably over the last years. In about 93% of cases the perpetrator is unknown. Note: it is not known whether the drop might be an artefact as a result of differences in crime reporting policies.

The next study is about personal victimization. Personal victimization is expressed in the percentage of persons who were at least once the victim of the specified acts. The data are from 1999 and represent one year only. See Table 12.1.18.

	Reported personal victimization
hit-and-run collisions	2,5
collisions	10,2
threat	6
abuse	1,1
theft of wallet without violence	3,9
theft of wallet with violence	0,3
other theft	7
other damage	8
other crimes	1

Table 12.1.18: *Personal victimization over 1999 (Anon., 1999b, p. 37, fig. 3.5).*

In most cases, the percentages dropped somewhat over the last years. In about 85% of cases the perpetrator is unknown.

The victimization depends strongly on the degree of urbanization. In almost all cases, the percentage in strongly urbanized areas is about twice as high as in rural areas (Anon., 1999, p. 41-43, figures 3.9 to 3.14).

Another study made in the context of the Police Monitor, relates to juvenile victims of violence. Table 12.1.19 gives the percentage of juveniles that were victim of violence.

Age bracket	Percentage
15-18	13
19-24	14
> 25	5

Table 12.1.19: *Juvenile victims of violence over 1999 (Anon., 1999b, p. 44, fig. 3.15).*

The percentages have increased considerably over the last four years.
Note: the definition of juveniles is rather wide.

The report of the Police Monitor gives rise to a number of interesting conclusions, although it does not discuss the night time separately, nor any possible influence of outdoor lighting. The report focusses on problems arising in the neighbourhood. Other aspects are not reported; the problems might be greater or smaller or the same.

(1) In one's neighbourhood, in the opinion of residents, damage to cars, burglary and theft are very important (1/5 to 1/4). Neighbourhood neglect is considered very important as well. Manure and trash score highest (1/2 to 1/3), but vandalism scores also high (1/5). Subjective safety is very important 31% felt insecure 'occasionally'; 6% 'often'. Many people avoid certain locations or make detours (1/8 to 1/10). 1/3 forbid children to play at specific locations. The conclusion is that in the opinion of residents, the different sorts of criminal behaviour and other socially unacceptable behaviour represent a serious problem. The report does not make any distinction between day and night situations but one might infer that many aspects are probably more serious at night than at day. In such serious matters, good lighting and/or good visibility are beneficial, even if the improvement is relatively speaking only small.
(2) Victimization. In relation to objects, 25% of all people suffered from damage to cars. Theft and attempted burglary are suffered by 5 to 7% and actual burglary about 3%. As regards the absolute values, it should be noted that there are more than 10 million bicycles in the Netherlands, about 7 million cars, and about 6 million houses. As mentioned earlier, the report does not make any distinction between day and night situations but also here one might infer that many aspects are probably more serious at night than at day. In such serious matters, good lighting and/or good visibility are beneficial, even if the improvement is – relatively speaking – only small, particularly in view of the very large absolute numbers involved. As regards personal victimization, this scores highest in relation to traffic (13%). Violence or threat with violence is also very high (almost 8%) and so is theft (11%). It is possible that a person is a victim of different crimes. However, disregarding this, the total number of victims is 40,9%. The population of the Netherlands is about 16 million people. So there are about 6,5 million victims and almost 1,3 million victims of violence per year in the Netherlands. This figure is of the same order of magnitude as quoted elsewhere. They are in reasonably good agreement with those given earlier, quoting Anon. (1999a). This is noteworthy, as they are collected in quite different ways. See also Anon. (1999b).

(c) The Haaglanden study

Haaglanden is a part of the Netherlands, centered around the city of The Hague (Den Haag). It totals about one million inhabitants (Anon, 1999, p. 5). This amounts to some 6 to 7% of the total population of the Netherlands. It a highly urbanized area. It has about 400 000 homes (Anon, 1999, p. 5). The report gives data about crime in 1997 and 1998. These data and the trends in them might be considered as exemplary for the Netherlands as a whole.

The overall data concerning incidents are given in Table 12.1.20.

Incidents	1997	1998	Ratio 1998/1997 (1997=100%)
threat	573	687	120
abuse	1 670	1 926	115
total violent acts	4 451	4 653	
per 1000 inh	4,8	5,0	
armed robbery	169	213	126
robbery in the street	969	834	86
theft from cars	13 897	14 382	103
theft from homes	7 233	7 187	99
total property acts	58 475	57 622	
per 1000 inh	63,1	61,6	
total vandalism	11 024	10 161	
per 1000 inh	11,9	10,9	
drug related crime	301	353	
drunken driving	2 538	2 864	
theft risk from homes	1,74%	1,71%	
number of police reports		72 414	98
total number of incidents		over 400 000	114

Table 12.1.20: *The incident data (Anon, 1999, p. 15, 17).*

(d) A study on violence on the streets

In 1999, the Ministry of Justice in the Netherlands initiated a study aimed particularly towards violence and violent crimes on the roads (Terlouw et al., 1999). As with the other studies discussed in this section, the study was not aimed at the night time situation nor at the contribution of outdoor lighting in crime prevention. However, a number of aspects and conclusions covered in the report are indirectly relevant for our study. The report contains a useful bibliography. All data refer to 1998, unless otherwise stated.

The study relates to background and motivation of street violence between strangers (Terlouw et al., 1999, p. 3). This is important to know, as it is well known that a large part of violence on the road and most violence indoors is between people who know each other. The crimes are classified according the general classes that are used in police reports. These are based on specific clauses from the legislation in the Netherlands. This means that 'theft with violence involved' and 'sexual crimes' are not covered (Terlouw et al., 1999, p. 6).

The study is based on the data from two police districts, one predominantly urban and one predominantly rural (Terlouw et al., 1999, p. 11). These districts relate to about 10% of the total population in the Netherlands. As a comparison, in the total country the nationwide estimate amounts to about 20 000 to 25 000 incidents (Terlouw et al., 1999, p. 20) whereas the region amounts to 1065 incidents (Terlouw et al., 1999, p. 16, table 3.1).

The report gives also some data for the Netherlands as a whole. In 1998, 76 600 acts of violence in the Netherlands were reported to, and recorded by, the police. From that, assault was 49,6%; crimes against life 20,4% and theft with violence involved 18,8%. One in five is related to sexual crimes (Terlouw et al., 1999, p. 3). As found elsewhere as well, the percentage of reported crime is low: most crimes are not reported. It is estimated that the total number of violent outdoor crime (reported and not reported together) is about 877 000, from which about half concerns threat and one in three assault (Terlouw et al., 1999, p. 4). It should be noted that the that the total numbers of the following tables differ, because sometimes data are not available.

For the two police districts, the number of reported incidents of violence was 6468, the total number of reported crimes was 124 044. So violence amounts to about 5% of the total. The study on street violence is based on 2935 cases (Terlouw et al., 1999, p. 15). The numbers of violent acts are given in Table 12.1.21.

Total reported violence acts 100%			
indoors 43,1%		outdoors 56,9%	
non-strangers 17,8%	strangers 25,3%	non-strangers 20,2%	strangers 36,6%

Table 12.1.21: *The numbers of violent acts (Terlouw et al., 1999, p. 15; fig. 3.1).*

So, about 38% of violence is between non-strangers and about 43% of violence is indoors.

When related to the location of the crime, the following data are found (Table 12.1.22).

Area	**Number**	**Percentage**
residential area	367	34,5%
transportation	260	24,4%
recreation	204	19,2%
shopping malls	58	5,5%
school	28	2,6%
public transport	18	1,7%
sport	9	0,9%
other	38	3,6%
total	**1065**	**100%**

Table 12.1.22: *Violence and location (Terlouw et al., 1999, p. 16; table 3.10).*

The residential areas score much higher than transportation, whereas recreation (bars etc.) is only third (under 20%). It seems therefore that alcohol plays an important but maybe not the predominant role in street violence as is sometimes assumed. Also, this clarifies the fact that one of the focal points in the government policy in the Netherlands is to try to make the 'neighbourhood' more safe.

A major aspect of street violence is group crime (See Table 12.1.23).

Number of perpetrators	Number of cases	Percentage
one	549	59%
two to four	303	32,6%
more than four	79	8,4%

Table 12.1.23: *Number of perpetrators ('group crime') (Terlouw et al., 1999, p. 21; table 4.1).*

In nearly 2/3 of al cases, street violence is an act of a single person. Group violence is common but not predominant.

It is usually assumed that street violence is typically a male affair. See Table 12.1.24.

Perpetrator	Victim							
	male		female		combined		total	
male	605	77%	86	11%	17	2,1%	708	89,5%
female	13	1,6%	59	7,4%	1	0,6%	73	9,2%
combined	6	0,7%	4	0,4%	–	–	10	1,3%
total	624	79,9%	149	18,8%	18	2,2%	791	100%

Table 12.1.24: *Gender (Terlouw et al., 1999, p. 26 table 4.3). Combined means both men and women.*

As was to be expected, almost all perpetrators are male. What is striking to note is, that the great majority of victims is male as well, and that a large part of the female victims are related to the (small number of) female perpetrators. This is contrary to what many seem to believe. The 'common opinion' seems to suggest that perpetrators are male and the victims are female. The findings are well in line with what one should expect if instinctive behaviour plays an important role in street violence. Instinctive behaviour is discussed in detail in sec. 10.1.5. It should be noted, however, that the figures given in Table 12.1.24 are based on recorded crime; the non-recorded crime may show a different distribution.

Age	Perpetrators		Victims	
	number	percentage	number	percentage
<12	11	0,8	31	3,2
12-17	552	41,8	265	27,6
18-24	363	27,5	261	27,2
25-40	298	22,6	252	26,2
41-60	86	6,5	136	14,1
>60	9	0,7	16	1,7
total	1319	100	961	100

Table 12.1.25: *Age of perpetrators and victims (Terlouw et al., 1999, p. 27 table 4.4).*

The distribution of the data of the age of perpetrators and of victims is very similar, although the very young and the old victims are overrepresented. Their numbers are, contrary to what many seem to believe, very small. Almost all victims belong to the same 12-40 year age groups as the perpetrators. A further subdivision seems to suggest that the age groups of the perpetrators is usually the same as that of their victims (Terlouw et al., 1999, p. 27 table 4.5). It would seem that victims and perpetrators belong to the same age cohort. The 12-17 age group is the most common in both cases. Also this is in line with what one should expect if instinctive behaviour plays an important role in street violence.

From 466 cases where data are available, 230 (49,4%) were 'first offenders'. The rest (236; 50,6% – more than half) had earlier contacts with the police, from one to more than five in the three preceding years (Terlouw et al., 1999, p. 29, table 4.6). It is not known in how far the system of registration and reporting could bias the results so that recidivism seems to be more frequent than is real. This is always a danger in this type of investigations.

The study does not give any information on whether the violence is at day or at night, nor about the prevailing light level. It is therefore not possible to reach any conclusion directly related to the question area: 'lighting and crime'. Nevertheless, some suggestions present themselves. In view of the authors, violence is a typical 'way of life' or attitude. If many people having a similar way of life meet, a 'sub-culture' may arise. Age distribution of perpetrator and victim is similar; very high prevalence of male violence against other males; high degree of recidivism, large proportions of violence indoors and between non-strangers. This idea leads to the notion that being seen and/or recognized is not a major concern for the perpetrators. Other noteworthy aspects are that most street violence is an act of a single person, and that alcohol plays a role that does not seem too great.

(e) International comparison

The Ministry of Justice in the Netherlands made a study regarding the international comparison of crimes of different types (Van Dijk & De Waard, 2000). The study was primarily focussed on countries from the European Union. In some cases, data from the USA, Canada or Australia were added. All countries are affluent, industrialized. Most have a large percentage of foreigners under the population. Most foreigners are from Asia or Eastern Europe. It is not known whether this has any influence on the crime data. As the study is primarily a comparison, cultural aspects that often go with the racial mix will have little influence. Comparing with countries from other parts of the world can be very hazardous as it is well-known that economic factors have a large influence on crime. See e.g. Sherman et al. (1997).

The first comparison deals with the total of violence incidents 1995 per 100 000 inhabitants where both an enquiry under victims and the police registration were used. The registration factor is the ratio between the two. This registration factor is always much larger than unity, mostly ten or even twenty. One should remember that, on top of this, also the numbers from enquiries under victims are considerably smaller than the reality. This means that the police registration is very incomplete. There are no guarantees that the 'sample' out of the total number of incidents is random. This implies that it is hazardous – or even worse – to draw any conclusions at all on police registration data alone. This point has been forcefully stressed by Painter (1999). Furthermore, the registration factor differs considerably from country to country. It is not known whether this difference is real or is a result in differences in the enquiry under victims. The data are given in Table 12.1.26.

Country	**Enquiry under victims**	**Police registration** (rounded off)	**Registration factor**
Austria	3 700	580	6,4
France	5 800	270	21,2
Canada	6 800	970	7,0
Netherlands	7 300	310	23,1
Sweden	7 700	770	10
U.K.	9 700	530	18,4
USA	10 000	710	14

Table 12.1.26: *Total of violence incidents in 1995 per country per 100 000 inhabitants (Van Dijk & De Waard, 2000, p. 19, table 5).*

The second comparison relates to homicides and people killed by fire arms. See Table 12.1.27.

Country	Homicides per 100 000 inhabitants Homicides in 1997	Killed by fire arms 1994
Germany	1,44	1,24
U.K.	1,49	0,41
France	1,60	5,15
Denmark	1,67	2,09
Netherlands	1,75	0,70
Sweden	1,77	1,92
Austria	1,82	3,70
Canada	1,91	4,31
Australia	1,93	2,65
Finland	2,76	6,46
USA	6,95	14,24

Table 12.1.27: *Homicides and fire arm deaths (Van Dijk & De Waard, 2000, p. 18, table 3).*

With the exception of the USA and possible of Finland, the homicide figures of the different countries are directly comparable. The fire arm death figures are very different. The report does not give an explanation of the fact that the number of fire-arm deaths is in most cases considerably higher that the number of homicides.

The third comparison deals with homicides per 100 000 inhabitants in a number of cities in different countries. Most cities in the survey are national capitals; Rotterdam and New York are added. The numbers are an average over several years, mostly 1995-1997. See Table 12.1.28.

City	Homicides
Vienna	1,6
Ottawa	1,9
London	2,2
Helsinki	3,0
Paris	3,3
Berlin	3,8
Stockholm	4,1
Copenhagen	4,6
Rotterdam	5,0
Amsterdam	7,9
New York	16,8
Washington DC	64,1

Table 12.1.28: *Homicides in a number of cities (Van Dijk & De Waard, 2000, p. 19, table 4).*

One suspects that the authors of the report, being confronted with the fact that Amsterdam (the capital of the Netherlands) is very unfavorable compared to the other national capitals, have added two notoriously dangerous cities from the USA to make things look a little better. It should be noted that, according to Sherman et al. (1997), the big cities often have a crime rate that is much higher than the national average. This also follows from other data quoted earlier. Furthermore, it is striking that the homicide rate in Washington (DC) is almost 4 times higher than that in New York – a city famous (or notorious?) for the zero-tolerance crime-fighting policy that is operational since the 1990s. Maybe this policy helps.

The fourth comparison is related to the use of hard drugs. Table 12.1.29 gives the comparison.

Country	**Number** (rounded off)
U.K.	110
Austria	150
Netherlands	170
Germany	180
USA	200
Sweden	210
Denmark	240
France	280
Australia	1050

Table 12.1.29: *Hard drug users per 100 000 inhabitants over 1994/1995 (Van Dijk & De Waard, 2000, p. 27, table 25).*

The data do not suggest that the hard drug use and the homicide frequency have much in common. It is not known whether all countries use the same definition of 'hard drug'. It should be noted that alcohol usage is almost universal for people over fifteen or so in the countries listed here. It was found that alcohol is particularly harmful for youngsters (Anon., 2003a). Cases of alcohol addiction number in the order of a few thousand per 100 000 inhabitants. In the Netherlands alone, every year about 2000 to 3000 people die as a direct result of alcohol use. Drugs claims only a few dozen per year. (Anon., 1998a).

It is well-known that the use of hard drugs is – directly and indirectly – a major cause of crime, particularly for violent street crime. The opinions about the use of soft drugs, however, is far from unanimous. Many believe that soft drugs really do not do much harm and should be legalized. This point of view is reinforced by the fact that the use of alcohol, being highly addictive and very harmful both in social as in health aspects, not only is left free, but is advertised widely, positively pushed by the media, as well as, for reasons of taxation, by many Governments.

The wisdom of this policy might be questioned, however, in the light of recent findings from the Police in Utrecht, the Netherlands (Anon., 2003). It was found that a drug addict, on the average commits 6 crimes each day in order to be able to pay for the drugs. The value of the stolen items amounts to about 200 000 Euro per year, whereas the additional costs (damage, insurance etc.) amount to another 300 000 Euro yearly. So each drug addict costs the society about half a million Euro each year. This includes only the direct costs; indirect costs like e.g. law enforcement, jurisdiction, enprisonment, and rehabilitation are not included. One might think that effective measures to counteract drug related crime would be very cost-effective indeed. Politicians, however, seem not to think so.

A recent study underlines the relationship between alcohol addiction and crime (Anon., 2003). In a study made by the RAND Corporation under 3400 school age children in the USA, it was found that 12-13 year old children who drink seldom (46%) as well as regular drinkers (31%) have significantly more problems with criminal behaviour and drug addiction than those who do not drink at that age. The study reached until the age of 23. At present, no specific reasons have been found. The study will be published in the Medical Journal of Pediatrics.

Alcohol and drugs are important factors in crime. However, there is more. It is a sobering thought to read the following quote from a well-known crime novel: "Almost all crimes could be considered as accidents, apart from the armed robberies, that were planned ahead. Unhappy, mangled people, who got, against their will, in hopeless situations. Alcohol and drugs played a role in nearly all cases. In part, you might blame the heat, but mostly is was a matter of the ruthless mechanism of the big city, that grinds the weak and the non-adjusted to pieces, and forced them to commit senseless acts." (Sjöwall & Wahlöö, 1993, p. 132).

(f) Terrorism

Terror means extreme, abject fear (Smith, & O'Loughlin, eds, 1948, p. 1070). A terrorist is someone who wields terror as a tool to arrive at a certain goal, and terrorism is the process. This description is more general than the ten or so descriptions that are given by Whittacker, ed. (2003, p. 3-4). These definitions are from the agencies who at present try to stem in terrorism. They all agree that terrorism is unlawful. They do not, therefore, include state-terrorism that is based in on legal decisions. Still, one might wonder what is the moral status of legal decisions that allow state terrorism, particularly if they are made by authoritarian governments. The crucial aspect of terrorism is that, by using indiscriminate violence that may strike at any moment and may hit any member of society, a constant level of fear is present throughout society. It is said that precisely this was the idea for Lenin to explicitly promote terror in the Bolshevik state: it is a simple and highly effective way to oppress the people and to keep them in line. Clever terrorists do not need to use the violence; the fear itself is enough to reach the goals they have set for themselves.

Although there are no studies on this, it is easy to make a simple cost-benefit approximation for the terrorist attack on Manhattan of 11 September 2001 ('9/11'). Assume that 50 people work on it full-time for 2 years, and that they cost 100 000 Euro per year. Add to this the same amount for equipment, bribes etc. The costs of the attack will be about 20 million Euro. The 'benefits' for the terrorist organization are much higher: 3000 people killed, costing each for insurance, pensions etc. at least 2 million Euro each, plus several thousand millions to clean up Manhattan. This gives a direct cost of some 10 000 million Euro – a benefit-to-cost ratio for the terrorists of 500 to one. If the wars in Afghanistan and Iraq are included, wars that probably would not have been waged, were it not for 9/11, one needs to add another 100 000 million Euro. This would raise the benefit-to-cost ratio for the terrorists to at least 5000 to one. Cynically as it might sound, a very high yield on their investment!

One thing that all terrorists have in common is that they all pretend to have some goal that justifies the means, that justifies the use of violence against innocents. They usually are 'true believers' (Whittacker, ed., 2003, p. 19). This agrees with what is explained in sec. 10.1.9b about conscience. Also, they all have some sort of organization. Terrorists should not be confused with urban guerrillas and other resistance groups, who also fight without any reference to what is considered 'decent' on the battlefield. Their goals are completely different, however. Also, terrorist organizations are completely different from organized crime and from organized hooliganism, who fight essentially only amongst themselves.

The goals of terrorist organizations can be different. Some are listed here; most are discussed in detail in Whittacker, ed. (2003, Part Two, p. 39-249).

(1) To establish a totalitarian political regime, usually Stalinist or Maoist (Red Army Faction in Germany; Shining Path in Peru).
(2) To found a separate State, not a part any more of the state they legally belong to (ETA in Spain; Liberation Tigers in Sri Lanka; PLO in Israel; PKK in Turkey; IRA in Ireland).
(3) Most are, however, Islamic religious organizations. Usually, their goal is to set up an Islamic state with Islamic Law. They fight against infidels and "apostate Muslim governments" (Whittacker, ed., p. 42). The most notorious is Al-Qaida, but similar groups operate in Indonesia, in the Philippines, in Algeria, in Palestine, in Pakistan, in Egypt and many other, mostly Muslim, states.

The way terrorists usually operate is to attack and murder as many innocent bystanders as possible, preferably in a very bloody way, without any warning. The reason for such blood-bath is usually sheer cruelty and blood-thirst, but a major objective is also to attract the highest possible media coverage.

It should be kept in mind that, in most industrialized Western countries, with a few the obvious exceptions, terrorism – either political or otherwise – was until recently, only a minor worry. However, in many parts of Asia, Africa, and Latin America, terrorism has been the order of the day for decades. This changed dramatically since the attack on the World Trade Center in New York on 11 September 2001. Even although many believe that many people, notably the Government of the USA, did grossly over-react, terrorism has become a factor to take into account. It is probably too early for serious, objective studies about modern terrorism to be published, but until now there are no signs that the improvement of the visibility, either by lighting or by cameras, in potential crime scenes is considered as an important crime countermeasure – contrary to street crime and street violence.

Prevention of terrorist attacks are virtually impossible, because the unpredictable nature of the attacks and the vast number of possible targets. So, the defence against terrorist attacks – aptly called 'counter-terrorism' (Whittacker, ed., chapter 19, p. 271-293) – is to attack the organizations. Here we end our remarks about terrorism, because it is a highly sensitive subject that seems to have little to do with lighting.

(h) Conclusions concerning non-lighting studies

The studies quoted in this part of this section, almost exclusively relate to the Netherlands. As follows from the data given under (d) earlier in this section, one may assume that they have some relevance for other industrialized, Western countries, although in detail, considerable differences may occur. The similarity seems, however, sufficiently great to give a number of more generally applicable suggestions that are relevant for the purpose of this book. It should be noted, however, that it is very doubtful that, based on the studies made in the Netherlands, any useful suggestions may be given for developing countries.

The only reason that lighting – and to smaller extent, television surveillance – may contribute to prevent or to reduce crime is actual or potential perpetrators of criminal acts are afraid to be seen and to be recognised. As has been mentioned earlier, there are many types of crime and many types of criminal, so it is no wonder that the lighting studies about crime do not give a clear answer to the question as to whether lighting 'helps'. The main reason to consider non-lighting crime studies in detail is to find out something more about the psychological attitude and the sociological background of perpetrators.

- Political violence and terrorism thrive on the attention of the media; one may expect that the perpetrators actively look for being seen and being recognized;
- Most street violence seems to belong to a specific sub-culture where perpetrators and victims may change role. There is some risk for 'innocent bystanders' to fall victim to the violence. There is no reason the assume that the perpetrators are overly worried by being seen or recognized.
- Vandalism and hooliganism seem, just as street violence, to belong to a specific sub-culture. There is no reason the assume that the perpetrators are overly worried by being seen or recognized.
- Perpetrators of crimes committed under the influence of alcohol or drugs are probably too intoxicated to pay much attention to being seen or recognized.
- The number of reported sexual assaults is limited, but their psychological and social consequences are very severe. Furthermore, one may safely assume that the 'dark number' of not-reported crimes is quite considerable. One may assume that perpetrators and potential perpetrators would prefer dark areas, so that lighting might be an effective countermeasure. The numbers of reported sexual crimes, however, are too small to

allow for statistically significant results. It may be added here, that it is likely that the fear for being a victim of sexual crimes is much more severe than the number of crimes would seem to justify. This fear for crime and the related considerations of subjective safety and amenity are discussed in sec. 12.1.4.

12.1.4 Fear for crime

(a) Objective and subjective social safety

The beneficial effects of the functions quoted above are often considered as very important. More in particular, the subjective aspects of social safety of residents and pedestrians ('fear for crime') and the amenity for residents are considered as being very important. In fact, in many countries, these aspects are the most important for the decision to light roads and streets, both urban and rural. Quantitative data, however, are very sparse. Some of the prevailing considerations are summarized in Schreuder (1989, 1998).

Enquiries showed that the opinion of residents about lighting and crime have three, closely interrelated, aspects:
(1) Amenity (is the situation agreeable?).
(2) Subjective estimates of crime reduction (do people believe that lighting helps against crime?).
(3) Fear of crime (are people less afraid for criminal acts when the lighting is good?).

For feeling secure and for avoiding criminal assault, it is necessary to be able to see the surroundings. So visibility and recognition are important aspects – during the day as well as in darkness. It works two-way: if the potential victim can see the potential aggressor, the aggressor knows that he or she can be seen and easily recognized. There is plenty of proof that this works as an effective deterrent, and not only as a means that pedestrians may feel more secure (Kraay, 1984). And finally, feeling secure is a deterrent of its own right. Most criminals are cowards; they prefer to attack weaker persons, and particularly those who are afraid. And feeling sure is reinforced by surroundings that suggest order – that someone around is caring. It the following part of this section, we will discuss briefly a number of studies related to feelings of security, fear of crime, and amenity.

(b) UK studies

In the UK, a large number of studies have been made regarding lighting and crime. Most have been discussed another sections of this book. In a number of these studies, special attention has been devoted to the relation between lighting and fear of crime. A study in Wandsworth – a part of London – gave seemingly conflicting results. Painter (1999) quotes Atkins et al. (1991): "The dominant pattern was of no significant change in levels of crime. However, womens' perception of safety after dark improved".

From social surveys and local agency initiatives, it is suggested that many people regard well lit streets as an important aspect of crime prevention. Also, crime, poor street lighting, vandalism, and dirty streets are often mentioned in the same context. This is in line with the results of recent studies made in the Netherlands (e.g. Kalisvaart, 1995).

Painter (1999) gives a detailed description of 15 different studies that have been made in the UK between 1987 and 1994. The studies were published since 1988. The original paper gives all relevant references. Some data are discussed as well in another sec. 12.1.2, when discussing the relation between lighting and – objective – crime.

The conclusions of these studies can be summarised as follows: "First there is some evidence that relighting can reduce crime and disorder. Second, there are fairly consistent indications that fears for personal safety and worries about crime are reduced following lighting improvements. Third, there is substantial evidence that relighting increases nighttime street use. Fourth, lighting improvements appear to have a particulary beneficial effect in reducing fear amongst women and elderly people" (Painter, 1999).

It seems that the negative opinion of US researchers regarding the use of statistical material had some influence in that decision. The opinion was quoted by Painter (1999) as follows: "Studies that rely on official statistics will not provide valid results because participation clearly increased the probability of a burglary being reported to the police (After Schneider, 1985)". At the end of the study, Painter states: "Crime was measured by means of victimization surveys rather than relying on official recorded crime data. This helped overcome the major shortcomings of previous research conducted in the USA" (Painter, 1999).

From the 15 studies, 8 show a decrease in crime and disorder. Two studies show an increase whereas 2 more do not show clear effects. The rest did not include this aspect. Painter (1999) concluded from this "that there is some evidence that relighting can reduce crime and disorder".

As regards the impact on attitudes and perceptions, it is stated: "It does appear that street lighting reduces fear among specific population sub-groups. Favourable results have been shown in relation to various indicators of fear, anxiety and worry about crime and disorder. The majority of projects provide strong evidence of fear reducing effect of lighting improvements, while others produce mixed results. There are fairly consistent indications that fears for personal safety and worries about crime are reduced following lighting improvements" (Painter, 1999). Also the impact on pedestrian behaviour, or pedestrian usage, was studied. 9 out of the 11 studies that covered the pedestrian night street use, reported an increase. This is considered as a success. It should be noted, however, that the increase in pedestrian movements will be a confounding factor in crime and probably also in attitudes and perceptions. This point is mentioned by Painter (1999).

Finally, some cost-benefit studies were made. For a number of the cases quoted earlier, an estimate of the cost-effectiveness of road lighting was assessed (Painter & Farrington, 1999). The study areas were two of the earlier locations. The lighting was brought up to meet the current British Standard (BS 5489, Part 3; Painter & Farrington, 1999, p. 20). The costs of the improved lighting was compared to the cost of the crimes 'saved' by the lighting. This saving was based on the assumption that the crime rates would be equal without the improvement of the lighting; thus, the crime reduction can be attributed to the lighting. It should be stressed that in this case, control groups were used. The monetary values are given in the paper (Painter & Farrington, 1999, p. 27). In a conclusion, it is stated that "The tangible savings from crimes prevented more that paid off the full capital costs within one year. The most conservative benefit-to-cost ratios after one year were 2,4 to 1 and 1,3 to 1 in the two cases respectively (Painter & Farrington, 1999, p. 29).

These conclusions are very impressive. It reinforces the conclusions from other studies that, at least for certain types of crime and in certain locations, lighting often is a very effective crime countermeasure.

It follows from these and similar studies, quoted by Painter (1999), that it not correct to dump all sorts of criminal and other socially unacceptable behaviour on one heap, together with experiences of the people living in the area.

(c) *Japanese studies*

In 1989, a study was published concerning the relationship between street robbery (the study speaks of 'snatch away') and the lighting level. The research was carried out in the Tokyo and Osaka regions. Further details are not mentioned. The results are given in number of incidents per 10 000 inhabitants; the light level is expressed in lumen/m^2. See Table 12.1.30 (Anon 1989).

Light level (lumen/m^2)	**Number of incidents**
0,35	1,65
0,4	1,75
0,6	2,15
1,3	1,0
1,3	1,3
1,35	2,4
1,5	0,7
1,55	1,35
1,8	1,5
2,05	0,55
2,3	0,85
2,45	0,6

Table 12.1.30: *Relation between robbery and light level (rounded off values; based on data from Anon. 1989)*

(d) Victim support study

In the Netherlands, the specialized organization that supports victims of accidents and of crimes, made in 2002 a survey under 2888 people (Anon., 2002b). The sample is not fully representative for the whole population of the Netherlands, but the results may still give a good idea about the state of affairs.

It was found that 54% of the respondents thought that the country is unsafe. Frequent victims, however, feel more unsafe than the average. See Table 12.1.31.

Opinion (%)		**Victimization**	
	never	**once**	**more often**
never unsafe	6	37	2
seldom unsafe	37	30	22
sometimes unsafe	54	62	62
often unsafe	3	5	13

Table 12.1.31: *Feelings of being unsafe. After Anon., 2002b, p. 2.*

Crime was considered far out the most common ground for feeling unsafe. Crime scored 84%, road accidents 11%, calamities 2% and other aspects 5% (Anon., 2002b, p. 1).

(e) Face recognition

It is generally assumed that being able to recognize a face at a certain distance is one of the major benefits of outdoor lighting as a crime prevention measure. A study that was set up for face recognition in court rooms during trials might be of interest here (Wagenaar & Van der Schrier, 1996). The diagnostic value – defined as the ratio between hits and false alarms – was determined in relation to the ambient lighting level and the distance. It was assumed that the diagnostic value should be at least 15. According to other authors, that value should be at least 200 in court cases (Wigmore, 1937). The value of 15 seems to be an acceptable, be it not very good, value in the fight against street crime. In order to reach that value, the illuminance should be at least 15 lux and the distance not more than 15 m. It should be noted that the recognition was made on photographs, that the illuminance is that on the vertical plane of the picture, simulating the real situation. The distance was simulated by enlarging the picture. If it assumed that the results can be applied to the actual street scene, it would imply that street lighting levels that are considered 'normal' are far too low for this purpose (CEN, 2002, 2002a; CIE, 1992a; NSVV, 1990). Although it is not certain how far these results are relevant for the night scene outdoors, but it seems that the study deserves further consideration.

It is interesting to compare these results with the work that has been done for facial recognition under office working conditions (De Boer & Fisher, 1981, p. 35-37). The aim of the study was to determine the luminance of the face so that the features were recognizable. Three conditions were involved, of which two are relevant for our study:

(1) The lighting on the face is just acceptable (i.e. the features are recognizable without any special effort on the part of the observer).
(2) The features are just recognizable.

The results are that, in case the face is seen against a relatively dark background (no background glare), the luminance should be at least 17 cd/m^2 for condition (1) and 1 cd/m^2 for condition (2). De Boer & Fisher (1981, p. 37) have assumed an average reflectance of 40% of the human facial skin, so that the vertical illuminance must be about 130 lux for condition (1) and 8 lux for condition (2). The original investigations are made by Fischer (1973). De Boer & Fisher (1981, p. 37) state that the minimum for (1) is 100 lux and that for office work, 200 lux is recommended. It should be noted that the reflectance used by De Boer & Fisher (1981, p. 37) relates to Caucasians; people from other ethnical groups have darker – often very much darker – skin, so that the illuminance values needed are considerably higher than those quoted by De Boer & Fisher (1981). The condition (2) 'just recognizable' seems to be similar to that used by Wagenaar & Van der Schrier (1996) for the 'diagnostic value' of 15. They seem to have used a mixture of people with different "racial features" (Wagenaar & Van der Schrier, 1996, p. 323). Assuming that the experimental conditions are comparable, the minimum illuminance values of the two studies are similar.

It should be noted that Schreuder (1977, 1979), in discussing the lighting of residential yards ('home-zones' or 'woonerf'), concluded from the same study of Fischer (1973) that 1 lux horizontal was sufficient as a minimum on the road surface. Even that value is much higher that the minimum value one might encounter in real streets, even if they comply to accepted standards or recommendations. The recommendations of the Netherlands allow for certain situations a minimum of $0{,}2 \cdot 3 = 0{,}6$ lux (NSVV, 1990).

Another study on facial recognition was made by Caminada & Van Bommel (1980). See also Van Bommel & Caminada (1983) and Van Bommel & De Boer (1980, p. 261-262). As a metric for the lighting level (lighting quality) the semi-cylindrical illuminance was introduced. See Schreuder (1998). It was found that for facial recognition at 4 m distance, a semi-cylindrical illuminance of 0,8 lux was sufficient. As there is no simple way to convert semi-cylindrical illuminances into vertical illuminances (that is the reason to use the complicated metric of the semi-cylindrical illuminance in the first place) the results of Caminada & Van Bommel (1980) cannot be compared directly to those of Fisher (1973), De Boer & Fischer (1981) and Wagenaar & Van der Schrier (1996). The illuminance sufficient for facial recognition seems, however, to be much lower. It may be the results of differences in the experimental set-up. The experiments of Caminada & Van Bommel (1980) were done in real streets in nighttime conditions, and not in a laboratory with simulated persons.

In Japan, similar studies have been made in order to find the lighting levels that needed for the security of pedestrians (Miyamae & Takeuchi, 1989). It was found by means of simulator experiments in the laboratory, that with a vertical illuminance of 1 lux and 2,1 lux on the face of on-coming strangers, their eyes, nose and mouth can be discerned at a distance from the observer of 4 m and 10 m, respectively. When the vertical illuminance is 1,8 and 5,0 lux, the persons can be recognised at a distance from the observer of 4 m and 10 m, respectively. The report also contains a survey of existing lighting installations in various towns like e.g. Osaka, Hyogo (Kobe) and Kyoto.

In conclusion one may state that the studies quoted here, give different results, but they all seem to point towards requirements that are higher, often very much higher, than is customary in road and street lighting at present. If this proves to be true for many different conditions, it might lead to recommendations for much higher lighting levels in areas with severe crime hazards.

12.1.5 Amenity

(a) Studies related to amenity and the fear for crime

Feeling secure is a major function of public lighting. This, strange as it may seem, is a quite recent idea. Until recently, the amenity and the crime prevention were almost completely disregarded in lighting considerations; and lighting was even more completely neglected in criminological studies. Lighting engineers and architects did, however, pay a lot of attention to the aesthetics of lighting. In the Netherlands, this changed only when – after a considerable amount of political pressure – a parliamentary commission was established to study the 'petty crime'. According to Dutch custom, the commission was named after its chairman: the 'Commission Roethof' (Anon., 1986). In other countries similar activities were launched, mainly under feminist pressure. At the CIE Congress in Venice (Italy), a first attempt was launched to study this aspect more systematically, and more in detail (CIE, 1987). Some of the considerations have been incorporated in the CIE Guide on Lighting for Urban Areas (CIE, 1992a). See also Zebun Nasreen Ahmed (2000). However, until now, little of the material can be used in a general way.

(b) Residents' opinion about lighting

In the early 1980s, the aftermath of the 'oil crisis' enticed may authorities to reduce energy consumption in all possible ways. One way was to use high-efficiency light sources for street lighting. High-pressure sodium lamps, and particulary low-pressure sodium lamps were widely introduced, and high-pressure mercury lamps and fluorescent tubes were gradually phased out, the main consideration being the luminous efficacy (lumens per Watt). In many residential areas, old fluorescent and mercury lighting were replaced by low-pressure sodium lamps. These lamps, being monochromatic, do not permit colour recognition. As was mentioned before, however, prevention of crime, and of the fear of crime, for which colour recognition might be important, did not come into the picture, and neither did the opinion of the residents.

In one or two places, protests of residents that came after such conversions, necessitated some action of the authorities. The first was a small section of the Dutch city of Schiedam, where all residential streets were converted to low-pressure sodium. In a small review-type study the converted streets were compared to streets with 'old' (usually fluorescent tube type) lighting. The illuminance levels in the study ranged from 1,7 to 14,7 lux. The study led to interesting results. At the one hand it turned out that for visibility (seeing obstacles like dog-droppings and loose pavement stones) the light level and not the colour of the light was considered as important. A level of 3 to 4 lux was usually considered as adequate – slightly above the level recommended by NSVV (1990). When, however, people were asked whether they liked the lighting, the general opinion was that the low-pressure sodium lighting was "ugly" or "eerie". The size of the study does not, however, permit robust conclusions (Schreuder, 1989, 1989a,b).

A second study was made in Utrecht. In a residential area with several thousand inhabitants, the existing lighting of varying age, type and quality was replaced by a lighting that was in agreement with the recommendations (NSVV, 1990) with the additional requirement that the semi-cylindrical illuminance should be at least 0,5, even in the darkest spots. The relighting involved a complete new lighting design; not only new lamps, but also new luminaires and if required, new columns were installed. The number of columns, however, was kept the same. Enquiries have been made before and after the relighting. The final results are not published, but a preliminary analysis showed that the feeling of safety and the opinion about the lighting did improve. As at the time of the Utrecht studies, compact fluorescent lamps had become available and were used at a large scale, these lamps were included in the study. The opinions of the lamps were rated in an ordinal scale from 1 to 10. It seems that the lamp type is not an important contributing factor in the overall opinion of the residents. The author concludes that the general impression is determined primarily by other factors (Van Tilborg, 1991). This conclusion is in line with the conclusion of other studies (Anon, 1991).

More recently, a study about the subjective safety was held in Zoetermeer (Kalisvaart, (1995). Zoetermeer is a medium-sized new city, close to The Hague. It has some 110 000 inhabitants. Of these, about 2000 took part in the study. The overall response was 73% (Kalisvaart, 1995, p. 3-4). The number of respondents differ for different questions.

A number of interesting data have been assembled. 48% of respondents consider specific locations in their direct neighbourhood as being unsafe. The causes they were given for this are listed in Table 12.1.32.

Causes for feeling unsafe	Percentage
insufficient street lighting	39,7
quiet/no people	27,8
own experience	11,9
too much greenery	10,2
other reasons	10,4
total (n = 891)	100%

Table 12.1.32: *Causes for feeling unsafe (Kalisvaart, 1995, p. 5-6, fig. 1, table 2.1).*

Note: the responses relate to both day and night. The number of 'own experience' is astonishingly high.

Another striking aspect is that 36% consider specific locations in their direct neighbourhood as being poorly lit. The causes given for this are listed in Table 12.1.33.

Neighbourhood lighting	Percentage
light level too low	36,9
no street lighting	34,3
light shielded by greenery	12,0
poor position of lighting	5,0
defective lamps	4,3
other	7,5
total (n = 601)	100%

Table 12.1.33: *Complaints about poor lighting (Kalisvaart, 1995, p. 7-8, fig. 2, table 2.2).*

Note: about one third (34,3%) of the complaints is about the absence of street lighting. Usually, it is assumed that in the Netherlands, all roads and streets within built-up areas have public lighting. Well over half (54%) are related to design errors; only just over 4% have to do with poor maintenance.

The appraisal of the road and street lighting differs considerably for different locations. See Table 12.1.34.

Location	good %	average %	poor %	total
shopping centers	92,5	7,0	0,4	1369
through roads	88,5	10,2	1,21	309
railway stations	70,9	23,0	6,1	1139
residential areas	68,0	29,1	2,9	1333
crosswalks	64,0	29,7	6,3	1217
pedestrian underpasses	47,7	37,6	14,7	1121
industrial estates	44,0	40,0	16,1	523
in and around schools	38,5	44,4	17,3	820
in and around apartments	37,9	48,9	13,3	864
parking garages	27,7	51,3	21,0	1112
walkways	27,7	54,0	18,2	1168
dog toilet areas	16,9	48,6	34,5	391
parks	14,2	50,2	35,6	1051
back alleys	10,6	39,9	49,5	1140

Table 12.1.34: *Street lighting appraisals (Kalisvaart, 1995, p. 26, annex 14). The data are arranged from high to low according to the appraisal 'good'. They do not always add up to 100% as a result of rounding off.*

(c) *Five criteria for social safety*

The work of the Commission Roethof that was quoted earlier (Anon. 1986), triggered a lot of activities in the Netherlands. The main reason seems to be that in the male-oriented world of that time, the typical problems of women were only just beginning to be recognized. The work was mainly initiated by the Ministry of Culture and Social Affairs. Most of the work was carried out by the (no longer existing) Consulting Company AREA and the Stichting Vrouwen Bouwen Wonen (the Women Build and Live Foundation). See Anon. (1987a; 1989a; 1991; 1991a; 1994); Hajonides et al. (1987); Huijben, ed. (2003):

The studies included some theoretical investigations but were mainly based on 'in situ' inspection of 'weird places'. The studies resulted in the formulation of the 'Five criteria for social safety':

(1) Presence of social control – supervision and surveillance. This point is rather obvious, and it includes supervision by casual bystanders or systematic surveillance;
(2) Absence of potential criminals. Usually this means that areas with high crime rates or high crime menace are avoided. On private premises it is often possible to refuse admittance to suspect persons, but on public premisses this is often difficult or impossible;
(3) Visibility. The lighting must be adequate, but also it is important to avoid other restrictions to the visibility. Shrubs should be trimmed, pillars and recessed doors avoided etc. If one cannot see anything, surveillance is not effective;
(4) The situation must be clear. One should be able to find the destination easily, and also have escape routes available if necessary;

(5) The surroundings should look attractive. Clear, clean and well-maintained surroundings make it clear that there are people around who care, and suggest that they may be nearby. This is a reinforcement for the patrons of the accommodations, and a deterrent for the potential criminals.

12.1.6 Urban beautification

(a) Cities and people

In sec. 2.4, city beautification is discussed in detail, focussing on the role it may play in the social development of urban areas. In this section, emphasis will be placed on the lighttechnical characteristics of lighting for city beautification as well as on its impact on the environment. See also Schreuder (2001, 2001a).

Cities have a function, and the aim of beautification is to enhance that function. The function of cities cannot be isolated from the motives of their inhabitants. When we look at the cities of today, it is easy to discern two main types. The first is the type of city that grew in an organic way out of a functional basis. As Mumford (1961) in his classical study did show, the basis may be threefold: commerce or strategy or religion. Commercial cities are located at rivers or at the seaside or usually on both. Strategic cities are located at places where armies might march, either by land or by sea. The religion-based cities are located at a place where religious functions are performed, usually combined with sanctuaries for pilgrimages. In many cases, it is possible to trace down a village or hamlet that was there first; however, some cities are founded straight-away. Examples of these are the so-called 'New Towns'.

There is another type of cities as well, which is not considered by Mumford (1961). These are the cities that did not grow organically and functionally. These are the cities that have been founded by bosses like emperors, dictators, or sometimes ordinary presidents, in order to exercise their power. They needed a seat of government, which in effect means a seat for the burgeoning bureaucracies. In spite of the fact that many of them are quite large, they are not living organisms but lifeless constructions. Sometimes, after several centuries, natural urban growth starts, in spite of the unfavourable conditions and some semblance of a real city begins to show itself. Thus, in summary, the function of cities can be one or more of four: commerce, strategy, religion, or status.

Usually, cities grow out of towns and towns grow out of villages and hamlets. Usually, this growth is more like a series of sudden changes and, between them, sort of continuous plateaus. For animals, similar processes are described by Gould (1989) and Mithen (1996). Cities grow by people migrating towards them, bringing their skills and their wealth with them. Real cities are the people, but they are more: as in many other cases, the total is more than the sum of the parts. Cities are more than just the sum of the people. As commerce and religion at the one hand and military aggression at the other hand grew and became more global, the cities grew in response. People come to those cites with a purpose in mind. They expect to find jobs in trade, in religion, or in the military. Cities grow because they fulfill a purpose in the pattern of society. They start to grow from villages by a chance process called contingency and they continue to grow by the process of 'big eats small'. The growth process itself is, of course, the result of people flocking into the cities, bringing along their skills, their wealth and their creativity.

Apart for all those people who have decided for themselves to come to the cities, there is of course a large number of people who do not like the city at all, but who fly from the countryside because they face certain death – or worse – by the hand of cruel landowners, warlords, or by famines organized by unscrupulous traders. They come to the cities with some slim hope to survive at least a little longer. Usually the try to eke out a living at the outskirts of the cities in 'shanty towns' that, as a result of the negligence and meanness of city governments, have no facilities like paved roads, schools, medical care, clean water or sewage. Shanty towns are riddled by crime, ignorance, and all sorts of epidemics. The life is destitute and the people are without hope – indeed, without any resemblance of a human existence. The process is described by Schreuder (1994).

Cities are populated by people coming from elsewhere often from other countries or even other continents. As an example, more that 50% of the population of the cities Amsterdam, Rotterdam, and a few other towns in the Netherlands are immigrants from outside Europe. Immigrants are strangers looking for a new life, a new home. They have left their home, their secure place in the social structure, often their family and always their culture behind them. Founding a 'China-town' in a Western-European city is no China! Coming to the city is for most people a complete breach with all common and traditional aspects of life. In order to survive as a human being, they must be able to identify with their new home. If they are not in the position to do so, they end up as human flotsam as described by Schreuder (1994).

It is well-known that the material and immaterial conditions are essential. For a life worth living, a number of basic requirements must be met: no crime, good living conditions both material (water, sewers, electricity) as well as non-material (social contacts, schools, amenity, hospitals, child care). In short, making the city a place worth living in. In summary, people living in present-day cities usually are strangers to the new life. If they are lucky and if they have the right type of motivation, they will succeed in finding a new identity with – and within – the city; the city will be their new home. Many of those that are not so lucky, live a life in squalor and degradation that often cannot be called human at all. Still, they are fellow human beings! One way to help them a little in finding the first step of the ladder out of the squalor may be to help them to find some pride in the city – to help them to feel the city also a little as 'their' city.

(b) We love our city

In the squalid conditions in shanty towns, there is not much desirable in life there. However, if it is possible to arouse the positive attitudes of human beings by boosting the stress-increasing motivations and thus to make people more responsive, more creative and more undertaking, a 'flip-over' might be possible. Flip-overs are known to happen frequently; they are characterized by reversing the feedback spiral from negative into positive.

It begins in the neighbourhood. When people in their own neighbourhood start to improve their own streets, to make them more enjoyable, the city governments will respond by making more means available. With this money the larger infrastructural works may be paid, such as paving roads, putting in water and electricity, improving sewage systems, promoting public transport etc. This will automatically lead to a further increase in self-esteem of the people and to the wish for better conditions on cultural and societal areas such as public safety and crime prevention, schooling, creation of jobs etc. In the end-phase, the flip-over results in a positive attitude of the people towards the city: they begin to love their city. This process of reversing the attitude is no Utopia. It is known to have worked in many cities, particularly in the slum areas.

As most people are not satisfied with loving the city in an abstract fashion, the affection usually focusses on a distinct part of the city. This what we may call the emotional city centre. At that place the things happen that really matter for the people; it is the place where they automatically assemble when memorable things happen – both happy and sad. It is the place where revolutions are proclaimed, where Olympic champions are honored, where artists and party-goers concentrate. In many countries, that emotional centre may function not only for that particular city but even for the whole country.

(c) City beautification

City beautification is a new concept. It may be described as a complex of measures that make a liveable city more liveable. Taking care of basic requirements like pavements or plumbing are essential but they do not qualify as city beautification. Making a city a place where human beings may live a decent life requires a large complex of measures – many of them having been mentioned earlier – like e.g. absence of crime, material conditions like water, sewers, electricity as well as non-material conditions like jobs, schools, hospitals, etc. This is the basic condition for making a large group of people living in a decent way close together into a city. It is the difference between a large village and a city.

City beautification is the set of measures that are implemented up and above the base minimum, material and immaterial, requirements. It is what makes life enjoyable and not just liveable. It is not a luxury, however. Human creativity, human dignity requires a set of conditions that are more than just the necessities. In short, making the city a place worth living in – making a city a place to love and to be proud of.

When we describe city beautification in this way, it is clear that a number of requirements must be fulfilled in order for any scheme to be successful:

(1) The scheme must represent the city. It must personify the love and pride the people have for their city. It must have some direct relation to the city and its characteristics.
(2) It must be recognized and appreciated by the people for whom it is meant. If the people feel that the scheme is wasteful or ugly, whatever you may do will be a failure.

(3) It must be functional. People must be able to 'do' something with it. A collection of statues might be a good element but only if you can walk between them, if you can sit on them courting, if children are allowed to climb on them.
(4) It must be functional throughout the whole day and night, in rain, sunshine or frost. If the emotional centre is invisible at night, it simply never can be a real emotional centre – if only because most nice and festive things happen at night!

(d) City beautification, amenity and fear for crime

City beautification starts with the maintenance. A scheme of whatever type that is not maintained well, will have an adverse effect. A dirty or damaged statue, a fountain that does not work, floodlighting that works spastically or that causes glare, will emphasize the negative aspects of the surroundings. Maintaining the scheme, keeping the surroundings clean and free from graffiti is one of the major aspects of making a city environments safe – not only enhancing the subjective feeling of safety but actually reducing the crime frequency – the objective safety. These aspects are discussed in sec. 12.1.4. A derelict scheme for so-called city beautification is worse than no scheme at all. This can be illustrated by the 'Five criteria for social safety', that are discussed in sec. 12.1.5c.

City centres are supposed to attract people – as we have seen, that is the whole purpose of them being the emotional centre of the city. When the people who enjoy the city are attracted, also other, less welcome, persons will be attracted. Making the centre attractive to the inhabitants means invariably also to make it attractive to drug addicts who in their wake attract drug dealers and the criminals associated with them, particularly prostitutes and muggers. Additionally, an attractive city centre is a welcome place for vandals and hooligans to disturb the peaceful gathering of people and to destroy whatever nice and beautiful things are set up.

In order to keep al these elements in check, a good lighting is needed. As is explained in sec. 12.1.4, crime studies made it clear that good lighting improves the atmosphere and reduces crime, vandalism etc. (Painter, 1999; Schreuder, 2000). The studies reported by Painter did show, however, a clear dilemma. At the one hand, good lighting makes the surroundings more agreeable, as is shown in other studies as well. At the other hand, good lighting attracts criminally inclined individuals, particularly male juvenile delinquents who make life miserable for passers-by and for residents alike – even if the actual number of severe criminal acts may be rather small. The answer is not to decrease the lighting although this has been suggested by several persons. The answer is in the first place to make the lighting installation itself and all the other city beautification elements vandal-proof, as they are likely to be the first elements to be vandalized or destroyed. But more important is to have a good surveillance system. Experience did show that in this respect both TV-surveillance and personal (police) surveillance are effective, and that the best results follow from a combination of the two. The lighting installation shall be such that the surveillance can be made effectively, also in rain or fog. It seems, however, that the requirements that have to be fulfilled for adequate city beautification lighting, are sufficient for surveillance as well.

12.2 Automobile lighting

12.2.1 Light pollution by vehicle headlamps.

In Chapter 2 of this book, the place of automobile headlighting in the total area of outdoor lighting is discussed in some detail. In this section, the emphasis is on the technical aspects of the lighting on the one hand and on the light pollution aspects on the other hand.

Vehicle headlighting has been an area of intensive research for many decades now. In the past, most research was carried out by road safety institutes, but in the last two decades or so, the research is almost completely done by the car lighting industry. New ideas and new products focus on the improvement of the visibility for the car driver. They all, invariably, increase glare for other road users. Much of the research results are summarized here. A more complete treatment of the earlier research is given in OECD (1972, 1980) and Schreuder (1976, 1976 a,b). The research of the 1980s is discussed in detail in Schreuder & Lindeijer (1987) and Schoon & Schreuder (1993). The results of recent research and development are discussed in great detail in the proceedings of the bi-annual PAL-conferences "Progress in Automobile Lighting", held in Darmstadt, Germany (Anon., 1991b, 1997, 1999e, 2001b, 2003b).

As is indicated earlier, the contribution of car headlighting to light pollution has never been studied in detail. Casual observation from hills, or from airplanes, shows clearly that the contribution may at times be considerable, more in particular in the directions just above and close to the horizon. Satellite studies did show that in the photographs taken from a satellite, a great number of bright points can be seen along the trunk roads carrying heavy traffic at night throughout the major island of Japan. However, most rural roads do not have continuous road lighting. The bright points seen on these roads are lights from the headlights of automobiles travelling on these roads. This evidently shows that the automobile headlights are one of the sources of light pollution emitting a considerable amount of the luminous flux in the upward directions (Narisada & Kawakami, 1998).

It is also reported by Petrakis (2003) that satellite images are capable of showing the headlights of individual cars.

In sec. 3.3.4, it is explained in detail why these directions are more in particular the 'light-pollution sensitive' directions.

On the basis of such casual observations from hills and from airplanes, one may assume that, in densely populated areas, the contribution of vehicle headlighting to the light pollution is small compared to that of other, fixed, outdoor lighting like street and area lighting. However, in sparsely populated areas, there is usually hardly any fixed outdoor lighting, or none at all. So all light pollution in those areas will come from vehicle headlighting. This is a more pressing situation because, obviously, it is in particular the sparely populated areas that are preferred to locate astronomical observatories. So it is important to know more about light pollution from vehicle lighting. Because no reliable data exist, it is necessary to make some estimates of the effects.

The point has been discussed briefly in a qualitative way in Anon. (1981). That report discusses ways to reduce energy consumption for fixed and vehicular lighting. One interesting item is the energy use. The overall electricity use for lighting is discussed in sec. 1.2.2. In the USA, electric energy amounted in 1976 to 28 % of the total gross energy use of the US, amounting to $1800 \cdot 10^9$ kWh. From this, $14{,}4 \cdot 10^9$ kWh was used for fixed lighting, less than 0,8% of electric energy and less than 0,2% of all energy. These data are almost in line with more recent data as given in Schreuder (1998, sec. 14.2.2.). Expressed in barrels of oil, daily the fixed lighting energy use in the USA was just over 18 000 bbls in 1976; for vehicular lighting consumption, the same amount of 18 000 bbls of oil per day were used. These data suggest the importance of energy use by car headlights, although the comparison has little value when the proportion of night time traffic on different road classes and the proportion of lighted roads are not indicated. It should be noted, that the quote is probably not completely correct, because it seems strange that for fixed lighting and for vehicular lighting, exactly the same amount of energy would be used. In spite of this, it seems to be worth while to quote this report.

12.2.2 The overall characteristics of vehicle lighting

(a) *Lighting and marking*

It is customary to make a distinction between vehicle lighting, vehicle marking and vehicle signalling. The main difference is, that vehicle lighting refers to the illumination of objects on or near the road in order to provide visual information for the driver, whereas vehicle marking and vehicle signalling refer to light equipment on the vehicle that signal the position of the vehicle or the changes – and the intended changes – in the position. Vehicle lighting requires a high luminous intensity from the lighting equipment because objects need to be illuminated. The luminous intensity from the lighting equipment for marking and signalling needs only to be modest, because the equipment itself serves as the source of information. The illumination is provided by the vehicle headlights. The differences between lighting and signalling are discussed in detail in Roszbach, 1972; Schreuder, 1972, 1976, 1976a,b; Schreuder & Carlquist, 1969; Schreuder & Lindeijer, 1987.

Historically, vehicle headlighting was meant to assist car drivers in their driving at night on road without overhead, fixed lighting. In sec. 12.2.4, details about the history of vehicle lighting are given. In the years before around 1920, night traffic was very limited. The situations where drivers did meet others that drove in the opposite direction, were rare. The lighting could be designed for the situation without opposing traffic. In modern traffic, this is usually not the case any more. The traffic is such that the meeting situation is common. This means that car headlights must be designed according to a compromise between much light (for one's own sake) and little glare (for the sake of the opposing driver). One must not forget, of course, that meeting drivers are mutually opposing! As is explained in the following parts of this chapter, almost all effort into improving vehicle headlighting systems is to try and reach an even better compromise between light and glare.

(b) Optical considerations

Car headlamps are aimed in such a way that the main luminous flux is emitted in a direction that is almost parallel to the road surface. Only in this way the required 'reach' of headlamp beams can be realized. Traditionally, headlamp systems have two beams; the 'driving beam' that is used when there is no opposing traffic, and the 'passing beam' that is used when other traffic is met. In two-beam systems, the beams usually are called the high beam and the low beam, each having its own beam pattern. In the modern lighting systems that are discussed in sec. 12.2.5, one would rather speak of different modes than of different beams or different beam patterns. To have some idea about the possible impact of vehicle headlighting on light pollution, we will discuss briefly the characteristics of headlamps, beginning with some considerations about the visibility, and following this with a historical overview. Further details can be found in Schreuder & Lindeijer (1987, sec. 2.1).

Here, we come back to the best compromise between light and glare, because in almost all cases, vehicle headlights are mounted lower than the eye height of drivers of normal cars and trucks. This means that the maximum reach can be arrived at when the amount of light just under the horizon is as large as possible, because that will not cause direct glare for opposing drivers. The direct glare for opposing drivers is a minimum when the amount of light just above the horizon is as small as possible. What is needed, therefore, is a steep decrease in luminous intensity when crossing the horizon from below. Such steep decrease is called the coupure or cut-off (Anon., 2001a, sec. 6.2.1, p.10). This coupure is the most essential feature of passing-beam headlighting systems.

In the past, a working group in CIE tried to define of the cut-off – or coupure – of vehicle headlights. Only a draft report resulted from the work, although it still seems to be important (CIE, 1992c). According to the draft report, a definition of the cut-off is needed because the regulations require one (CIE, 1992, p. 1). This is a strange turn-around of the matter. Why a sharp cut-off is needed is not discussed in the report; it is only hinted that it is needed because one wants high values of the illuminance on the road (CIE, 1992, p. 11). Because the need of a sharp cut-off is not discussed, this report will probably only add to the wish for more light just in front of the car. In sec. 12.2.7, it is explained that this increase does not add to the visibility but it does add to the light pollution.

Traditionally, such sharp coupures were made by placing a filament in the symmetry axis of a parabolic reflector, but slightly before the focus. This contrary to the beam of the driving beam, where a filament was placed right in the focal point of the parabola. Incidently, this arrangement allowed to place both filaments into one bulb; going from the driving beam towards the passing beam required just to switch out the one filament and to switch on the other. No moving parts were needed. The sharp cut-off of the coupure was realized by placing an opaque screen just under the passing beam filament. This allowed only light directed under the horizon to leave the lamp. The principle is depicted in Figure 12.2.1.

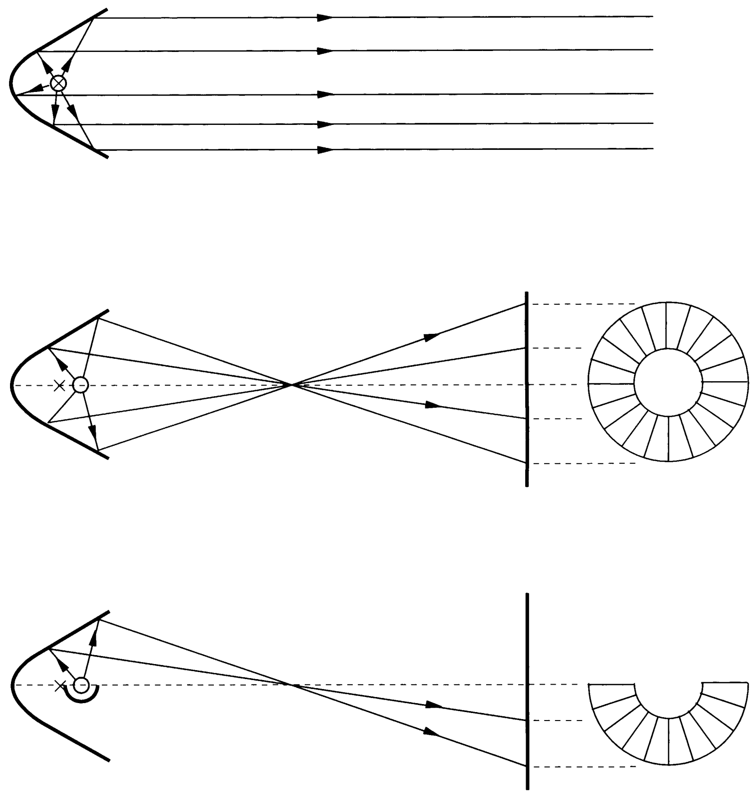

Figure 12.2.1: The optical principle of vehicle headlamps. After Schreuder & Lindeijer, 1987, Figure 1.

In Figure 12.2.1a, the standardized measuring screen for right-hand traffic, that is used for measurements, is depicted.

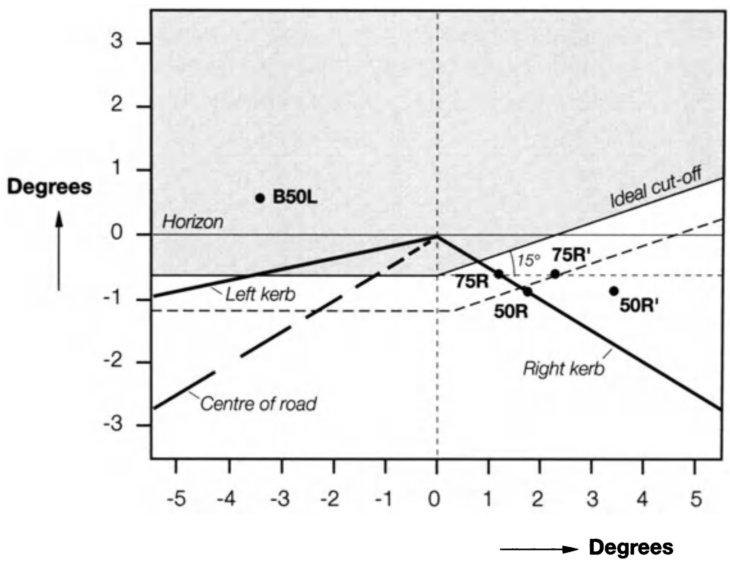

Figure 12.2.1a: *The standardized measuring screen for measurements. After Schreuder & Lindeijer, 1987, Annex 1, Figure 1.*

12.2.3 Visibility when using car headlighting

In those regions of the world where meetings at night between cars traveling in opposite direction on the same carriage-way is common – that is, on two way, two lane roads – is it customary to aim the car headlamps in such a way that the main luminous flux is emitted in a direction that is almost parallel to the road surface. The objective is to illuminate obstacles that represent traffic hazards. If such obstacles are hit, an accident would occur.

A numerical relation to define the reach of vehicle headlamps in terms of visibility is reported by Kosmakta (1995). Based on earlier research of Olson et al. (1990), Meese & Westlake (1975), Roper & Howard (1938) and Hills (1976), the following relation was derived for the illumination directed at an object, for a non-expectant driver:

$$E = I \cdot \frac{1}{d^2} \cdot A_a \cdot f \qquad [12.2.1]$$

with
E = illuminance (lux);
I = total luminous intensity of the headlamps (cd);
d = distance (m);
A_a = atmospheric attenuation;
f = light occlusion factor by dirt or moisture on the lens (Kosmatka, 1995, eq. 7).

The equation [12.2.1] can also be written as:

$$I = \frac{E \cdot d^2}{A_a \cdot f} \qquad [12.2.2]$$

It was found that for all distances up to about 190 m, the high beams of current headlamps provided more than the required illuminance. For that distance, the required illuminance is about 2,8 lux – the break-even point (Kosmatka, 1995, Figure 1).

For the break-even point, I = $(E \cdot d^2)$, I is just over 100 000 cd. As is explained in sec. 3.3.4, such high values of the luminous intensity directed right at the horizon, will cause considerable light pollution.

It should be noted that the original publication is not very clear about the units or the numerical values involved. As glare is not considered, it might be assumed that the considerations are made for high beam lighting.

As is explained in sec. 10.3.1, such objects are called 'traffic obstacles', contrary to 'visually critical objects' that are used to describe the visual aspect of the driving task (Padmos, 1984: Schreuder, 1984; see also Schreuder, 1998, sec. 8.2.3). The direct consequence is, that reach of the lighting system must be at least equal to the 'preview' distance – the distance over which the driver can overlook the road ahead. The required preview depends, as is explained in sec. 10.4.3, amongst others on the type of manoeuvre that is made necessary by the obstacle (Schreuder, 1991). Usually, one considers the manoeuvre "stop in front of a stationary obstacle" as the most crucial. So, finally, the foresight and thus the reach of the lighting system must be at least equal to the stopping distance.

As an example, values of the stopping distance are given for different situations in Table 12.2.1.

T	a	v	s	v	s	v	s	v	s
1	2	10	35	20	120	30	255	50	675
3	2	10	55	20	160	30	315	50	775
1	5	10	20	20	60	30	120	50	300
3	5	10	40	20	100	30	180	50	400
1	7	10	17	20	48	30	94	50	229
3	7	10	37	20	89	30	154	50	328

Table 12.2.1: *The stopping distance (m) for different values of the reaction time T (sec), the speed v (m/s) and the retardation a (m/s²). After Schreuder 1998, table 8.2.2.*

From Table 12.2.1, it follows that for a speed of 30 m/s (about 100 km/h) and for the values of the reaction time and the retardation that relate to an emergency stop, the stopping distance – and thus the reach of the lighting system – must be 120 m; for normal driving, it must be over 300 m. Considering that for optical reasons, the reach of low beams cannot be much more than 80 m, the maximum speed while driving on low beams should not be over about 20 m/s (some 70 km/h) for emergency situations and just over 10 m/s (about 40 km/h) for normal driving. Nevertheless, driving speeds 120 km/h on unlit motorways are legally permitted in almost all countries of the world, and often still considerably higher. Thus, there is a large discrepancy between the 'supply' and the 'demand' of visual information. These concepts are explained in sec. 10.3.1b. See also Schreuder (1998, sec. 10.1.3) and Schreuder (1977a; 1998b). Strangely enough, this discrepancy is accepted in all countries without any serious complaint, although in the past it has played a role in the considerations of motorway lighting, in particular in Belgium (Boereboom, 1966). Indeed, almost all motorways in Belgium have overhead street lighting, much to the chagrin of astronomers! See also Forcolini (1993, fig. 6). At present, motorways are not lit 'as a matter of principle' (Germany; Pfundt, 1986), or only if the traffic density is very high (The Netherlands; ROA, 1990; RONA, 1990; Schreuder, 1998, Chapter 10). Also lighting is considered necessary if the driving task is very difficult (Schreuder, 2000b; IJsselstijn, 2000).

Usually, the performance of a road traffic lighting system is expressed in terms of the visibility distance. This, in turn, can be quantified by the required preview (Schreuder, 1998, sec. 8.2.2) or by the required visibility level (Adrian, 1993; Gallagher et al. 1973; Janoff 1993; see also Schreuder, 1998, sec 9.2). However, for easy and safe driving, the subjective appraisal of the visual range is important as well. Comparisons between the visibility distance and the subjective appraisal have been reported by Völker (2001). The visibility distances were assessed according to a method recommended by Schmidt-Clausen (1982). When compared to the subjective appraisal of the visual range, a reasonably good correlation was found with a spread of about one step in the subjective appraisal. The subjective appraisals were assessed by seven observers. Details of the experimental set-up are given by Völker (2001, p. 130). The resulting 'best fit' is depicted in Figure 12.2.2. The subjective appraisal is expressed in the well-known nine-point scale where '3' corresponds to 'insufficient'; '5' to 'just acceptable' and '7' to 'good'. This scale is based on the 'glare mark'-scale introduced by Schreuder (1967, p. 147). See also sec. 9.2.3c.

When, as usual, the appraisal 'just sufficient' is considered as the minimum, we might conclude from these experiments that a visibility distance of about 80 m is minimally required for traffic without discomfort. The situation is that without opposing traffic where the cars are supposed to use the low beam – a beam that will explained in detail later on in this section. The visibility distances that follow from the driving tests where the meeting situation is simulated are about 50 m or even considerably less; without doubt this sort of traffic situation should be considered as showing discomfort. We will discuss the meeting situation in detail in further parts of this section.

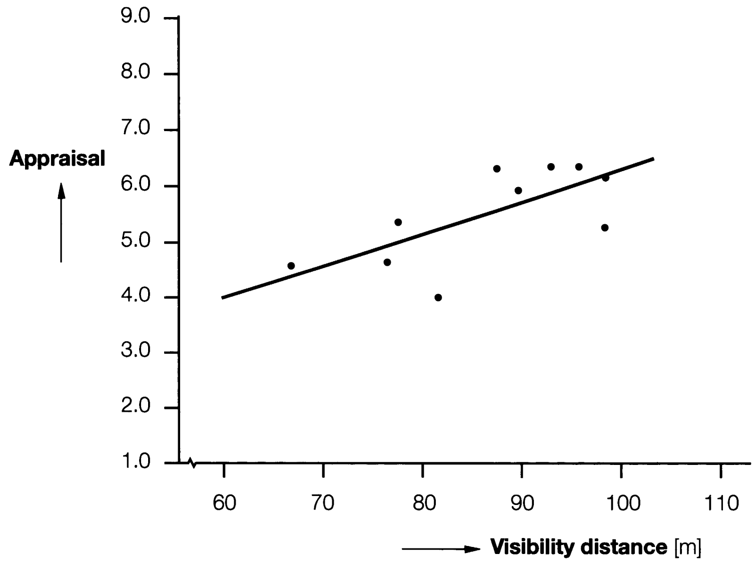

Figure 12.2.2: *The relation between the visibility distance and the subjective appraisal of the visual range. After Völker, 2001, Figure 1.*

12.2.4 The history of the low beam pattern

(a) High and low beams

In the beginning of the 'motor age' (that is before around 1920), night traffic was very limited. Cars had acetylene lamps and later electric searchlights that aimed the light straight ahead. As traffic was rare, glare of opposing traffic was hardly a problem. Sometimes, a mechanical device was introduced that could, if needed, 'dip' the headlight down. Of course, when meeting opposing vehicles, drivers could see not much during the meeting, but as speeds were low as a result of the poor and narrow roads, this was not much of a problem. The situation that was prevalent at that time is described in detail in Devaux (1970); Monnier & Mouton (1939); Preston (1969) and Schreuder (1976, 1976a). When, however, night traffic increased and consequently the frequency of meeting opposing traffic, this situation could not be tolerated any more. A passing beam was needed. It should be stressed that in most rural areas in developing countries and even in many densely-populated industrialized countries, 'high beams' are still the predominant 'driving beams'. It is therefore not justified to consider the high beam 'only' as a signalling device (Schreuder & Lindeijer (1987, p. 17). This is particulary true in the sparsely populated regions where most major astronomical observatories are located. For those, the light pollution from high beams may be the major problems as regards automobile lighting.

(b) Twin beam lighting

Because the important differences in the traffic and vision conditions when opposing traffic is met or when the road is free, traditional car headlamp systems have two beams, as explained already: the 'high beam' or 'driving beam' that is used when there is no opposing traffic, and the 'low beam' or 'passing beam' that is used when other traffic is met. In the past, all lamps were 'dual beam' lamps; they had, within one bulb, two filaments, one for the high beam and one for the low beam. From the point of the optical design of the headlamp system, this poses a difficult compromise (Anon, 1975; De Boer & Schmidt-Clausen, 1971; Schmidt-Clausen & Bindels, 1974 and Schreuder & Carlquist, 1969). The principles of the optical design are depicted in Figure 12.2.1.

The low beam is characterized by a light distribution that shows a sharp cut off; little light is emitted above the horizon, where the eye of opposing drivers may be, whereas as much light as possible is emitted just under the horizon to maximise the reach. Because the low beams are used in meeting situations where glare might be crucial, the light distribution of low beam headlights is subject to stringent regulations. The regulations for different parts of the world up to the 1970s are summarized in OECD (1972, 1980).

Very little is said about driving on high beams. There are hardly any restrictions on the beam pattern of high beams. The beam luminous intensity is only subjected to a minimum value and even the number of lamps is free (OECD, 1980). However, as has been explained in an earlier part of this section, high beam driving may result in a particular severe case of light pollution. As an example of what might happen we quote two studies, one from France and the other from the US (Schreuder & Lindeijer, 1987, p. 51). Both studies suggest that a vertical illuminance of 10 lux at 200 m and 100 lux at 70 m in front of the car – considered as sufficient for high speed driving – can easily be reached. One needs 'only' a beam peak intensity of 5 000 000 cd (Thiry & Devaux, 1971; Hemion & Hull, 1973). To the consequences of allowing such high values of the luminous intensity near – and in part above – the horizon are discussed in sec. 3.3.4.

(c) *The early history of the low beam pattern*

Though the direction of the luminous flux projected from the headlight is critically controlled, some light is still emitted to the upper directions. Over the years, the beam pattern has been adapted to the advantage of the drivers by increasing the intensities just under and also sometimes above the horizon. This means that the glare for opposing traffic as well as the light above the horizon, which may cause light pollution, did increase as well. Before World War II, European beam patterns were symmetric, showing a very sharp cut-off (Schreuder, 1972). Practically no light was emitted above the horizon, restricting glare but also the reach and therefore the permitted driving speed. In the 1940s, in North America the 'sealed beam' pattern was introduced. This was characterized by two almost identical beams, the high beam pointing straight ahead and the low beam pointing slightly down to the right (for right hand traffic). The reach of the low beam was much higher than for the European symmetric cut-off beam pattern, allowing higher speeds. However, glare and stray light above the horizon were considerable.

The optics of the two systems were fundamentally different. In the European system, the optical system – in fact, the parabolic reflector – made an image of the small shield within the lamp itself, on the road ahead of the car; as long as the optics were adequate, the optical image was very sharp, resulting in an sharp cut-off (See Figure 12.2.1). This is described for the asymmetric passing beam by De Boer (1955). Essentially, the same was true for the earlier symmetric passing beam. In the American 'sealed beam' system it was the low beam filament itself that was imaged on the road. The result was a much brighter image but a less well-defined cut-off (Schreuder & Lindeijer, 1987, p. 18). The system is described in Davey (1976) and Meese & Westlake (1971).

12.2.5 Recent developments in passing mode lighting

(a) *The multiple beam concept*

In sec. 12.2.2, it is explained that vehicle front lighting has two main functions, viz. marking and lighting. Traditionally, these two functions have been separated by means of different equipment. As is explained in that section, the lighting aspect was split up in two as well, related to the traffic situation. A driving mode was introduced to cope with the situation when no opposing cars were present, that might be hindered by glare. A passing mode was introduced for the meeting situation. As is explained in sec. 12.2.4a, in traditional vehicle front lighting systems, two separate and distinct beam patterns have been defined, the high beams and the low beams respectively. In most cases, one single lamp or bulb provided the two beams with two separate filaments. Switching from one lighting mode to the other was done simply by switching on one of the filaments and switching off the other.

With halogen lamps, this simple device was difficult to combine with a constant lamp temperature and therefore with an optimal lamp operation; with high-intensity gas discharge lamps it was not possible at all, because the lamp size prohibited the required small distance between the separate light sources. So, in a natural way, the multiple beam concept was born. The basic idea was to provide a separate lamp as well as a separate optical system for each lighting mode. The idea itself was not new at all. In the past, several attempts have been made, particularly in view of the fact in real traffic, several more lighting modes are required, and the two traditional ones (the driving mode and the passing mode) were actually too restrictive to provide adequate vehicle front lighting. Some attempts have been more successful than others, like e.g. front fog lamps (Behrens & Kokoschka, 1972, 1976). Others have been less successful like e.g. town beams (Sabey, 1972; Schreuder, 1972, 1976, 1976b; Schreuder & Carlquist, 1969: Yerrell, 1976); motorway beams (Anon., 1973; Hemion et al., 1973; OECD, 1980; Wichert, 1972); cornering lamps, and high-speed pencil beams. These different attempts have been described in detail Schreuder & Lindeijer (1987).

When the idea of providing only two beams, catering for only two modes of lighting, was abandoned, novel ways to provide lighting for car drivers were introduced. They usually follow the multiple-beam concept. The first step was to introduce a separate lamp with its own optics for the beam. The most successful was the projector type, which is basically identical to the traditional slide projector. The main problem with this type of lights is that the – simple and cheap – lenses that are used, show severe chromatic aberrations, which results in colour shifts that are considered unacceptable (Schoon & Schreuder, 1993). Nevertheless, projector lamps are used on a large scale in many car types.

An improvement was found when a lamp – either a halogen lamp or a gas discharge lamp – was placed in one of the two focal points of an ellipsoid mirror. In the other focal point, a screen was placed to provide the cut-off; an image of the screen is projected by a lens onto the road ahead (Röhling, 1998). Instead of a simple ellipsoid, a free-form reflector is often used (Bunse, 1998; Lindae, 1985). The most important characteristic of these new developments is, however, the fact that recent headlighting systems are interactive. The adaptive front-lighting systems – or AFS systems – are discussed in a further part of this section. First, however, we need to give some attention to the developments of lamps, without which AFS is not feasible, although several attempts to do it with halogen lamps have been made (Frickenstein et al., 1998).

(b) Lamp developments

In sec 12.2.4c, it is explained that, after the acetylene and the tungsten filament lamps, halogen lamps became the standard light source for vehicle headlighting systems. The luminous efficacy of halogen lamps, being essentially tungsten filament lamps as well, is restricted to some 20 to 25 lumen per Watt (sec. 11.3.2b). As the power supply of cars is restricted, the total luminous flux cannot be much more than some 1500 lumen. High-pressure gas discharge lamps or 'HID'-lamps, however, can reach a much higher efficacy – up to 85 lm/W. It should be pointed out that, being a plasma, the contour of HID light sources are more fuzzy than filaments that are a solid (Ernst, 1998, Figure 2). This usually will lead to a fuzzy image of the beam pattern on the road and thus to more glare, notwithstanding the opinion expressed by Hamm (1991). Further details are given by Ernst (1998). The 'sharpness' of the coupure that can be reached with HID-lamps, is discussed in Rendu (1992). Some data about the two lamp types are given in Table 12.2.2. This table gives the situation of about 1990.

Characteristics	**Halogen lamp** (H1)	**HID-lamp** (13,2 V)
Average luminance	2000 cd/cm^2	6000 cd/cm^2
Wattage (incl. ballast)	68 W	45 W
Luminous flux	1550 lm	3000 lm
Luminous efficacy	25 lm/W	85 lm/W
Colour temperature	3200 K	4500 K

Table 12.2.2: *Some technical details about halogen and HID-lamps. After VEDILIS, 1990.*

As the actual discharge tubes of HID-lamps are, as mentioned earlier, much smaller and therefore much brighter than the filament of filament lamps, there is a risk of increased glare. This possible effect is studied in some detail. See Schoon & Schreuder (1993). Flannagan et al. (1992) determined the difference as regards discomfort glare between HID low beam headlamps and conventional 'sealed beam' low beams in a field study, using stationary passenger cars. Using the same light intensity for both types of light, observers assessed the discomfort, using the nine-point scale, that is explained in sec. 9.2.3. The study showed that for the same luminous intensity, HID-lamps caused a higher degree of discomfort, as compared to sealed beam lamps. Furthermore, the discomfort in the field test was greater than predicted from laboratory tests.

The influence of the size of the light source on glare was studied in several investigations. In all of them, the light sources in the tests were much larger than the size of the actual discharge tube or the actual filament. However, higher source luminance of HID-lamps allows to make a headlight that is much brighter than that with filament or halogen lamps. Consequently, the small headlights for HID-lamps are brighter than those for the standard size filament or halogen lamps.

In one study, the discomfort glare of small lamps of 9 cm × 5 cm – correponding to 45 cm^2 – was compared to the glare caused by a lens with an area of 181 cm^2. The luminous intensity was varied. It was found that size only had a slight effect. On the well-known nine-point glare scale, the glare from the small lamps was only 0,2 points higher than that of the larger lamp (Sivak et al., 1990).

The effect of the smaller dimensions of the HID-lamp on discomfort glare also has been studied in the context of the European research project VEDILIS (1990). Discomfort was rated by means of laboratory experiments using the nine-point scale. The glare sources consisted of rectangles with areas of 3×6 cm^2, 6×12 cm^2, and 12×24 cm^2. Glare angles 1,72° to 6,84° were used, corresponding with observation distances of 25, 50, and 100 m. The illuminance on the eyes of the observers varied from 0,03 to 3 lux. It was found that the dimensions of the glare source have a small but significant effect. If the dimensions of the glare source were decreased by a factor of 2, the discomfort caused by dazzle increased by 0,1 points on the nine-point scale. This increase in discomfort glare can be compensated by reducing the luminous intensity of the lamp by 11%. Age and sex were found to have no effect on the degree of discomfort caused by dazzle. However, there was found to be a correlation between age and disability glare. There seemed to be a link between the dimensions of the headlight and the angle of dazzle: with small angles the effect of the dimensions is greater than with large angles (Alferdinck & Varkevisser, 1991b).

(c) Developments in the light distribution

Lamp developments are primarily aimed at improving the visibility conditions for drivers. Usually, they did prove to be not beneficial, or even harmful, for other traffic participants. In a comprehensive study on the benefits for the road safety from HID-lamps, it is concluded that: "The proposed light distribution from the low beams when HID-lamps are used, is higher than current ECE standards for virtually all points of measurement. These values need to be reduced on account of the negative aspects regarding the possibilities of perception of the other party (oncoming traffic and intersecting traffic) and the anticipated increase in driving speed. In addition, solutions should be sought with regard to headlights which are dirty or aligned incorrectly. If these conditions cannot be met, the use of HID headlights for passenger cars should be discouraged from the point of view of road safety. Furthermore, the light distribution of the low beam should be better adapted to the needs of vulnerable road users" (Schoon & Schreuder, 1993, summary).

Taking this into account, the functional requirements for low beams are more complex than is sometimes assumed (Sivak et al., 1992). In the Netherlands, a proposal is made to improve the low beam light distribution. The research is made by IZF/TNO, under contract of the Ministry of Transport. It is concluded that: "the proposals of TNO Institute for Perception as reported by Padmos & Alferdinck (1988) and Alferdinck & Padmos (1990) come closest to the functional requirements" (Schoon & Schreuder, 1993, p. 12).

In Table 12.2.3, the proposals of IZF/TNO are compared to the ECE European Standard ECE reg. R20, that was valid in 1993.

Point/zone	**ECE reg. R20**	**IZF/TNO**
Above the horizon		
• Point B50L	max. 250 cd	max.500 cd
• Zone III	max. 440 cd	max. 1000 cd
Below the horizon		
• 50V	min. 3750 cd	min. 20 000 cd
• 50R	min. 7500 cd	min. 20 000 cd
• 75R	min. 7500 cd	min. 50 000 cd

Table 12.2.3: *Comparison between the ECE European Standard ECE reg. R20 and the IZF/TNO-proposal (Schoon & Schreuder, 1993, p. 12).*

Comment: the points and zones used in this table are the conventional definitions for low-beam photometry. See e.g. Alferdinck (1987).

The IZF/TNO Institute for Perception's maximum light intensity 'above the horizon' is approx. factor 2 higher than European requirements. The minimum values 'below the horizon' are especially high compared with the other values. (Schoon & Schreuder, 1993, p. 12).

(d) Interactive headlighting systems

As mentioned earlier, the most important recent developments are in the field of interactive headlighting systems. The adaptive front-lighting systems 'AFS' react automatically to changes in the traffic conditions or in the environment (Kalze & Damasky, 1999). It should be stressed that not only the introduction of new lamps, but also the developments in micro-electronics are essential for this (Lange et al., 1999). More in particular, in recent years it became customary to install computers in cars, and it is a small step only to install computers dedicated to headlighting systems. AFSs are not yet in production, but it is expected that this will be the case within a few years. The first application of AFS will be the bending light, where a more or less standard low beam is adapted to the curve in the road. It is, therefore, not a 'cornering light' which is an additional lamp that has been customary in many of the more expensive US car types for some decades now. The first generation based on a mechanical displacement of the cut-off shield, is described by Wallaschek (1998).

When combined with the multiple-beam concept, a number of individual optical units can be installed, each with its own function (Hogreve, 1997; Manassero et al., 1999). An example is given in Figure 12.2.3.

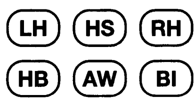

Figure 12.2.3: *An example of a multiple-beam AFS-system. After Hogreve (1997).*

Notes to Figure 12.2.3:
LH: Left hand bend light
HS: Hot spot
RH: Right hand bend light
HB: High beam
AW: Adverse weather illumination
BI: Base illumination

(c) Dead-ends: ultra-violet and polarized light

Because HID-lamps have an abundant luminous flux, alternative lighting systems that may use up a part of this, have been seriously considered, viz.: ultra-violet lighting and polarized light. The ultra-violet radiation itself is, of course, not visible, but the effect is, so that the term 'ultra-violet lighting' is justified. Neither of these alternatives resulted in a product that could be sold to the car makers, nor to the public. The reasons are not clear, but both alternatives deserve more careful considerations. When matters of glare and light pollution get a higher weight in public opinion, the tide may still change.

UV-lighting, compared to low beams increase of visibility distance of 25-50%, provided the objects have fluorescent pigments. The visibility distance of 30 cm wide road markings was 20% longer than that of 10 cm wide markings. Pedestrians are seen better because most clothing contain fluorescent pigments that stem from brighteners in the soaps and detergents. However, UV-radiation may cause eye-damage (Anon., 1993a; Lundquist, 1993; Schoon & Schreuder, 1993). The influence of UV-radiation for car headlamps on light pollution has not been studied. It might be considerable because most conventional light sources do not emit much UV-radiation, whereas these headlamps do. The results may be an increase in disturbance in a wavelength region that is rather 'clean' at present. Measurements are, however, not yet available, so this is just conjecture.

With the use of HID-lamps as vehicle lighting, it seems possible to apply the principle of polarized headlighting also in practice. At the time the idea of using of polarized light was launched, only conventional filament lamps were available. Fairly large lamp capacities are required for the application of polarized light. At the time polarized systems were considered, this was felt to be a drawback in financial terms. However, with the introduction of HID-lamps the situation has changed considerably: the total luminous flux emitted by HID-lamps is so high that polarized light may become a workable proposition.

In a headlighting system that uses polarized light, generous illumination can be combined with an almost total lack of glare. The idea is an old one; the first publications date back to the 1930s (see e.g. Chubb, 1937). It is rumored that the polaroids that were constructed in the 1930s were aimed at road traffic application. They were the first successful product of the company that still carries the name Polaroid Company. A lot of research has been carried out which has resulted in an OECD report, in which almost all theoretical and practical aspects of polarized headlighting are discussed (OECD, 1976).

Light can be considered as electromagnetic waves. Contrary to sound waves, light waves are transversal, i.e. the direction of vibration is perpendicular to the direction propagation. All directions of vibration are possible. Any direction of vibration can be broken down into two mutually perpendicular planes, which implies that light waves can be polarized. By placing a 'polarizer' in the light beam, only light which vibrates in a certain direction is transmitted. The rest of the light, which is therefore perpendicular to the direction of vibration, is absorbed. Because the light is broken down in two directions, half of the total light energy is absorbed in this process.

If another polarizer – usually called an 'analyzer' – is placed further along the light beam, the light that is transmitted through the combination, depends on the relative position of the two polarising filters. If the analyzer is placed in a way that light is transmitted in the same direction as the polarizer, then no 'extra' light is absorbed; the transmission with the two filters together is the same as the transmission with just the polarizer (half of the incident light). If, however, the direction of vibration transmitted by the analyzer is perpendicular to that of the polarizer, then no light at all is transmitted by the system. The light which is able to pass through the polarizer is stopped by the analyzer and the light which is able to pass through the analyzer is stopped by the polarizer beforehand.

This idea can be applied to car headlights. A polarizer is placed in front the headlamp; all emitted light is therefore polarized. For the most part the light is depolarized by the lighted objects in nature; it becomes 'natural' light again. If an analyzer is placed before the eyes of the opposing traffic, the direction of light transmission of which is perpendicular to the polarizing direction of the emitted light, then light from the lamp to the opposing eyes cannot pass through the combined polarizers; therefore the lamp appears to emit no light. Glare, therefore, is absent. However, the depolarized light which is reflected by natural objects – at least half of it – is transmitted by the analyzer and can be seen by the opposing traffic. It should be noted that the 'opposing traffic' may be car drivers, cyclists or pedestrians. They all will benefit from the reduction of the glare, as long as they carry an analyzer in front of their eyes. The physical principles of the polarization of light are discussed in detail in Feynman et al. (1977, vol. 1, chapter 32). Technically, the system are almost completely worked out. Many studies have been made in the past. Surveys are given in OECD (1976); Schreuder & Lindeijer (1987); Schoon & Schreuder (1993). Details may be found in e.g. Billings & Land (1948); Chubb (1937); Flannagan et al. (1992); Jehu (1956, 1956a); Rumar (1970); Rumar et al. (1970); Schwab & Hemion (1971); Schmidt-Clausen (1998); Van Bommel (1970).

Polarizers must be placed in front of the headlamps. These may be dipped lights with an HID-lamp applied in such a way that the light output with filter is the same as the output of a 'normal' dipped light without filter. An alternative way is to use high beams for the polarized scheme. The latter is, however, much more difficult to introduce, because, during the transition period, the 'unprotected' traffic participants will be subjected to very severe glare. So, most systems are based on an adapted low beam for the polarized systems. This is important to note for the light pollution aspects, that are discussed in a further part of this section.

Analyzers must be placed before the eyes. This can be done in various ways but practice has shown that for car drivers who do not wear glasses, the simplest solution is to fit a narrow strip of polarization filter at the bottom of the sun visor. For drivers who wear glasses, cyclists and pedestrians, such a narrow strip can be attached to the top of their glasses. It should be a narrow strip, so that the road and traffic can be observed below the filter.

The introduction of a system of polarized headlighting is difficult because, during the transition period, part of the road users are 'protected' and others are 'unprotected'. Several different strategies for the introduction have been studied by Hemion (1969) and Jehu (1963), and more in particular in the OECD-report that was mentioned earlier (OECD, 1976).

One might wonder why a headlighting system that seems to have benefits for all parties involved – the traffic, the industry etc. – and only minor disadvantages, never had a real chance. It was mentioned earlier that the light sources, that were available in the 1970s were too weak, but since HID-lamps are available now, the system is quite feasible. Probably, the polarizers and analyzers were considered too expensive, but many believe that it was just a lack of political courage of the decision makers. It is likely now that such a system will never be introduced on a large scale.

As regards light pollution, one needs not be too sorry about that. In a polarized headlighting system, the lamps emit a lot of light. It is polarized and it can be filtered out at the road by other road users, but when it is scattered and it ends up in the atmosphere, it is depolarized. As the intensity of a polarized headlight is much higher than that of a low beam headlight – if not, the whole system would make no sense at all – the light flux that ends up in the atmosphere, and that contributes to the light pollution, will be mich greater as well. In sec. 12.2.9, it is explained that the contribution of normal low beams to the light pollution can be already be quite considerable. So, polarized headlighting would have a large benefit for road safety, but it would be unfavourable for the reduction of light pollution.

12.2.6 Standards and regulations

(a) *Traffic conditions*

As has been indicated earlier, none of the many efforts to create a world standard for vehicle front lighting systems, ever had any success. As in many instances, the world seems to be divided in two: North America and the rest of the world, headed by Western Europe. Contrary to some other cases, where the division seems to be only a historic or nationalistic one, in vehicle headlighting there is some ground for it in the characteristics of the nighttime road traffic.

In the USA, almost all car traffic takes place in urban areas. The most important urban areas are very large indeed and stretch over hundreds of kilometers; their interdistance is usually very large. Fixed roadway lighting is not universal, and often the light level is low. The street patterns almost always follow a rectangular grid with extensive one-way streets and very little other traffic like e.g. pedestrians and cyclists. The small amount of rural nighttime traffic is on unlit divided highways with a very wide median. In the rural areas where traffic is a factor to take into account, the countryside is almost completely flat. Finally, rural nighttime traffic consists almost exclusively of trucks where the driver sits high above street level. The consequence is that forward visibility is essential, whereas glare is hardly a problem.

In the industrialized regions of Western Europe, the situation is quite different. The most important urban areas are compact and not very large; they are close to one-another. Urban areas have fixed roadway lighting throughout at a quite high light level. The street patterns are irregular; one-way streets are an exception. Particularly in the evening, pedestrian traffic is dense, and cyclist traffic is often considerable. A large proportion of car traffic takes place between urban areas, mostly on narrow, unlit two-way, two-lane roads. Although Western Europe contains regions where the countryside is flat, the typical landscape shows hills or low mountains. Flat, straight roads are a great exception. Divided highways or dual carriageways are common only in densely populated areas, and usually they have a narrow median. Rural nighttime traffic consists for a large part of cars. Only in a few cases, trucks form the majority. The consequence is that glare is always a problem, and almost always the dominant factor. Forward visibility is hardly ever essential, even not on high-speed freeways, where the traffic usually is very heavy at all hours. The driving task on such roads is primarily to follow the car ahead – or rather, its taillights!

In most other parts of the world, the traffic situation is, again, very much different, more in particular in the developing countries. Because, until recently, almost all cars were made either in the USA or Western Europe, all other countries follow the regulations of the one or of the other. Because Japan followed the USA standard, almost all other countries did the same, even if they have since founded important national car industries. The reason probably is, that most of these national car industries grew out of assembly plants of Japanese or USA car makers. It should be stressed that the typical traffic situation of the USA, that is depicted earlier in this section, does not apply at all to most of the countries in the rest of the world. This implies that most countries are stuck with regulations that do not fit their national or regional characteristics at all.

There is one more point to make. Although car and headlamp production is concentrated in the USA, research and development stems mainly from continental Europe, with Germany as its focus. This fact is clearly visible when one considers the most recent developments in vehicle headlighting systems, that are explained in an earlier part of this section. The consequence is, that new headlighting systems are designed in a way that reflect the German situation. The most striking difference between Germany and the rest of Western Europe – the rest of the world for that matter – is that Germany has an extensive motorway system where, in most cases, there is no speed limit and that almost all are unlit at night. The design, therefore, shows emphasis on very fast driving on unlit divided highways. When we state 'very fast driving', that may mean 200 km/h or considerably more! Again here, it should be stressed that the typical German traffic situation does not apply in any other country in the world. This implies that most countries are stuck with headlighting systems that do not fit their national or regional characteristics at all.

(b) Current UN standards

Although many countries follow the American standards, we will discuss the United Nations ECE standards here. There seems to be a trend that the use of the UN standards is increasing. In order to estimate the influence of vehicle headlighting on light pollution, the differences are maybe not too important. As will be explained in sec. 12.2.8, the practical deviations are considerable; probably they are more important than the standards themselves.

Here, we will discuss briefly the regulations for asymmetric headlamps that use a separate lamp. There are a number of regulations and a number of annexes to them. The main items are all the same, whether for standard filament lamps or for halogen lamps of different kinds. The major regulations are given in Anon. (2001a,c; 2002d, 2002a). All asymmetric beam patterns have to comply to the same standard as regards glare protection, independent of the lamp type. The halogen lamps require a higher value of the illumination on the road, i.e. in directions below the horizon. It should be noted that, at present, there are no separate regulations for multiple beam or AFS systems. Usually it is assumed that these systems also have to comply to the same standard. The photometric tests regarding the low beam must follow the following procedure:

(1) A screen is set up at 25 m distance;
(2) The measurements are made with a standard lamp rated at 12 volt;
(3) The headlamp must provide a cut-off that is sufficiently sharp to permit adjustment. The shape of the cut-off for right-hand traffic is depicted in Figure 12.2.1a. (after Anon., 2002, annex 4). For left-hand traffic, the cut-off is the mirror-image. The consequences of the peculiar shape of the cut-off for the restriction of light pollution are discussed in sec. 3.4.4;
(4) The required illumination values at the screen at 25 m are summarized in Table 12.2.4. For the designation of the measuring points, see Figure 12.2.1a.

Point	**Illuminance** (lux)	
	(req. a)	**(req. b)**
B 50 L	<0,4	<0,4
75R	>6	>12
75L	<12	<12
50L	<15	<15
50R	>6	>12
50V	–	>6
25L	>1,5	>2
25R	>1,5	>2
zone III	<0,7	<0,7

Table 12.2.4: *Photometric requirements for low beam headlights.*

Notes:
(1) < means smaller or equal; > means equal or larger.
(2) (req. a) means filament lamps, class A (Anon. 2001a, sec. 6.2.5).
(req. b) means filament lamps, class B (Anon. 2001a, sec. 6.2.5) and halogen lamps (Anon. 2002, sec. 6.2.5). It should be noted that 'filament lamps, class B' effectively means halogen lamps as well.

(c) Current US standards

Headlighting in the USA is regulated by National Highway Traffic Safety Administration NHTSA. SAE documents generally are viewed only as recommended practice. The present US Regulation is FMVSS 108. In Table 12.2.5, some relevant photometric requirements are given for the lower beam of mechanical aim headlighting systems (Anon., 2002, Figure 15-1). The values refer to two-lamp and four-lamp systems. For other systems, slightly different photometric requirements are given (Anon., 2002, Figures 15-2; 17-1; 17-2; 27-1; 27-2).

Test points (degrees)	**Maximum** (candela)	**Minimum** (candela)
above 10U	125	–
0,5U-1R to 3R	2 700	500
0,5D-1,5L	3 000	–
0,5D-1,5R	20 000	10 000
H-V	5 000	–

Table 12.2.5: *Some selected photometric requirements for USA lower beam headlights.*

Note: U: up; D: down; R: right; L: left; H horizontal; V: vertical. The point H-V is straight ahead. Based on data from Anon., 2002, Figure 15-1.

12.2.7 Operational aspects of front lighting systems

(a) Driving tests

In sec. 12.2.4c, it is explained that in the 1930s and 1940s, two systems of vehicle low-beam headlighting were in use. The first was the European symmetric low beam with a very sharp cut-off; the second was the American sealed beam pattern. The reach of the low beam was much higher than for the European symmetric beam, but glare and stray light above the horizon were higher.

Naturally, the question arose whether one of the two systems was, in traffic, superior to the other. This matter was investigated in great detail – and, according to many, solved once-and-for-all – in the famous driving tests on the Zandvoort race track under the auspices of CIE, United Nations and Groupe de Travail Bruxelles GTB (Anon, 1955). The results have been summarized by De Boer & Vermeulen (1951, 1951a). Essentially, the tests were a measurement of the visibility of objects. In sec. 12.2.4, the value of this type of tests for road traffic is discussed more in detail. The bottom line of the test results was that, in a one-to-one meeting situation on a two lane, two way straight road, the visibility distance of various objects on or near the road was always very similar as long as the two vehicles used the same lighting system (Schreuder, 1970). This was true for both the old – pre-war – European symmetric beam and the American sealed low beam. In all cases, the visibility was a minimum when the two cars were about 50 m apart; the visibility distance was usually about 30 to 60 m. On the basis of these test, neither North America nor Europe felt the need to adapt their system; hence we still find that the world is divided in two. One part (North and South America, Australia, UK) follows the US system. The other part follows the European beam (Continental Europe, most of Africa and Asia). As mentioned earlier, none of the many attempts to define a ‘harmonized beam’ had any lasting result.

Several years later, similar experiments were conducted in Sweden, where the European asymmetric low beam that is explained later on in this section, was compared with the American sealed low beam. The results are published in Johannson et al. (1963); Johannson

& Rumar (1968) and Rumar (1970, 1972, 1972a, 1973). They did find that in some cases the visibility in meeting situations was so low that the objects were actually hit. They concluded that low beam driving was to be considered consistently safe only for speeds under 25 km/h. They found also that the visibility often was just as high or sometimes even higher when both cars used their high beams (Schreuder, 1970, p. 61). The reason for this discrepancy must probably be found in the type (position, shape, and reflection) of the objects that have been used.

It is striking to note that, in spite of the results of these tests that suggested that low beams can be used at low speeds only, for decades low beams are used all over the world for high speeds, up to 80 or 100 km/h on two-way, two-lane roads. High speeds seem to be a specific danger at night, but catastrophic results seem to be absent (OECD, 1972, 1980). In general, higher speeds are more dangerous but the effect is not as great as the driving tests would suggest. See e.g. Anon., 1990; Oei Hway-liem, 1990 and SWOV, 1971. A 'sensible' speed limit may contribute to road safety, particularly to the severity of accidents (Anon., 1993; 1996a; Koornstra et al., eds., 1992).

(b) Visual objects and traffic hazards

One might tentatively conclude that the Zandvoort tests, although very carefully executed, do not represent the actual situation in nighttime driving; they are not relevant for traffic. In other words, the seeing tasks in the tests are no indication for the actual driving task on the road. Nevertheless, tests of this type are important to compare different beam patterns, even if their value for statements about the absolute value of the visibility in vehicle headlighting are questionable.

In sec. 10.3.1e, it is explained that, traditionally, the lighting criteria are based on the timely detection of hazardous obstacles. One has defined a 'standard object' that represents the visibility of 'visually critical elements'. These standard objects were supposed to represent the visual task, and thus they were selected very small; usually about $20 \cdot 20$ cm^2 (Adrian & Schreuder, 1971; De Boer, 1967; Schreuder, 1967, 1998) See also Blaser (1990); CIE (1981, 1984, 1990, 1992); Narisada (1955); Schreuder (1964). Some more details about the use of standard objects in visibility studies are given in sec. 11.8.5a. In the USA, even smaller objects are used – the Small Target Visibility concept (Adrian, 1993; Janoff, 1993; Keck 1993). A split-up in accidents did lead, however, to a completely different idea of what traffic hazards really are. In Table 12.2.5, some examples are given for the Netherlands. This table is used as well in sec. 10.3.1 (Table 10.3.1). The data stem from 1988 (CBS, 1989). More recent data all show the same trend (Schreuder, 1998, chapter 8).

Manoeuvre	Injury	Death
1 vehicles, same road, same direction	5 201	82
2 vehicles, same road, opposite direction	3 104	147
3 + 4 same road, leave road	8 243	153
5 + 6 intersection	12 036	299
7 collision with parked vehicle	1 307	25
8 collision with pedestrian	4 054	192
9 object (without 931 and 951)	4 308	254
931 crash barrier	549	28
951 loose object on or near the road	240	5
0 single-sided accident (without 011, 021, 022)	847	48
011 skidding on the road	1 749	21
021 off the road – straight	120	3
022 off the road – curve	101	1
total	41 859	1 258

Table 12.2.5: *Number of injury accidents. After Schreuder, 1998, table 8.2.4. Data and numbers of categories as given in CBS, 1998.*

As is explained in sec. 10.3.1, it can be seen from Table 12.2.5 that more than two-thirds of injury accidents involve cars that take part in traffic; the majority of those concern moving vehicles. About 10% involve pedestrians, whereas more that 20% involve road side obstacles like trees and lighting columns, or single-vehicle accidents like skidding. Collisions with loose objects on or near the road are very rare and concern just over half of a percent (0,57%) of the total number of injury accidents. However, these objects represent the 'standard object' we have discussed earlier in this section.

(c) Glare

As is explained in detail in sec. 9.2.1, glare implies a reduction or even an obstruction of the visual observations. Glare has three aspects:
(1) absolute glare or blinding glare;
(2) disability glare;
(3) discomfort glare.
As is indicated earlier, blinding glare occurs rather frequently in daily life, particularly when, in the dark, an opposing car does not switch back to low beam headlighting. This is precisely the reason for the existence of the passing beam. However, even the best passing beams create severe glare, both disability glare and discomfort glare.

As has been explained in sec. 9.2.1, glare sources create a light veil that seems to stretch over the complete field of view. The veil reduces the contrast in the field of view. The ocular stray light veil can be described by an equivalent luminance factor L_{seq} – the equivalent veiling luminance – and can be expressed in cd/m^2. The veil depends on the angle between the directions for the eye to the object and to the glare source respectively. In the meeting situation on a two-way, two-lane rural road, this angle is very small indeed. On a 7 m wide road – quite common – the near-side lamp of the one car and the eye of the driver of the other car are about 1,5 to 2 m apart. At a meeting distance of 50 m, the corresponding glare angle is less than 2 degrees – the limiting value of validity of the Stiles-Holladay relation that is discussed in sec. 9.2.2b.

Even the most casual observation, when driving a car at night, makes a number of points abundantly clear:

(1) Disability glare by opposing vehicles is the outstanding problem in nighttime road traffic.
(2) Disability glare increased very clearly with each step in the further development of vehicle headlighting systems, in spite of the fact that they are all supposed to comply with the same regulations, as is explained in sec. 12.2.6. These systems are discussed in sec. 12.2.5, but they are briefly listed here:
    - symmetric low beams;
    - asymmetric low beams;
    - halogen lamps in asymmetric low beams;
    - projector type headlamps with halogen lamps;
    - gas discharge lamps in asymmetric low beams;
    - projector type headlamps with gas discharge lamps.
(3) Disability glare does increase very clearly when the following conditions are met:
    - rain;
    - dirt on the road;
    - winter salt on the road;
    - curves;
    - bumpy or uneven roads;
    - roads with a pronounced superelevation or camber;
    - etc.
(4) Disability glare increases very severely if a number of opposing vehicles is visible at the same time.

In view of these observations that any-one can make, it is difficult to understand that very few investigations have been made about the glare of headlights in practical situations, and hardly any during the last two or three decades, with the exception of several studies on glare from HID-lamps.

In the past, some measurements have been made about the maladjustment of headlights. These studies will be summarized in the following parts of this section. It is often assumed that maladjustment, as a problem in nighttime traffic, is eliminated by automatic levelling systems on cars, but again, no evaluation studies ever have been made.

Although there are reasons to believe that severe disability glare represents a more serious traffic hazard than discomfort glare, most attention given to discomfort glare by headlights.

One aspect that was studied is the relationship between the size of the light source and the experienced discomfort glare. It is well-known that, contrary to disability glare, the luminous intensity of the source is not sufficient to describe the discomfort effects. The discomfort glare is determined by the light source dimensions as well as by its luminance. This matter became acute when high-intensity gas discharge lamps were used in vehicle headlighting systems. These lamps are much smaller and thus much brighter than filament of halogen lamps.

The design of vehicle headlamps is influenced by considerations about discomfort glare (Völker, 1999). The considerations themselves are based on earlier studies like e.g. those of Schmidt-Clausen & Bindels (1974); Olson & Sivak (1984); Sivak et al. (1988); Alferdinck & Varkevisser (1991); Alferdinck (1996) and Lachenmayr et al. (1997). "The survey is not complete but it represents a part of the investigations that have been made in recent years concerning discomfort glare" (Völker, 1999, p. 90). "Although the data from the literature agree rather well, further studies are needed about the discrepancies between different experiments" (Völker, 1999, p. 95). The only conclusion worthwhile quoting is that "According to Alferdinck & Varkevisser (1991), halving the size of the light source results in a deterioration of 0,1 point in the subjective nine-point scale" (Völker, 1999, p. 94). The relation between dimensions, luminance and glare experience are for vehicle signalling lamps are studied by Levitin (1997).

In a theoretical study, a large number of earlier tests, from 1938 onwards, were compared (Manz, 2001). This study is important as a work of reference, but it does not give any specific recommendations.

(d) Test procedures and deviations

In sec. 12.2.6, the different regulations as regards different systems of vehicle headlighting are discussed. The most important characteristic of these regulations is that all are based on type testing. This means that the decision whether a specific product is allowed on the marked, depends on the test result of small sample, that sometimes even consists of only one item. Obviously, this almost invites the provider to select the best possible item for the test. This is made more profitable, because all type testing is done on new items. The disadvantages for the situation on the road are obvious; some regulations therefore require an attestation of conformity, meaning that the provider must declare that the complete production is in agreement with the test items. As the sanctions usually are vaguely described, if at all, this provision is more or less a theoretical one. In some cases, this is complemented by random tests made on items taken from the stock of trading companies or shops; in a very few cases, there are tests made on items in use, e.g. as part of the periodic vehicle testing procedures. Tests in actual traffic are not made.

Many people believe that periodic test would do the job. Measurements, however, do not exist. A simple, unpublished, survey on defect low beam headlights suggest that the situation is far from perfect. The observations were made in 2002 and 2003. From a total of 14 950 vehicles that were observed in several countries, at day and at night, in dry weather and during rain, 377, or 2,52%, had a defective low beam headlamp. This figure, although not dramatically high, shows that a considerable number of drivers do not even take the trouble to change a defect bulb. More important, even the authorities do not enforce the regulations.

As an example, we quote the experience of the official German test stations, organized by the German Tourist Organization ADAC. In the winter of 2002-2003, about 40% of all cars had defective lighting. Misaim was not included in these numbers, only malfunctions like burnout lamps etc (Anon., 2003g).

So one may expect that misaim and dirt are even more frequent – although, as indicated, only very few recent measurements do exist. Some of them are discussed in a further part of this section.

But also the tests themselves did meet severe criticism. In a number of specific tests to check the test procedures, it was found that quite considerable production tolerances were permitted (Zucknik, 1978; Zaccharini, 1970). Furthermore, it was found that the combination of elements, that each did fall within the permitted range of tolerances, may lead to considerable deviations (Zaccharini, 1970a; De Grijs, 1970). See also Schreuder & Lindeijer, 1987, p. 22-23, and Olson & Sivak, 1983.

There is more to this. Formally, headlighting systems are vehicle parts, and not parts of a vehicle. Thus, they are tested separately. The way they are mounted on the vehicle, falls outside the regulations.

12.2.8 Deviations in practice

(a) Defective equipment

In practice, there are many reasons why the actual performance of the lighting equipment differs, in real traffic, from what could be expected if all was in agreement with the regulations. The deviations stem mainly from four causes:

(1) Deterioration or damage of the equipment.
(2) Deviations in the operation of the equipment on the vehicle, more in particular uncontrolled variations in the lamp voltage.
(3) Deviations in the mounting of the equipment on the vehicle and, consequently, misaim of the lamps. Misaim also may result from the loading of the vehicle.
(4) External conditions; some of them have been mentioned in an earlier part of this sections, like e.g. weather, road conditions, road layout, and traffic conditions.

As has been mentioned earlier, these deviations are discussed in more detail in this section. To begin with, we will discuss the defective equipment. It seems that there are no systematic investigations in this area. We will suffice to repeat the simple, unpublished, survey on defect low beam headlights that is mentioned earlier in this section. It was found that, during 2002 and 2003, from a total of 14 950 vehicles, 377, or 2,52%, had a defective low beam headlamp. The observations were made in several countries, at day and at night, in dry weather and during rain.

(b) Variations in operation

The variations in operation primarily mean voltage differences. These were studied by Schmidt-Clausen (1998). The measurements were made at the brake light fitting, but the point is clear: the differences are considerable. The results are depicted in Figure 12.2.4.

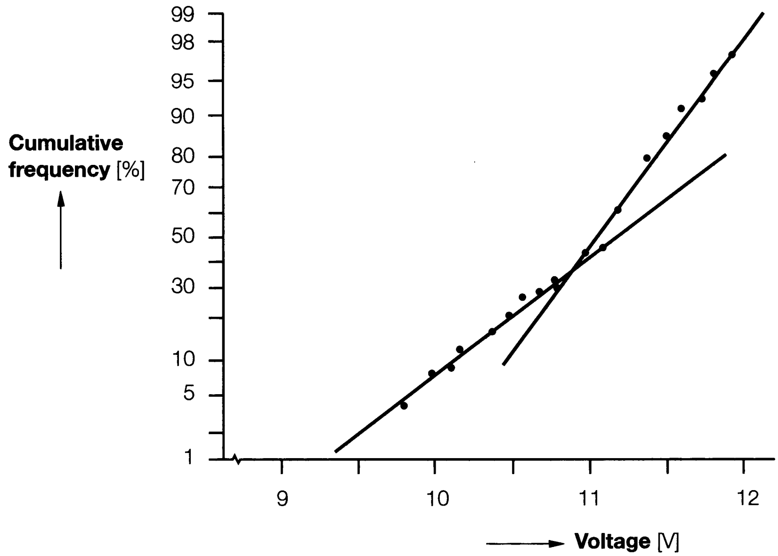

Figure 12.2.4: *Frequency distribution of the voltage with idling engine. After Schmidt-Clausen, 1998. Figure 9.*

It should be noted that during the tests, the car engine idled. In practical traffic situation with a engine in normal use, the deviation probably will be much larger.

Similar results have been reported by Wördenweber & Alferdinck (1997). The results are depicted in Figure 12.2.5.

The ageing of the headlight seemed to have a great effect; it seemed that older lamps had a higher light intensity than new lamps. 80% of new lamps complied with the standard for intensity of dazzle at point B50L and only 39% of old lamps, both measured at a voltage of 12 V (Schoon & Schreuder, 1993, p. 15).

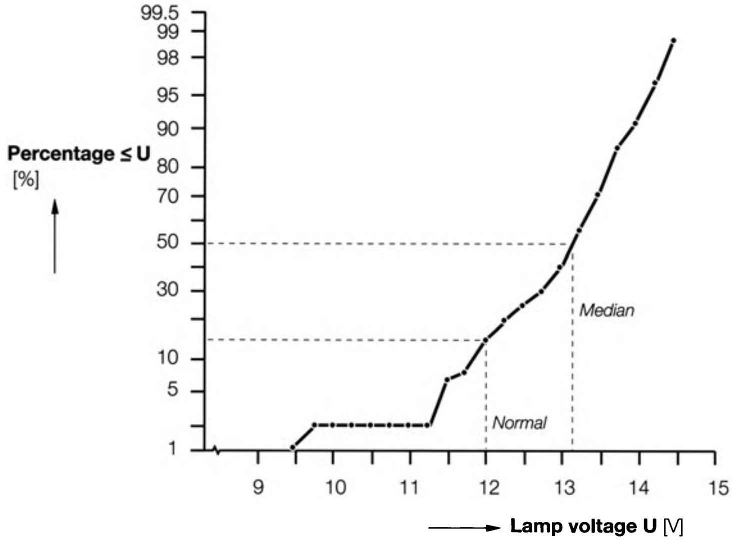

Figure 12.2.5: *Actual bulb operating voltage in motor vehicles. After Wördenweber & Alferdinck, 1997, Figure 1. Based on measurements by Alferdinck & Padmos (1988) and Alferdinck (1987).*

(c) Variations in installation

In the past, several measurements have been made regarding the deviations one may find in practice. Most studies are restricted to the actual aiming procedures and the loading of the vehicle. Some results are given in the Figures 12.2.6-12.2.9. It should be noted that all studies are rather old. More recent studies are rare.

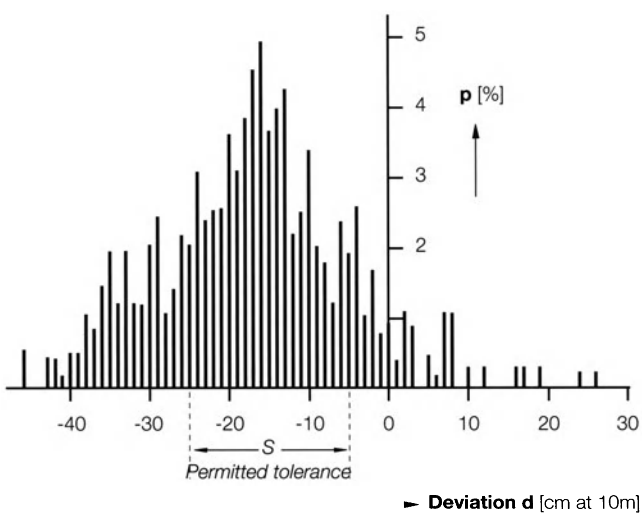

Figure 12.2.6: *Frequency distribution of the aiming of low beam headlamps. S: tolerated area. After Schreuder & Lindeijer, 1987, Figure 4. Based on Lindae (1969)*

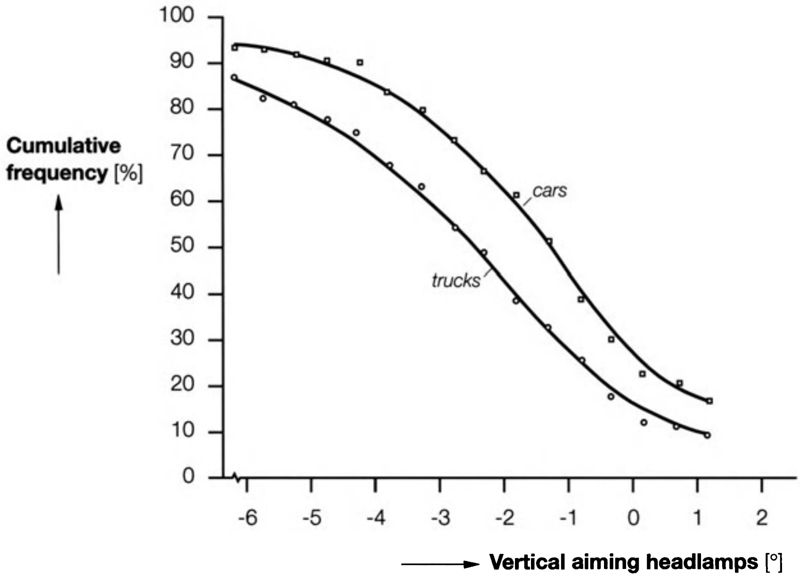

Figure 12.2.7: *Cumulative frequency distribution of the aiming of low beam headlamps. After Schreuder & Lindeijer, 1987, Figure 5. Based on Glover (1963)*

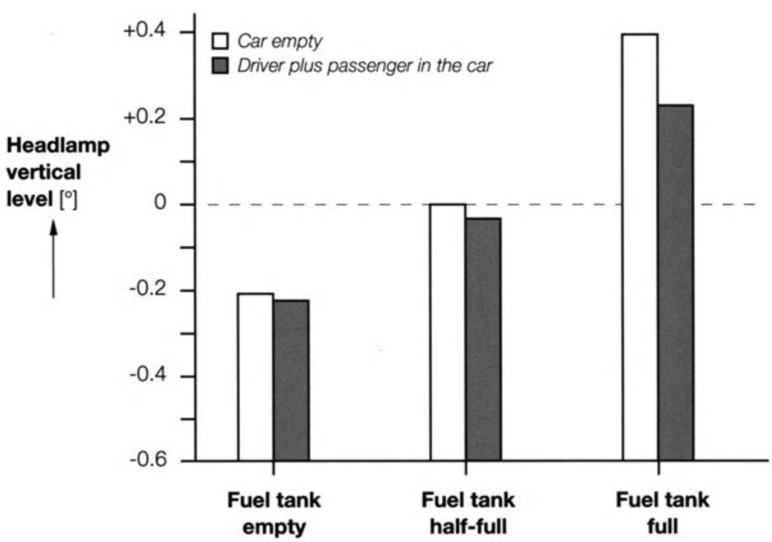

Figure 12.2.8: *Effect of loading on the position of the headlamps. One car only. Car empty (white bars), driver plus passenger in the car (grey bars).*

After Schreuder & Lindeijer, 1987, Figure 3. Based on Walker (1972).

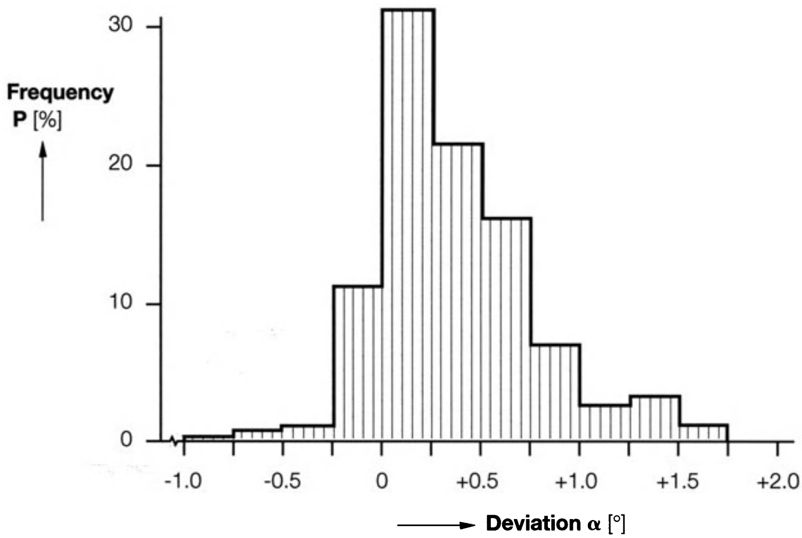

Figure 12.2.9: *Effect of loading on the position of cars and light vans. P: frequency. After Schreuder & Lindeijer, 1987, Figure 6. Based on Hignett (1970)*

Speed and changes of speed have an influence on vehicle position. Most cars tilt backwards when driving at high speed or when accelerating; they tip forward when decelerating. Some data are given in Table 12.2.6.

Mode	**Vehicle shift** (degrees) **average**	**spread**
driving on motorway	+0,18	-0,24 – +0,64
driving in town	+0,11	-0,51 – +0,61
gentle accelerating and decellerating		-0,65 – +0,86
decel. 6 m/s^2	-1,1	
decel. 8 m/s^2	-2,2	

Table 12.2.6: *Vehicle shift. After Wördenweber & Alferdinck, 1997. p. 512-513. Based on data from Damasky (1995).*

The large influence of loading the vehicle on headlamp aim triggered international European legislation concerning levelling systems. From 1990 onwards, new vehicles have to be equipped with manual levelling systems (Thiemann et al., 1999, p. 35). Still, large deviations may occur, not only as a result of incorrect compensation for loading, but also from acceleration and deceleration while driving. For this, semi-automatic or automatic levelling systems are needed. Some basic considerations of semi-automatic or automatic levelling systems have been reported by Thiemann et al. (1999).

Some results are depicted in Figure 12.2.10, where the influence of the front end and the rear end compensation is given. The figure suggests that, at least for the system depicted here, the rear end compensation almost completely counteracts the deviations from the vehicle loading without compensation. Also, it can be seen that in this case the deviations without compensation easily fall outside the permitted tolerance range.

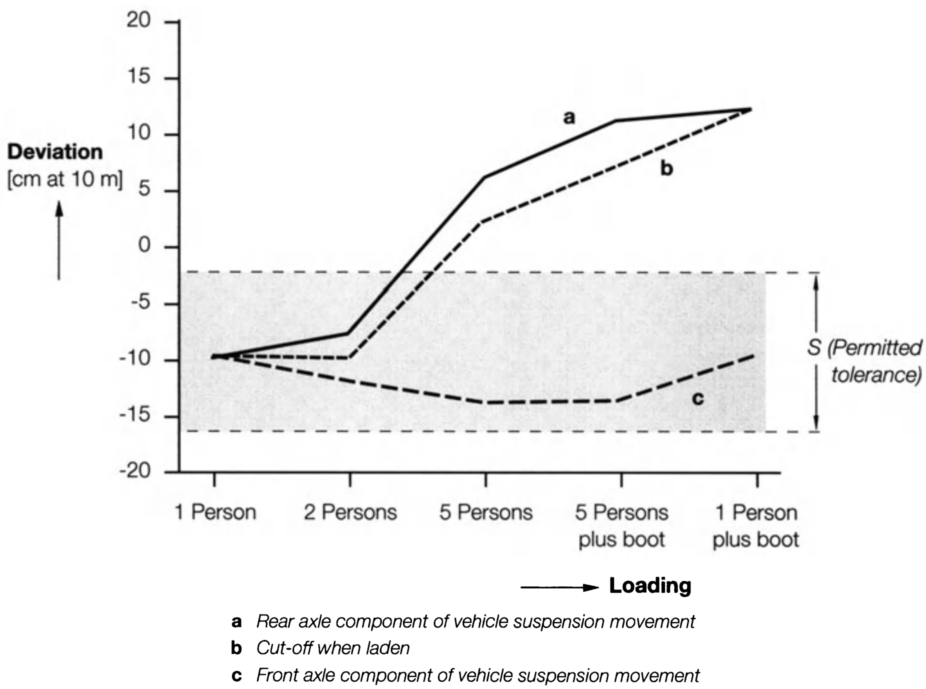

Figure 12.2.10: *Loading conditions in relation to EC Guidelines. After Thiemann et al., 1999, Figure 8. S: Permitted tolerance.*

(d) Environmental influences

The influence of dirt, and particularly of road salt, on the performance of headlighting systems has been studies extensively in Sweden. It was found that after a very short time – a few minutes only – while driving on dirty roads, a thin layer of dirt began to form. This layer scattered the light, thereby increasing the glare. After a while, however, the layer of dirt becomes so heavy that most light is absorbed. The glare decreases, but so does the overall light output. After driving for half an hour or so on a road covered with salt, the effective intensity towards the road could decrease by 80%. Worse still, it took a decrease of some 50% or more, before the driver began to notice that there was something wrong. These results triggered the decision to make headlight wipers and washers obligatory (Rumar, 1973a).

Cleaning of headlights result in a sizeable reduction of glare at point B50L (eye-level for oncoming traffic). Considering that many lamps had been set too high, the glare would be reduced still further by setting them correctly. Cleaning had a lesser effect on the light intensity on the right-hand verge (points 75R and 50R); on the other hand, correct alignment had a considerable effect (Alferdinck, 1987).

Rain drops on the cover or on the lens of the headlamp will cause scatter of the light. Usually, this will result in an increase in the glare (Cox, 1968). The reflection in wet road surfaces will increase the glare for opposing traffic even further (Rumar, 1973a; Yerrell, 1971).

Recent research from the University of Darmstadt, Germany, did show the very large effect of dirt on headlights. Here, the absorption of the headlight cover was measured for dry and wet roads. (Schmidt-Clausen, 1998). The results are depicted in Figure 12.2.11.

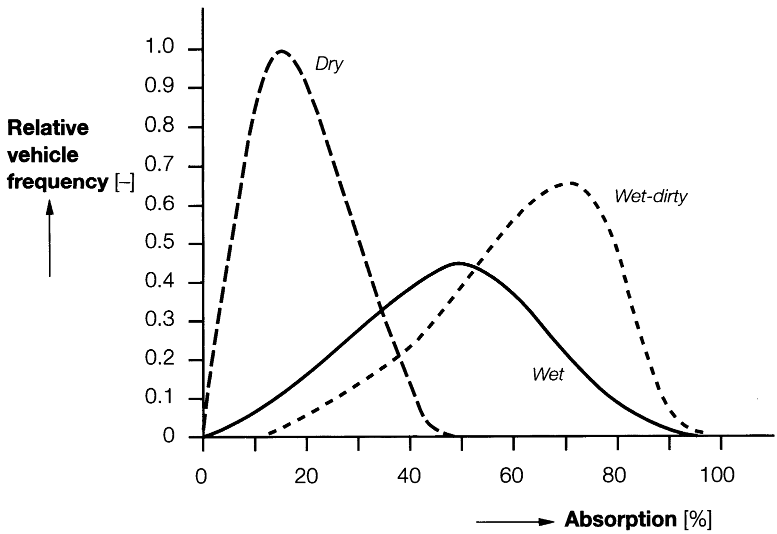

Figure 12.2.11: Road condition and soiling of headlamp cover lenses. After Schmidt-Clausen, 1998, Figure 11.

A number of earlier studies regarding the effect of headlight dirt on glare is summarized by Alferdinck (1996). The results are depicted in Figure 12.2.12.

Dirt in the lens may result in a typical increase of glare between 20% and 50% (Sivak et al., 1996, quoted by Wördenweber & Alferdinck, 1997). A soiling factor of 30% may cause a 60% reduction in performance and an increase of a factor 3 in glare (Orth, 1995, quoted by Wördenweber & Alferdinck, 1997).

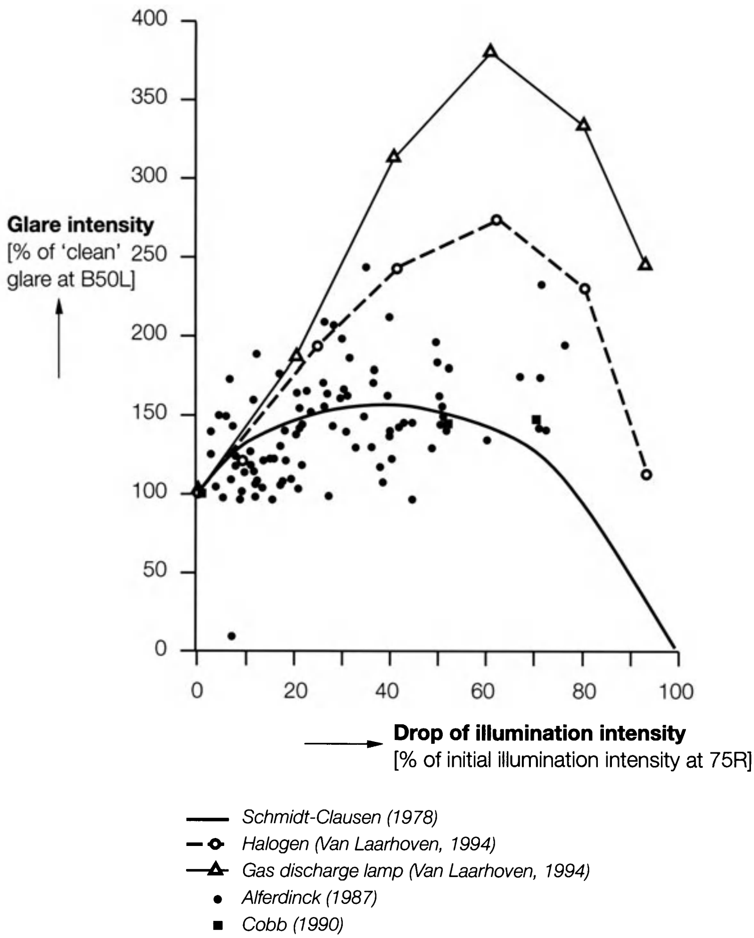

***Figure 12.2.12:**. Glare in relation to dirt on the cover lens. After Wördenweber & Alferdinck. 1997, Figure 2. Based on measurements of Schmidt-Clausen (1978); Alferdinck (1987); Cobb (1990) and Van Laarhoven (1994).*

(e) *In-traffic test*

Finally, there are a few studies made on the road in real traffic. For the first major test, the set-up was to measure the luminous intensity of each lamp of each passing vehicle at carefully chosen test sites in four countries in Continental Western Europe, viz.: Belgium, France, (West) Germany, and the Netherlands. The design of the studies was such that all influence of the weather, the road conditions, the road layout, and the traffic conditions were eliminated. The only variables tested were the deterioration or damage of the equipment and the misaim of the lamps (Yerrell, 1971). The main part of the results is depicted in Figure 12.2.13.

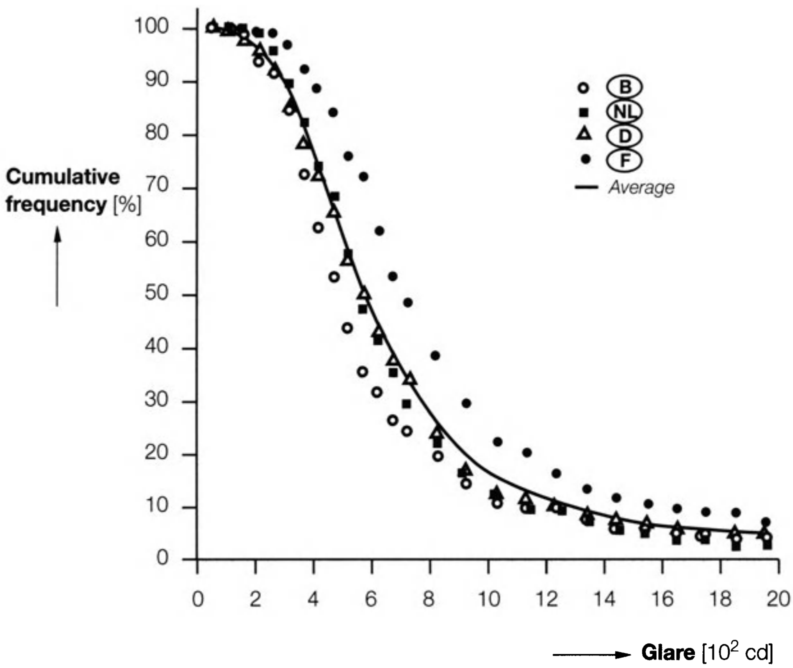

Figure 12.2.13: *Cumulative frequency distribution of luminous intensity in the 'glare direction'. After Schreuder & Lindeijer, 1987, Figure 7. Based on Yerrell (1971).*

Later, a pilot experiment, based on the same set-up, was made in the Netherlands (Alferdinck & Padmos, 1986). It was found that:

(1) The glare of 96% of all car headlamps is above the legal maximum for filament lamps;
(2) The glare of 88% of all car headlamps is above the legal maximum for halogen lamps;
(3) In the period between 1971 – the Yerrell studies – and 1986, glare became, on the average, twice as severe.

A part of the measurements is depicted in Figure 12.2.14.

Rys et al. (1992a,b) developed a system which could be used to take measurements along the road both on a temporary and permanent basis. Points can be taken which correspond with the standard requirements for distribution of light from car headlights (Schoon & Schreuder, 1993, p. 15). It is not known, however, whether this system ever has been used in real traffic situations.

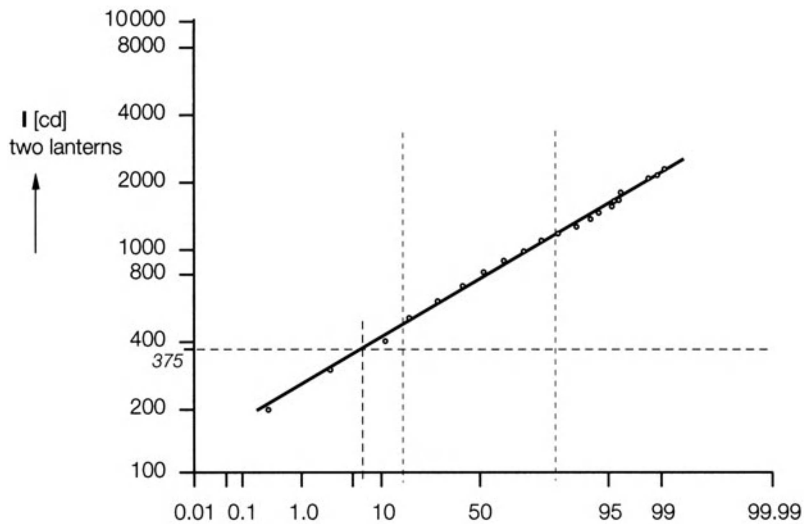

Figure 12.2.14: *Cumulative frequency distribution of the glare intensity of headlamps (two lamps). Based on data from Alferdinck & Padmos (1986).*

12.2.9 Influence of vehicle headlighting on light pollution

As has been explained in Table 12.2.4, the regulations stipulate that for a new, well-aimed and well-adjusted headlighting system, the illumination at the point B 50 L shall not be more than 0,4 lux at 25 m, whereas in all region III it shall be not more than 0,7 lux at 25 m. These values correspond for two lamps or combination of lamps to 500 cd and 875 cd respectively. For light pollution, as well as for glare, the region III is more important than the point B 50 L. As we have pointed out in the earlier sections of this chapter, many influences lead to an increase of the light above the horizon. To name a few: misaim, voltage variations, position shifts, dirt, rain and salt. It is difficult to assess the amount of increase from all these sources combined, but it seems to be justified to assume an increase by at least a factor of 3. This would mean that two lamps may have an above the horizon intensity of almost 3000 cd. As is explained in Table 7.1.4, the maximum horizontal luminous intensity of a full cut-off all-purpose road lighting is 2 cd per 1000 lumen of the lamps, and for a CIE cut-off lantern 10 cd per 1000 lumen. For a 250 W SON lamp with 32 000 lumen, the luminous intensity is 64 cd or 320 cd respectively. One more or less normal low beam will have a luminous intensity almost 50 times, resp. almost 10 times as much.

It is important to note that for right-hand traffic, the cut-off of the low-beam towards the right-hand side of the road may stick out above the horizon. The illuminance below the cut-off is not limited. However, in the point 75 R the illuminance shall be at least 12 lux. A point at 75 m is, according to the regulations, about half a degree below the horizon –

250 mm at 25 m. As is explained in sec. 12.2.8c, misaim may result in an upward tilt of one degree, sometimes even more. Therefore it is safe to assume that in a number of cases, the illuminance above the horizon may be as high as 10 or even 15 lux. This corresponds to a luminous intensity of two lamps of almost 13 000 cd or even almost 19 000 cd. When we compare these values in the same way as above, to the full cut-off luminaire, the headlamp intensity is over 200 resp. almost 300 times as high; compared to a CIE cut-off, the headlamp intensity is over 40 resp. almost 60 times as high. When we take the most unfavourable of these figures, which is perfectly possible in practice, and if we assume that a road lighting installation consists of 25 luminaires per km, one car might cause as much light over the horizon as a road lighting installation of 12 km! Even in the least unfavorable case that we have discussed earlier, one car might cause as much light over the horizon as a road lighting installation of almost half a km.

The conclusion is, that vehicle headlighting may cause severe light pollution, particularly in directions close to, and over the horizon. In most cases, the headlighting will cause considerably more light pollution than a regular road lighting installation. The consequences of light emitted close to the horizon on light pollution is discussed in sec. 3.3.4. It should be stressed again, that in densely populated areas in highly industrialized countries, it is likely that the light pollution from other outdoor lighting installations – like e.g. sport stadiums, industrial sites, advertising etc. – is more severe than that of vehicle lighting. However, in the sparsely populated areas, where most important astronomical observatories are located, it is likely that vehicle lighting is about the only form of outdoor lighting present, and that – due to the small amount of traffic – many cars will drive on high beams. Consequently, it seems to be highly desirable to pay close attention to the dangers of light pollution by vehicle lighting

12.3 Cost benefit assessments of road lighting

12.3.1 Cost-benefit and cost-effectiveness

Many measures that would diminish the impact of light pollution are not implemented simply because the costs are high, irrespective of the benefits. A wise Government, however, decides to take any policy measure when the benefits exceeds the costs.

It is not always simple to assess the precise costs, nor the benefits, because of two complicating factors. The first is that many measures, particularly large-scale measures, might influence the existing income distribution over the population; the second is that many costs and many benefits are non-monetarian of nature, i.e. they cannot be expressed simply in money. For long-term measures, things are complicated by a third factor, because the level of prices change over time, e.g. as a result of inflation. In a theoretical study, several of these factors are discussed (Wesemann, 2000).

The first factor is disregarded on the basis of the classical theory of Pareto regarding wealth, where the existing income distribution over the population is considered constant (Bannock et al., 1988, p. 308-309; Wesemann, 2000, p. 23). It seems that this simplification is justified for all except the largest measures, but not for measures that are aimed at a redistribution of incomes. These measures are not relevant when discussing light pollution. The third factor, that is mentioned earlier, can be disregarded when the constant-cost method is used, where all prices are normalized at one moment in time, usually the moment when evaluations are made (Wesemann, 2000, p. 22-23). The second factor will be discussed later.

The first and most important evaluation method is the cost/benefit evaluation, where all advantages and all disadvantages of a measure are expressed in money value (Wesemann, 2000, p. 23). For each measure a ratio, the benefit-to-cost ratio (B/C ratio) can be determined. When a number of alternative measures are compared, the only thing to do is to list them in a decreasing order of B/C-values. The first measure to take is the highest one; when the budget is fixed, one goes down the list until the money is finished. This method is used – at least, suggested – for many road safety measures. When only one measure is considered, the ratio itself is used. Usually, one requires it being larger than unity, where the benefits exceed the costs.

When not all aspects of the costs or the benefits can be expressed in money value, the cost-effectiveness evaluation method can be used (Wesemann, 2000, p. 26-27). Here, a variation of the constant-cost method can be used, as long as the aspect can be expressed in a straight-forward, quantifiable unit. In road safety research, as well as in research regarding crime, the number of fatalities can be used. One can always state that two fatalities is twice as bad as one fatality, even if it is not possible to express the 'value' of a fatality in money. Also, it is sometimes possible to use a survey method where a sample of the population makes an estimate as to how much money they think they would be willing to pay to avoid some specific damage. This method is often called the 'willingness-to-pay' method (COST, 1994; Elvik, 1995,1997; Wesemann, 200, p. 37-39). As an example, a study will be quoted where some cost-benefit relations of road lighting are assessed (Schreuder, 1998, 1998a).

12.3.2 Cost-benefit relations of road lighting

Road lighting is functional lighting. Its functions are those for traffic (through-put, safety, and driving comfort), for social safety (crime prevention), for public convenience (amenity), and for economic promotion (trade, tourism). It is important, but not sufficient to assess the effectiveness of road safety measures, that is the degree in which the required accident savings are really achieved at. When more than one measure is considered, and priorities need to be established, it is necessary also to know the efficiency of the measure, that is the degree in which the costs of the measure and its benefits are related. For setting priorities, it is also necessary to know the effectiveness of other measures that are considered as alternatives. Benefits can be regarded as costs that are not made, so that costs and benefits can be expressed in the same units, and can be compared on one scale. Usually a money value scale is used. When the costs of the lighting installations and the benefits of the lighting as quoted above both can be expressed in money value, and if the expenditure of public (road lighting) authorities can be compared to the money savings of individuals, cost/benefit assessments can be made. On the basis of a number of recent investigations in the Netherlands, it is found that in most cases, road lighting is an effective accident countermeasure; an increase in light level often coincides with an increase of the effectiveness and the efficiency is such that the presence of lighting as well as a lighting level – in broad agreement with CIE-recommended values – is cost/effective for a considerable fraction of the road network in the Netherlands (Schreuder, 1992, 1993, 1994b, 1995, 1996, 1998, 1998a).

The costs of accidents depend on a number of different aspects:
(1) Costs of accident victims (e.g. the medical costs, including rehabilitation; costs of production losses; 'human' costs like suffering and grief);
(2) Material costs (e.g. damage);
(3) Maintenance costs (e.g. police);
(4) Costs of research.

In the Netherlands, not much is known about these costs. Most quoted data go back on a non-published study of McKinsey and Co. from 1983. See Anon. (1985). Their value is limited (Flury, 1990; 1992). Recently, on the basis of several studies, more realistic cost estimates are given (Flury, 1995; Muiselaar et al., 1995). The new data were not yet available when an international comparison was made (COST, 1994). The main draw-backs of this compilation are that the data relate to victim costs only, and that the data from the different countries are difficult to compare.

In the cost/benefit estimation, the costs are assessed in the following way:
(1) Victim costs are based on COST (1994); as far as feasible, the data from different countries are averaged;
(2) The 'human' costs are also taken for COST (1994), although they are not given by all countries;
(3) The material costs and the additional costs are based on the McKinsey-study from the Netherlands, as adapted by Flury (1992);
(4) The other costs are disregarded, although they may represent sizable sums, because it is not always possible to determine whether they belong to the costs or to the benefits (e.g. education).

On the basis of accident studies, it was found that for important roads a 'good' lighting usually correlated with an average reduction of 30% in nighttime injury accidents (CIE, 1968; 1992; Hargroves & Scott, 1979; OECD, 1972; Scott, 1980). This is globally reconfirmed in more recent research. See sec. 12.1.1e, Schreuder (1993) and Vis (1993; 1994). It should be noted that the motorways in the Netherlands, when lit, comply very well to the current CIE design requirements (CIE 1995; see also CIE 1977a). The results are summarized again in Table 12.3.1.

Road type	Lit (yes/no)	Accident ratio night/day	Accident ratio with/without lighting	Reduction %
Motorways	yes	0,396	0,792	21
	no	0,500		
Trunk roads	yes	0,37	0,587	41
	no	0,63		

Table 12.3.1: *Accident reduction on lit roads. Based on data from BGC, 1990.*

12.3.3 Quantification of accident costs

As costs of lighting are considerable, they should be compared to the benefits. This can only be done on a monetary basis. As no general methods nor general data do exist, the only possibility is to use examples. The benefits are usually defined as the total costs of all the accidents that are saved by the road safety measure – i.e. the road lighting.

An estimate of these benefits are derived from the COST Report 313 mentioned earlier (COST, 1994). On the basis of data from 13 European countries the costs are assessed in Euro. When needed, the values in Hfl from the original publications are converted into Euro, using an exchange rate of 2,31. In order to allow for differences in time, this rate differs from the official rate between Hfl and Euro, which is, of course, 1 Euro equals Hfl 2,20371.

Type of casualty	Costs per victim
Killed	750 178
Seriously injured	53 059
Slightly injured	2 995

Table 12.3.2: *Accidents costs (in Euro, based on COST 1994).*

The costs include loss of labour, hospital costs, and 'human' costs (suffering, loss, mourning, etc). These costs are multiplied with the number of accidents. As only some of the accidents is reported, the real numbers are higher. For fatalities the increase can be neglected. For serious injuries the actual number is about 1,43 higher, and for slight injuries about four times as high (Harris, 1989, 1989a, 1990). A cost estimate for the total of all casualty accidents, expressed in Dutch Guilders (Hfl), for the Netherlands for 1990 is given in Table 12.3.3.

Type	Costs (Hfl)	Reg number	Reg %	Corr factor	Total costs (million Hfl)
killed	750 178	1 253	100	1	940
severe injuries	53 059	11 648	70	1,43	884
slight injuries	2 995	36 673	25	4	439
total					2263

Table 12.3.3: *Accident cost estimate for the Netherlands (1990)*

Notes to Table 12.3.3:
Type: type of casualty;
Costs: cost per case;
Reg. number: number of cases reported by the police;
Reg. %: percentage of registration by the police;
Corr factor: correction factor;
All prices in Hfl, base 1990.

The total costs amounted in 1990 to 2263 million Dutch guilders for accidents with casualties. The total economic loss as a result of road accidents includes other costs as well (damage, juridical costs, police etc). A Dutch study gives a multiplication factor of 2,62 (Flury, 1990, 1992). For 1990 the total costs of the Netherlands was Hfl 5 929 million. More recent cost estimates give a considerable higher value: Hfl 12 300 million. (Muiselaar et al., 1995). There are some differences due to inflation, overall increase in GNP, the different reference year and some differences in calculation. In a more recent study, the value of Hfl 13 645 million is used (Schreuder, 1998, p. 203-206).

For each registered casualty the loss is about 13 645 000 000/49 574 = 275 200 Hfl (for 1992). This figure should be corrected for all accidents. This can be done as follows, using data from Vis (1993, 1994) for motorways. See Table 12.3.4.

Type of accident	Number
with fatalities	177
with injuries	3 046
with casualties (total)	3 223
damage only	24 501
total	27 724

Table 12.3.4: *Accidents on motorways. After Vis (1993).*

For each registered accident (all accidents) the costs are (for motorways) (3223/27 724) · 275 200 = 31 993 Hfl. We will use this figure for rural trunk roads as well. This figure is of the same order of magnitude as one of the very few other numbers that is quoted in the literature. Dictus (1983) quotes Hfl 9400 per accidents for all accidents for the year 1981. In view of the inflation during the last 15 years, the corrected number would be similar to the one we have assessed.

12.3.4 Costs of road lighting

It is not possible to give a generally acceptable estimation of the costs of road lighting. The reason is that there are large differences is the method of assessing the costs, more in particular as regards the items that are considered as a part of the lighting installations. Transformers, cables, etc. are sometimes taken as part of the lighting installation, and sometimes it is not so. Also here we will use several examples of road stretches between intersections. One is a two-lane trunk road with an average road luminance according to the Dutch recommendations of 1 cd/m^2, the other a 2*3 lane motorway with 1,5 cd/m^2, with catenary low-pressure sodium lamp lighting, and with an experimental single-sided high-pressure sodium lamp installation respectively. The costs are total annual costs per km, and include investments and amortisation, maintenance and energy. Details are given in Schreuder (1993). The costs for these examples are given in Table 12.3.5.

Road type	Lanes number	Geometry	Level (cd/m^2)	Total costs (Hfl per km per year)
motorway	2*3	Catenary	1,5	55 892
motorway	2*3	Single sided	1,5	26 404
trunk road	1*2	Single sided	1,0	16 862

Table 12.3.5: *Total costs Hfl per km per year for different road types and different lighting geometries. Based on data from Schreuder, 1993.*

12.3.5 The cost/benefit ratios road lighting

The benefits of road lighting in the Netherlands are explained in an earlier part of this section. In summary, road lighting, for road stretches between intersections, correlates with a reduction in the night/day accident rate for motorways of about 21%, and for trunk roads of about 41%. A similar study for urban streets could not be made, because in the Netherlands almost all urban streets are lit.

On lit motorways it is shown that the night accident risk is 0,40 (registered accidents per million vehicle km). As the saving is about 21%, one could expect, if the roads were not lit, an accident rate 100/(100 – 21) = 1,266 greater, or 0,506 (in registered accidents per million vehicle km). The 'saving' is 0,506 – 0,40 = 0,106. Multiplying with 365 · n gives the savings per year (n: number of vehicles per 24 h period). Using the costs of Hfl 31 993 per registered accident (all accidents) the saved costs are (0,106 · 365 · n · 31 993)/1 000 000 = 1,238 · n Hfl per km per year. The costs for a 2*3 motorway with 1,5 cd/m^2 and with catenary lighting are Hfl 55 892 and for one-sided lighting Hfl 26 404. From this, the break-even point can be assessed. It is for catenary lighting at n = 45 147 vehicles per 24 hours, and for one-sided lighting at n = 21 328. Under the assumptions used here, the catenary lighting is cost-effective for more than 30% of the present network, and the one-sided lighting for more than 80% of the network (See Vis, 1993, fig. 3).

In the original study, a similar calculation is made for rural non-motorways. It was found that the break-even point for L_{av} 0.75 cd/m^2 is 7100 veh/24 h, and for L_{av} 1.5 cd/m^2 : 9700 veh/24 h (Schreuder, 1993).

Also, data are given for the pay-back period for doubling the light level for urban streets and roads. The results are given in Table 12.3.6.

Road function	**Pay-back period** (years)
traffic	0,53
mixed	0,49
residential	1,69

Table 12.3.6: *Pay-back period (in years) four doubling the light level for urban roads. Data from Steenks (1994) and Schreuder (1996).*

12.3.6 Conclusions

In view of the values of the break-even point of the traffic volume, road lighting on rural roads is often a cost-effective accident countermeasure. For increasing the light level on urban roads, the indications are that the payback period is quite short indeed, somewhere between half a year and a year. Increasing the light level on urban roads is an efficient (cost/effective) accident reduction measure.

12.4 Flat glass controversy

12.4.1 Upwards light emission

(a) ULR

Obviously, an effective way to reduce the light, that is emitted upwards by outdoor lighting, is to reduce the light emitted upwards by the luminaires. There are some complications, however, that will be discussed in this section.

As is explained in sec. 1.2.2, the light that is emitted upwards by outdoor lighting, is more than the light emitted upwards by the luminaires. Because the function of outdoor lighting is to illuminate some specific outdoor area, there is always light that is reflected upwards by the surface of that area. If that were not the case, the luminance would need to be zero, making the whole idea of outdoor lighting pointless. It is not very useful to concentrate on the Upward Light Output Ratio (ULOR) of the luminaire that is explained in sec. 11.6.6. Some of the most important reasons are listed here.

(1) ULOR is a ratio that expresses the amount of light that is emitted upwards in a laboratory set-up, compared with the amount of light emitted by the lamp. So, luminaires with small lamps and luminaires with large lamps may have the same ULOR, although the latter emits much more light upwards than the former;
(2) The ULOR does not indicate at all in which direction the light is emitted. Light that is emitted close to, but above the horizon has different adverse effects on light pollution than light emitted straight up. Astronomical observations are particularly disturbed by the light that is emitted close to the horizon by distant sources (Cinzano & Diaz Castro, 2000). The urban sky glow is primarily the result of light that is emitted straight up (Schreuder, 2000);
(3) ULOR is a quantity that is measured under laboratory conditions. Its function is to give a first, overall impression, to be included in the product documentation, of the light distribution of the luminaire. This is useful to make a first selection of which luminaires are probably suitable for a certain outdoor application. The final decision can, of course, only be made on the basis of a complete lighting design;
(4) The ULOR does not take into account the actual position and aiming of the luminaire in the outdoor lighting installation (CIE, 1997).

(b) Luminaire classification for road lighting.

In sec. 7.1.4, a classification system of luminaire is introduced that allows a wider application than the common classifications that are proposed by CIE (1977). See also CIE (1965); NSVV (2002); Pimenta (2002); Schreuder (1998, sec. 7.3) and Van Bommel & De Boer (1980, p. 103). The original CIE classification was restricted to three classes:

Name	Designation	I90	I80
Cut-off	CO	10 cd/1000 lm	30 cd/1000 lm
Semi cut-off	SCO	50 cd/1000 lm	100 cd/1000 lm
Non cut-off	NCO	(no requirement)	1000 cd (total)

Table 12.4.1: *Luminaire classification for road lighting (CIE, 1965, 1977). After Schreuder, 1998, table 7.3.2.*

When setting up the classification system that it introduced in sec. 7.1.4, a number of other classification systems were used. We will mention two of them. First the classification introduced in the Netherlands in 1957. See Table 12.4.2.

Name	I_{max} per 1000 lm	I_{hor} per 1000 lm	Φ for $\delta > 80°$ (lumen)
shielded deep emission	0-30	<15	>600
shielded wide emission	50-70	<15	>500
diffuse deep emission	0-30	30-50	550-650
medium emission	45-65	50-150	450-600
wide emission	60-75	100-300	450-550
free emission	50-90	>100	300-400

Table 12.4.2: *Luminaire classification for road lighting (NSVV, 1957). After Schreuder, 1998, table 7.3.1.*

As a second source of input, we mention the classification proposed by IESNA, which is followed by IDA (IESNA, 1999, sec. 2.4.2, p. 6-7). See also Paulin (2001). The nomenclature differs slightly from that of CIE.

- Full Cutoff – A luminaire light distribution where zero candela intensity occurs at or above an angle of 90 degrees above nadir. Additionally the candela per 1000 lamp lumens does not numerically exceed 100 (10 percent) at or above a vertical angle of 80 degrees above nadir. This applies to all lateral angles around the luminaire.
- Cutoff – A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 25 (2,5 percent) at or above an angle of 90 degrees above nadir, and 100 (10 percent) at or above a vertical angle 80 degrees above nadir. This applies to all lateral angles around the luminaire.
- Semicutoff – A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 50 (5 percent) at or above an angle of 90 degrees above nadir, and 200 (20 percent) at or above a vertical angle 80 degrees above nadir. This applies to all lateral angles around the luminaire.
- Noncutoff – A luminaire light distribution where there is no candela limitation in the zone above maximum candela.

Notwithstanding these restrictions, the light emitted upwards by the luminaire itself remains a crucial element. Some misunderstanding of the physics of light propagation as well as a lack of understanding the technical and optical restrictions of outdoor luminaire design, did give rise, however, to a controversy that would not exist if all people involved had adequate knowledge of physics at the one hand and luminaire design at the other hand. It is necessary to discuss this 'flat glass controversy', because it is wide-spread, and because it has even influenced legislation at a regional level in some countries (Broglino et al., 2000, Fellin et al., 2000).

12.4.2 Basic luminaire construction

(a) Luminaires for outdoor lighting

As is explained in detail in sec. 11.4, outdoor lighting luminaires consist of five main elements, viz.: the lamp, the optical systems, the transparent cover, the electric gear, the housing, and the supporting systems. From these, only the lamps, the optical systems, and the cover have any relevance for the light distribution of the luminaire. Apart from a few exceptions that can be disregarded here, all outdoor lighting luminaires are equipped with gas discharge lamps. These lamps consist of a tubular discharge tube (or burner). Burners show in their construction a circle-symmetry along the axis of the burner. The tube is transparent or translucent; cross-wise, the light is emitted in all directions in exactly the same way. In the lengthwise direction, however, this is not the case. As is explained in sec. 11.3.1b, gas discharge lamps require an electrode at each end. Thus, the ends block the light that comes out in a direction parallel to the lamp axis. This results in a light distribution with a toroid shape of the (bare) lamp. We have, for a moment, disregarded the compact fluorescent lamps, some of which have a folded discharge tube. Practice shows, however, that the light distributions of (bare) compact fluorescent lamps are very similar to the light distributions of (bare) discharge lamps of other types.

(b) Light distributions of luminaires for outdoor lighting

The lighting of outdoor spaces require, however, a light distribution that differs essentially from a toroid. In almost all cases, the function of the space requires a more or less uniform distribution of the luminance over the area under consideration. The light distribution of the luminaire – actually of the lamp-luminaire combination – must be adapted to the geometry of the area, the geometry of the lighting installation, and the reflection properties of the ground surface in the area. Only in case of an installation where many lamps are evenly distributed over the whole ares, and where the interdistance between the luminaire is equal or less than their mounting height, the requirements are simple. This type of outdoor lighting installations are not uncommon. One may find them on greyhound race tracks, on the fields of beach volleyball, on horticulture show areas, or for car dealers, on booth areas on toll roads, and on some large-scale parking lots. Some of these installations are described in secs. 11.2.9 and 11.2.10. However, the great majority of outdoor lighting installations show a fundamentally different geometry of the lighting equipment. In almost all cases, the luminaires are mounted separately or in small groups on columns or masts, that are much further apart than the mounting height of the luminaires. In some large sports stadiums, the luminaires are not arranged separately or in small clusters, but in lines. Most installations of these types are described in sec. 11.2.8. The implication is, that the light distribution of the lamp-luminaire combination must be essentially different from the toroid-shaped light distribution of the bare lamp. It is the role of the optical system in the luminaire to remodel the lamp light distribution into the luminaire light distribution. This change of light redirection is called light control.

It should be stressed that, as long as road and street lighting is about, there is, and always has been, a large contingent of luminaires that have no optical systems at all. There is no light control, and the light distribution of the luminaire is basically identical to that of the lamp within. Not completely so, of course, because the housing of the luminaire casts shadows. Two major types prevail: the globes and the 'vintage' lanterns. Globes are very popular with urban planners for modern pedestrian areas like shopping malls and residential streets; the lanterns being very popular for city centres that are ancient, or should look ancient. As is mentioned in sec. 11.4.3c, architects are not always so fond of them; many architects complain that the lighting industry has nothing better to offer. As is explained in that section, the globes and the lanterns usually are the main culprits for the light pollution caused by road and street lighting (Pasariello, 2003; Stroppa, 2003).

(c) *Optical systems*

As is explained in sec. 11.4.2, some luminaires use reflectors (or mirrors) as the optical system, whereas other use refractors (prisms, lenses etc.) as the optical system. In some cases, the two methods are combined; for reasons of simplicity, we will disregard this type of hybrid luminaire. There is no fundamental difference between the two, as long as we disregard the wave or particle characteristics of light, thus limiting ourselves to the geometrical optics that are described in sec. 11.1.1a. Both systems serve to 'bend' the light rays into the required directions. In practice, however, reflector and refractor type luminaires are quite different. Before we will explain in more detail this difference, and its consequence for the design of outdoor lighting, we must mention right-away that in almost all cases of area lighting, the is no need for the luminaires to emit light above the horizon. There are exceptions, of course: floodlighting of tall buildings, the lighting of golf ranges and the lighting of ski slopes. As they are not fundamentally different, we will disregard here these types of lighting installations. The implication is that, in order to fulfill the lighting requirements, all light emitted upwards is not necessary. It is always a waste, and it only contributes to the light pollution.

(c) *Refractor luminaires*

In the earlier years of public lighting, refractor luminaires were the most common type, particularly for road lighting. The reason was that these luminaires were easy to manufacture. They had a cast housing, either from aluminum or from steel, and a press-glass cover, in which the optical elements were incorporated. The parts were very sturdy and had a long life. Because of their sturdiness, they were easy to seal, so maintenance was simple and cheap. As a result of the characteristics of press-glass, the lenses or prisms did not have a precise shape. Because in most cases bulky high-pressure mercury lamps with a coated envelope were used, that did not matter, because the big lamps did not allow for a precise light distribution. Finally, at that time, shiny road surfaces were used, so that it was economic to use a very large space-to-height ratio, often up to about 10 (Christie, 1962).

As an example, we will quote a few details from the classical handbook published in 1967 with De Boer as editor (De Boer, ed., 1967). In 1967, the practical lighting design was based on four light distributions, that were used as examples to arrive at an acceptable lighting installation. These four are briefly described in De Graaff (1967, p. 339). Also, a large number of sample installations were described in detail, with the aim that the designers could select the one that was closest to the actual situation (De Graaff, 1967). These sample designs cover about 25 pages in that book. One should keep in mind, that in 1967, personal computers were not yet around, so that this 'receipt-approach' was about the only useful way to help designers. The four sample luminaires can be described as follows (the Philips designation of that time is used), See Table 12.4.1.

No.	Philips designation	Type	Light distribution	Details Knudsen, 1967, p.:
1	HRD	open diffuse reflector	full cut-off	286-289
2	HRP	closed mirror type reflector	cut-off	290-293
3	SRM	refractor	semi cut-off	314-317
4	HRF	refractor	non cut-off	294-297

Table 12.4.1: *Receipt-examples for lighting design. After De Graaff, 1967.*

The cut-off classification is explained in sec. 7.1.4. The refractor type luminaire HRF, mentioned as no. 4 in Table 12.4.1, may be considered as a representative of the 'old school' we have mentioned earlier. This luminaire was equipped with a 125 W high-pressure mercury lamp of 5600 lm (Knudsen, 1967, p. 274). The luminous intensity in the horizontal direction (I90) was 130 cd per 1000 lamp lumen. The upper-hemisphere luminous flux was 840 lm, the lower-hemisphere luminous flux was 3080 lm (Knudsen, 1967, p. 294-297). Over the years, shiny road surfaces were banned on the grounds of road safety. Shiny surfaces are very smooth, and the skidding resistance, when wet, is far too low to allow for safe, high-speed motor traffic. Also, the long spacings required a non cut-off light distribution. Such luminaires were phased out in the last part of the 20th century, mainly on grounds of unacceptable glare. The Glare Mark G, as explained in sec. 9.2.3, did range from 2,1 to about 4 for different luminaire arrangements and different road surfaces. Usually, it was about 3 (De Graaff, 1967). Nowadays, the ULOR would be prohibitive.

As a conclusion, one may say that, at least in modern, new road lighting installations in industrialized countries, non cut-off refractor luminaires are nor applied any more at any considerable scale.

(d) Reflector luminaires.

Semi-cut-off refractor luminaires (no. 3 of Table 12.4.1) are still used on a considerable scale. However, contrary to refractor luminaires, reflector luminaires are applied almost universally. There are two types of reflectors: diffuse and specular. Diffuse reflectors use the housing of the luminaire itself as the reflector. In the past, they were quite common, also for highway lighting (No. 1 of Table 12.4.1). Now, they are used in only in small-scale installations, more in particular in developing countries. As No. 1 of Table 12.4.1, usually they have no cover. We will come back to the advantages – and also to the disadvantages – of open luminaires.

Nowadays, specular reflectors are used most frequently. Specular reflectors or mirrors, obviously must be able to reflect the light. This means that only a few materials can be used. In practice, only anodized aluminum and stainless steel come into consideration. Anodized aluminum has a very high reflectance for visible light. Usually, values between 80 and 85% are quoted (Ris, 1992, p. 119). Depending on the definition of 'specular reflection', some times higher values are quoted, even up to and above 95%. Aluminum reflectors are, however, vulnerable. The aluminum itself is weak, and requires a sturdy frame to keep its shape. It can be applied only in separate units, that must be mounted inside a more sturdy housing. This allows, however, to adjust them individually, and to adapt, within limits, the light distribution of each individual luminaire to characteristics of the area to be lit. The material can easily be bent or pressed in almost every required shape, so it is very suitable for luminaires with precise light control, particularly in combination with small light sources, like metal halide or high-pressure sodium lamps. The surface can easily be damaged, and in the long run cannot withstand severe corrosion. This implies that anodized aluminum can only be used in closed luminaires. Thus, luminaires with aluminum mirrors are particularly suitable for high-class lighting installations, like e.g. freeways, important sports stadiums, large squares, high-quality floodlighting, etc. For 'simple' lighting installations, like e.g. residential streets, they are too complicated to install, aim and maintain, and in the long run the results often are disappointing.

As has been mentioned earlier, luminaires with anodized aluminum, must be closed by a transparent cover. The cover does not contribute to the forming of the light distribution, like it was the case with refractor luminaires. The cover must be clear and completely transparent. Each blemish, and each curve or bend, will influence the direction of the 'light rays', and consequently the light distribution that is formed by the lamp and the mirrors combined, must be avoided. Nevertheless, there is some freedom in selecting the shape of the cover, in order to reach an optimum in the mechanical construction. We will come back to this point, because this is the core of the 'flat glass controversy'.

Dust, dirt and water in the luminaire have a considerable influence on the overall light output and on the light distribution of the luminaire. So, the luminaire must be absolutely dust and water proof (Van Bommel & De Boer, 1980, p. 101). For tunnel lighting, a degree of protection IP65 is required, according to IEC. Publication 598 (CIE, 1990a). It seems reasonable to require the same for outdoor lighting – if that is really strict enough, a thing nobody seems to know. It is interesting to note that, in practice, IP54 was considered adequate ingress protection (NSVV, 1990, p. 16; Baer, 1990, p. 260). In a further part of this section, the Ingress Protection system (the IP system) is explained. See also sec. 11.6.9c. The minimum requirement of IP65 is needed, not only in new conditions, but also after the luminaires has been opened several times for maintenance purposes or for lamp replacement. As will be explained in a further part of this section, if the design of the luminaire and its maintenance are not first-class, often an open luminaire is to be preferred.

Stainless steel is the second material that can be used for mirrors in luminaires. The reflection by stainless steel of visible light is considerable lower than that of anodized aluminum, not much more than 60 % (Bean & Simons, 1968, p. 185, table 6.1). The reflection in the infrared region is very low. Stainless steel easily heats up. Also, stainless steel is not easily 'workable'; it cannot easily be bent or folded in any shape. So it is not particularly suitable if precision in the light control is required. At the other hand, stainless steel is a sturdy material, so it is quite possible to give the housing the right shape to act as a reflector. Usually, these luminaires have no cover – they are 'open' luminaires.

(e) The Ingress Protection system

As is mentioned earlier, dust, dirt and water in the luminaire have a considerable influence on the overall light output and on the light distribution of the luminaire. So, to operate properly, luminaires should be absolutely dust and water proof, and not allow 'breathing'. See sec. 11.4.1c; Van Bommel & De Boer (1980, p. 101). It has been mentioned earlier that, for tunnel lighting, a degree of protection IP65 is required, according to IEC. Publication 598 (CIE, 1990). It seems reasonable to require the same for outdoor lighting – if that is really strict enough, a thing nobody seems to know. It is interesting to note that, in practice, IP54 was considered. The degree of tightness is expressed in the Ingress Protection, or IP number (sec. 11.6.9c).

The IP-number consists of two digits. The first digit refers to the safety to touch 'live' electric components, the second the protection against the ingression of water. In Tables 12.4.2 and 12.4.3, a shortened version of the official designations is given (NSVV, 1997). For the full designation, see e.g. (DIN, 1980, Tables 1 and 2). See also DIN (1981, 1982).

Number	Protection against: accidental touching	ingress
0	none	none
1	by hand	large objects > 50 mm
2	fingers	medium large objects > 12 mm
3	wire > 2,5 mm	small objects > 2,5 mm
4	wire > 1 mm	small objects > 1 mm
5	impossible	no harmful dust
5	impossible	fully dust proof

Table 12.4.2: *IP, first digit. Protection against touching and against ingression of objects and dust. After NSVV, 1997.*

Number	Water protection	CEE-designation
0	none	
1	drops falling straight down	
2	drops falling 15° down	dripping waterproof
3	splashing water max. 60° with vertical	rainproof
4	splashing water all directions	splash waterproof
5	spray water all directions	spray waterproof
6	waves, heavy seas	
7	submersion (set pressure and time)	waterproof
8	submersion (set pressure, indefinite time)	waterproof

Table 12.4.3: *IP, second digit. Protection against water ingression. After NSVV, 1997.*

12.4.3 Open luminaires

(a) Luminaire deterioration

In the foregoing section, we discussed the use of one-piece stainless steel housings for luminaires, that, at the same time, can act as reflectors. When the luminaire is open, this leads, of course, to a simple and cheap luminaire. In the past, such luminaires were used at on a large scale. We mentioned already the 'classic' treatise of De Boer, ed. (1967). It is also interesting to note that the first edition of the Recommendations for Public Lighting in the Netherlands did mention 12 luminaire types as examples that were recommended for 'good' lighting. Half of them were open, the other half closed (NSVV, 1957, table 3.4.2.). It should be mentioned, that some of the open luminaires had glass diffusers, in stead of steel-specular reflectors. The point of view about closed luminaires was made clear: "Practice shows, that even closing the lanterns against the surroundings, does not prevent the depreciation" (NSVV, 1957, p. 49).

Luminaires with one-piece stainless steel housings can be used in all sorts of environment, more in particular in developing countries. However, this type of luminaire is used a lot in industrialized countries as well, even in major urban traffic arteries. Data are scarce, because it seems that lighting authorities are reluctant to admit the use. Some data are given in sec. 11.6.6, where the upward luminous flux is discussed. Open luminaires are used in the Italian town of Treviso, that was used as "a 'sample' assessment of present-day light pollution levels" (Medusa, 1998). It was found that from a total of 7478 street lighting luminaires, 3953 or almost 53% are open (Broglino et al., 2000, Table III). Casual observation shows that modern installations, using open luminaires, are frequently in use in many towns in France as well.

The attitude of being reluctant to admit the use of open luminaires is not restricted to industrialized countries. One of the authors did receive in 2002 a letter from a colleague in India, whose name will be withheld for obvious reasons: "I personally have no experience in India with open street lighting luminaires, because to my mind they have ceased to be installed "ages" ago, primarily because of the reasons you have mentioned, pilferage, vandalism, and dust". This reluctance seems to be based on the results of the research, performed in the later part of the 20th century in the Netherlands and in the UK on street lighting deterioration.

In the study in the Netherlands, four conditions were compared: Clean air – Corrosive air; Close to sea – Inland. A number of selected luminaires were used for full-scale trial installations in all four conditions. The installations were followed for several years; at regular intervals, the illuminance and the illuminance patters were measured. The results are summarized in Table 12.4.4.

Lantern type	**Optical system**	**Atmosphere**	**Depreciation** (%; one year)
closed		clean	88
closed		dirty	80
open	mirror	clean	80
open	mirror	dirty	75
open	diffuse	clean	80
open	diffuse	dirty	55

Table 12.4.4: *Depreciation factors for luminaires. After Schreuder, 2001b, table 2. Based on Knudsen, 1967, p. 230, Table 6.5.*

It came out that, particularly for the combination 'Corrosive air/Close to sea', the fall-back of open luminaires was considerably larger than for closed luminaires. On the basis of these experiments, it became customary in the Netherlands – and consequently in other countries as well – to exclusively recommend closed luminaires for all road and street lighting (see e.g. Forcolini, 1993, p. 239). It is mentioned in an earlier part of this section, that, in spite of these recommendations, open luminaires are used on a considerable scale, even in modern installations.

The British studies relate to closed luminaires only. They compare luminaires with different IP-classes in different environmental conditions. The depreciation factors for specific cleaning intervals are given. See Table 12.4.5.

From Table 12.4.5 it is clear that, particularly in condition of high atmospheric pollution, an Ingress Protection IP23 really is not very useful at all. Some believe that IP23 will be all at is left over from an IP65 or, even worse, from an IP54 luminaire, if it is opened and closed several times by unskilled labour! At the other hand, a comparison between Table 12.4.4 and Table 12.4.5 shows that, in a clean atmosphere, an open luminaire fares hardy less well than an IP23 luminaire.

Cleaning interval (month)	IP-class								
	IP23			IP54			IP65		
	Atmospheric pollution								
	high	ave.	low	high	ave.	low	high	ave.	low
12	0,53	0,62	0,82	0,89	0,90	0,92	0,91	0,92	0,93
18	0,48	0,58	0,80	0,87	0,88	0,91	0,90	0,91	0,92
24	0,45	0,56	0,79	0,84	0,86	0,90	0,88	0,89	0,91
36	0,42	0,53	0,78	0,76	0,82	0,88	0,83	0,87	0,90

Table 12.4.5: *Depreciation of luminaires. After Schreuder, 1998, Table 13.3.6 and NSVV, 1996, table 4.1. Based on data of BS 5489, Part 2, 1992. See also Marsden, 1993.*

(b) Low-maintenance luminaires

A lighting installation must follow certain requirements during its full life span. However, as with all technical equipment, the quality of street lighting deteriorates in time. Part of the effect is reversible such as soiling and break down of the equipment. Other aspects are irreversible, such as corrosion and surface deterioration. In many developing countries, installation and maintenance expertise is often low or even absent. A low maintenance lighting design seems to be the most promising solution (Schreuder, 2001b). Often, it can be he best solution for industrialized countries as well, because the expertise is available, but maintenance budgets usually are low.

In the following, a low-maintenance two-lamp open luminaire with maintenance intervals of 6 and 12 years will be compared with a low-quality one-lamp closed luminaire with a maintenance interval of 6 years. Details are to found in Schreuder (1996a, 2001b).

Data for really long cleaning intervals of the order of 12 years are not available. As one may assume that in the long term the deterioration will level off, we will use the value of 0,45 as the most appropriate estimate for the depreciation factor for open diffuse luminaires. In this value the depreciation of the lamp itself as a result of accumulated dirt and dust is included. For 6 years, one may assume a value of 0,50. For the IP23 luminaire we assume by means of a crude extrapolation from Table 12.4.5, that after 6 years the depreciation factor will be about 0,25.

If this rough estimate makes any sense, it would mean that, after 6 years without any maintenance, the illuminance of an installation with open luminaires would be double the value of an installation with low-quality closed luminaires.

12.4.4 Optical considerations in luminaire design

(a) The shape of light distribution

In sec. 7.1.4, a proposal is made for a system to classify luminaires for outdoor lighting. It is based on the shape of the luminous distribution (light distribution) of the luminaires, taking into consideration that light that is emitted in different directions by the luminaire has different effects, not only on the function of the luminaire as a lighting device, but also on its characteristics as a source of light pollution.

The proposed classification is based on the luminous intensity in specific angular ranges:
(1) U_1: from the zenith, downward to 15° above the horizon.
(2) U_2: from 15° above the horizon to the horizontal direction.
(3) D_1: straight in the horizontal direction – also designated as I90.
(4) D_2: from the horizontal direction down to 15° below the horizon. The area resembles, but is not the same as, I80;
(5) D_3: from 15° below the horizon to 45° below the horizon.
(6) D_4: from 45° below the horizon to the nadir (straight down under the luminaire).

The classification is based on the assumption that the luminaires are circle-symmetric along a vertical axis; all values apply to all lateral angles around the luminaire. The angular ranges apply to the luminaires of all types of outdoor lighting.

The angular ranges are depicted in Figure 12.4.1.

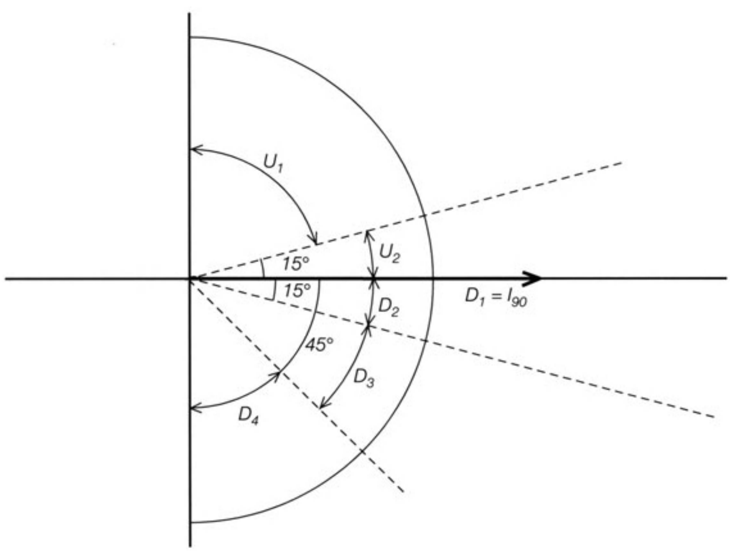

***Figure 12.4.1:** The angular ranges for the proposed classification of the light distribution of outdoor lighting luminaires.*

As is mentioned in sec. 7.1.4, the relevance of the different angular ranges for the restriction of light pollution can be illustrated as follows:

(1) The upper range (U_1) is relevant for the sky glow that will result from the lighting installation. This sky glow effects influence more in particular, the possibilities for experiencing the night sky in urban areas (sec. 3.3.4; Cinzano & Diaz Castro, 2000, p. 253).

(2) The range above, but close to, the horizon (U_2) is particularly relevant for the interference of astronomical observation at distant astronomical observatories (sec. 3.3.4; Cinzano & Diaz Castro, 2000). This effect is depicted in Figure 12.4.2.

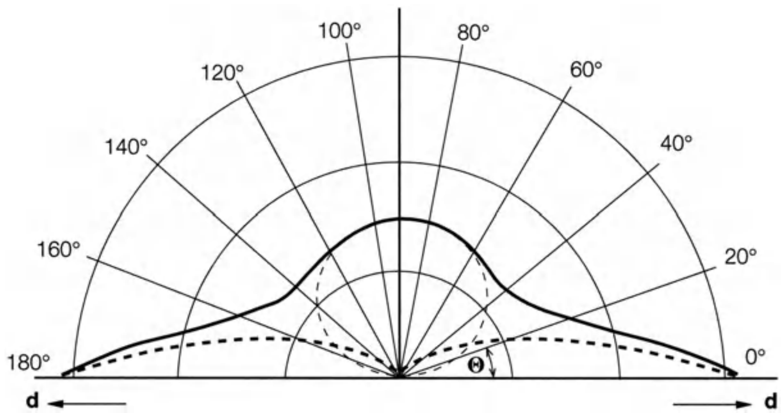

Figure 12.4.2: *Average city emission functions. After Cinzano & Diaz Castro, 2000, Fig. 1; based on data from Garstang, 1986. d: Distance (no scale given).*

It should be noted, that the figure as given by Cinzano & Diaz Castro (2000) is not very clear. They refer to parameters that are not explained, and that seem to come from the publication of Garstang (1986). It seems safe, however, to assume, that the striped curve in Figure 12.4.2. represents the light emitted directly by the luminaires, the dotted curve the light reflected from the surface, and the full-drawn curve the total effect.

(3) The directions near the horizontal direction (D_1 and I_{90} – with some 'tolerance' around it) is particularly relevant for the glare that is experienced from the lighting installation. The different glare phenomena are discussed in detail in sec. 9.2.

(4) The directions just below the horizontal direction (D_2 and also I_{80}, but then with some 'tolerance' around it) is particularly relevant for the luminance efficiency of the lighting installation, particularly for road lighting installations. As is explained in sec. 11.3.2, this results from the way the light is reflected – from the reflection characteristics of the road surface. As is explained in sec. 14.1.8b, almost all road surfaces reflect the light predominantly in a specular fashion: almost all road surfaces are 'shiny' even if

they look diffuse. Details are given in Burghout (1977, 1977a); CIE (1990); Schreuder (1967, 1998); Westermann (1963, 1964). Thus, light falling at grazing angles onto the road surfaces, will be reflected much stronger than light, that strikes the surface at angles more close to the normal to the surface. The luminance yield will be higher (Schreuder, 1967, p. 154). In other words, the road luminance will be much higher, for the same luminous flux, when the light strikes the surface at a glancing angle, rather than when it strikes the surface at a more obtuse angle. So, as a consequence, for almost all road surfaces, the angular range (D_2) between the horizontal direction down to 15° below the horizon is the most important from the point of view of the system efficiency.

(5) The directions between 15° below the horizon to the nadir (D_3 and D_4) are mainly relevant for the illuminance in an area close to the luminaire. These directions are also relevant for the degree of sky glow that will be experienced near the lighting installation. This is explained in sec. 3.3.4.

Over the years the low skidding resistance of shiny road surfaces did lead to a preference of more coarse road surfaces (Sabey, 1971; Schreuder, 1992a, 1998). Usually, coarse road surfaces show a less specular, and a more diffuse, reflection (Dijon, 1990; Erbay, 1974; Erbay & Stolzenberg, 1975; SCW, 1974, 1984; Schreuder, 1998). See also sec. 14.1.8b. This means that for examples of this phenomenon, we need to go back to older publications. See Table 12.4.6. This table is quoted form De Graaff (1967, Table 7.5). The table gives the values of the average road surface luminance for a road of 10 m wide, a spacing of 36 and 45 m, a mounting height of 10 m, and a 1 m overhang (or outreach). The luminaires were placed in a staggered (or 'zig-zag') arrangement. All lamps were normalized at 10 000 lumen. The table gives the results for four luminaire types and four road surfaces, that are described below.

Luminaire type	**Spacing 36 m road surface type**				**Spacing 45 m road surface type**			
	a	**b**	**c**	**d**	**a**	**b**	**c**	**d**
1	0,76	0,69	0,43	0,39	0,64	0,55	0,35	0,32
2	0,81	0,74	0,47	0,43	0,65	0,60	0,38	0,35
3	0,80	0,73	0,47	0,50	0,62	0,58	0,38	0,40
4	0,70	0,73	0,47	0,52	0,56	0,59	0,38	0,48

Table 12.4.6: *The average road surface luminance for different lighting installations. After De Graaff, 1967, Table 7.5.*

Notes to Table 12.4.6:

- Characteristics of the luminaire types 1 to 4 as given in Table 12.4.1.
  no 1: HRD, open diffuse reflector, full cut-off
  no 2: HRP, closed mirror type reflector, cut-off

no 3: SRM, refractor, semi cut-off
no 4: HRF, refractor, non cut-off.

- Characteristics of the road surface types a to d
  type a: q_0 0,10 κ 0,23 (diffuse)
  type b: q_0 0,10 κ 0,29 (semi-diffuse)
  type c: q_0 0,07 κ 0,36 (semi-specular)
  type d: q_0 0,07 κ 0,60 (specular)
- Road surface reflection characteristics are explained in sec. 14.1.8b.

The values of Table 12.4.6 show clearly that for a full cut-off luminaire (no 1), the luminance decreases as the surface becomes more shiny (higher κ). For a cut-off luminaire (no 2), the luminance is almost equal for the different road surfaces, whereas for a semi cut-off luminaire (no 3) and for a non cut-off luminaire (no 4), the luminance increases considerably as the surface becomes more shiny .

(b) Cover shapes

In practice, several shapes of clear, transparent covers are used. We will use a classification into four shapes. This classification is based on the study of Laporte & Gillet (2003). In that study, the following terms are used: flat, sagged bowl, deep bowl and box. We will use the same terms, only use 'shallow bowl', in stead of sagged bowl:
(1) Flat glass.
(2) Shallow bowl.
(3) Deep bowl.
(4) Box.
The terms are self-evident. One more note: we will use 'flat glass', also if the actual material of the cover is some sort of plastic.

(c) Light transmission of the cover

In an earlier part of this section, it has been indicated that many lighting authorities prefer the use of closed luminaires for outdoor lighting. It is also explained that the light distribution of the luminaires must have a precise shape, in order to be adjusted in an optimal way to the outdoor area to be lit. In day-to-day practice, this can be reached only with a clear, transparent cover, implying that for precise lighting, refractor luminaires usually are not suited.

The cover must be clear and transparent. It is mentioned earlier, that bends, folds, but also damages, dust, and water interfere with the unhampered transmission of the light through the cover. It has been stressed several times already, that precisely these points make, in many cases, open luminaires a better choice, particularly if the dirt is dust and sand, and not mud or salt (Schreuder, 1996a). Dust and sand, if they would accumulate in the luminaire, will fall out easily, without any negative consequence for the performance of the luminaire. However, as the 'flat glass controversy' obviously has nothing to do with open luminaires, we will discuss only closed luminaires. For the further considerations, we will disregard deterioration, and concentrate on new luminaires.

Covers for outdoor luminaires need to be able to withstand the influences of weather, but also of vandalism. Therefore, most covers are made of polycarbonate or other materials that can withstand blows and hits by sticks or stones. The optical properties, in new condition, of these materials are similar to those of clear glass. Clear glass, between 1 and 4 mm thick, has a transmission of about 90-92%; an absorption of about 2-4%, and a reflection of about 6-8% (Hentschel, 1994, Table 6.3, p. 158). Here, however, arises a severe problem. The reflection as quoted, being between 6 and 8 %, refers to vertical incidence. At a striking angle, glass, however, reflects much more light. This is depicted in Figure 12.4.3.

Figure 12.4.3: *Reflection for a polished glass surface with a refractive index of 1,5. After Moon, 1961, Figure 9.08.*

As is explained in sec. 14.1.8b, a high luminance yield of road lighting installations, and consequently a high road surface luminance per installed lumen – or, in other words, a high system efficiency – requires the utilization of light emitted under angles close to, but under, the horizon. When, at the same time, excessive glare must be avoided, the emission angles between 70° and 80° with the downward vertical are to be preferred. If a flat glass cover – or a flat cover of any other transparent material for that matter – is used, it is clear from Figure 12.4.3. that the reflection at the glass surface at the interior of the luminaire is between about 20% and 40%. Consequently, the transmission if far from the 90 to 92 % that is quoted earlier in this section. It is somewhere between 60% and 80% at the utmost.

It must be pointed out that the light that is reflected at the inner surface of the cover, is not lost – at least, not all of it. It is reflected upwards into the housing of the luminaire. If, as is usually the case, the inside of the housing is diffuse white, most of the light is scatted back towards the cover. It will hit the cover at angles more close to the normal at the surface of the cover. The reflection is much lower, and most of the light is emitted out of the luminaire. One should realize, however, that this 'secondary light' comes out of the luminaire at a small angle with the downward vertical. Therefore, it will contribute to the illuminance right under the luminaire, but not much to the road luminance. The influence on the visibility is difficult to estimate. It is likely, however, not to be higher, and probably even lower, compared to the situation where the light is emitted at larger angles to the downward vertical. The visibility in road lighting is explained in sec. 9.1.3. See also Narisada, 1999; Narisada et al., 2003.

If the cover has another shape, however, the incidence of the light can be selected closer to the normal to the surface of the cover. The reflection can be much lower that at grazing angles, and consequently, the transmission can be higher. Here, again, comes the problem which was dubbed the 'flat glass controversy'. Obviously, any shape other than a flat glass will result in some light being emitted upwards, directly from the luminaire.

Solving the flat glass controversy means, as is mentioned earlier, finding a compromise between the different conflicting influences on the total upwards flux as well as on the total energy consumption.

(d) Shielding

There is some misunderstanding about the contribution of the reflected light to the upward flux of outdoor lighting installations. It is sometimes stated, that the direct light is predominant. This is deduced from how urban areas look from a distance, e.g. from a hill, or from a plane. "This view from nearby hills shows plainly that most of the waste light comes from the luminaires, not from the ground" (Mizon, 2002, p. 64, figure 1.62). As is explained in sec. 9.1.7, views of this kind can be misleading, because concentrated light sources, like street lighting luminaires, are highly conspicuous to the dark adapted eye, even if their actual luminous intensity is modest. So, from a distance, one will easily see the light points, but not the diffuse contribution of the ground.

There is a further point to be mentioned here. In sec. 3.3.4, it is pointed out that, at distant astronomical observatories, the observations are disturbed most by light that is emitted by the source at angles close to the horizon (Cinzano & Diaz Castro, 2000). At such angles, the light that is reflected at the ground in the direction of the observatory, is limited by buildings, trees etc., at the site of the source. So, the shielding should be taken into account. It might be argued that, as regards distant observatories, the direct light is the most damaging, and that, therefore, luminaires with the minimum upward flux should be recommended. In terms of the 'flat glass controversy', this would mean luminaires with a flat cover. However, it is also pointed out in sec. 3.3.4, that the light, that is emitted more straight up, contributes most to the 'sky glow' that is experienced over towns, cities, industrial sites, etc.

12.4.5 Comparisons between luminaires with different cover shapes

Because the issue was considered very important, several attempts have been made to compare luminaires with different cover shapes. In some cases, the comparison were made between different versions of the same luminaire. In Figure 12.4.4. to Figure 12.4.6. an example of such a comparison is given. Figure 12.4.4. gives the data for the luminaire with a flat glass cover, Figure 12.4.5. the data for the same luminaire with a shallow bowl cover, and Figure 12.4.6. the data of the same luminaire with a deep bowl cover. The data are made available by Industria Technische Verlichting B.V. in Cappelle aan de IJssel, the Netherlands.

The figures 12.4.4. to 12.4.6., show clearly the influence of the shape of the bowl. The comparison is summarized in Table 12.4.7.

Item	Flat glass	Shallow bowl	Deep bowl
I_{max}, degrees	62	71	72
I_{max}, cd/klm	492	352	318
$I_{90,max}$, cd/klm	0	0	0
$I_{80,max}$, cd/klm	70	130	170
upper hem. lm (%)	0	0	1
total efficiency (%)	78	78	79
designation	FCO	FCO	FCO
E_{max}, 30%	1,5h	1,4h	1,4h
E_{max}, 10%	2,5h	2,2h	2,2h
E_{max}, 2%	3,4h	3,9h	4,0h
Output ratio, 2h	0,48	0,46	0,45

Table 12.4.7: *Comparison between three versions of the same luminaire.*
Based on data from Anon., 2002d.

The differences are marginal. The flat-glass version has a slightly better performance overall, but the reach is slightly shorter. The illuminance at 2% of the maximum is found at a somewhat longer distance for the deep-bowl luminaire. It is not easy to see in which way that could be an advantage; probably, the deep-bowl luminaire can be used at a slightly longer spacing for the same length-wise uniformity. However, the average luminance might be slightly lower. These points can be decided only, of course, when the luminance and the uniformity are assessed, either by calculations or by measurements. One may expect, however, that the flat-glass version may be slightly better as regards the glare restriction. Also here, calculations or measurements are needed in order to be certain about this point.

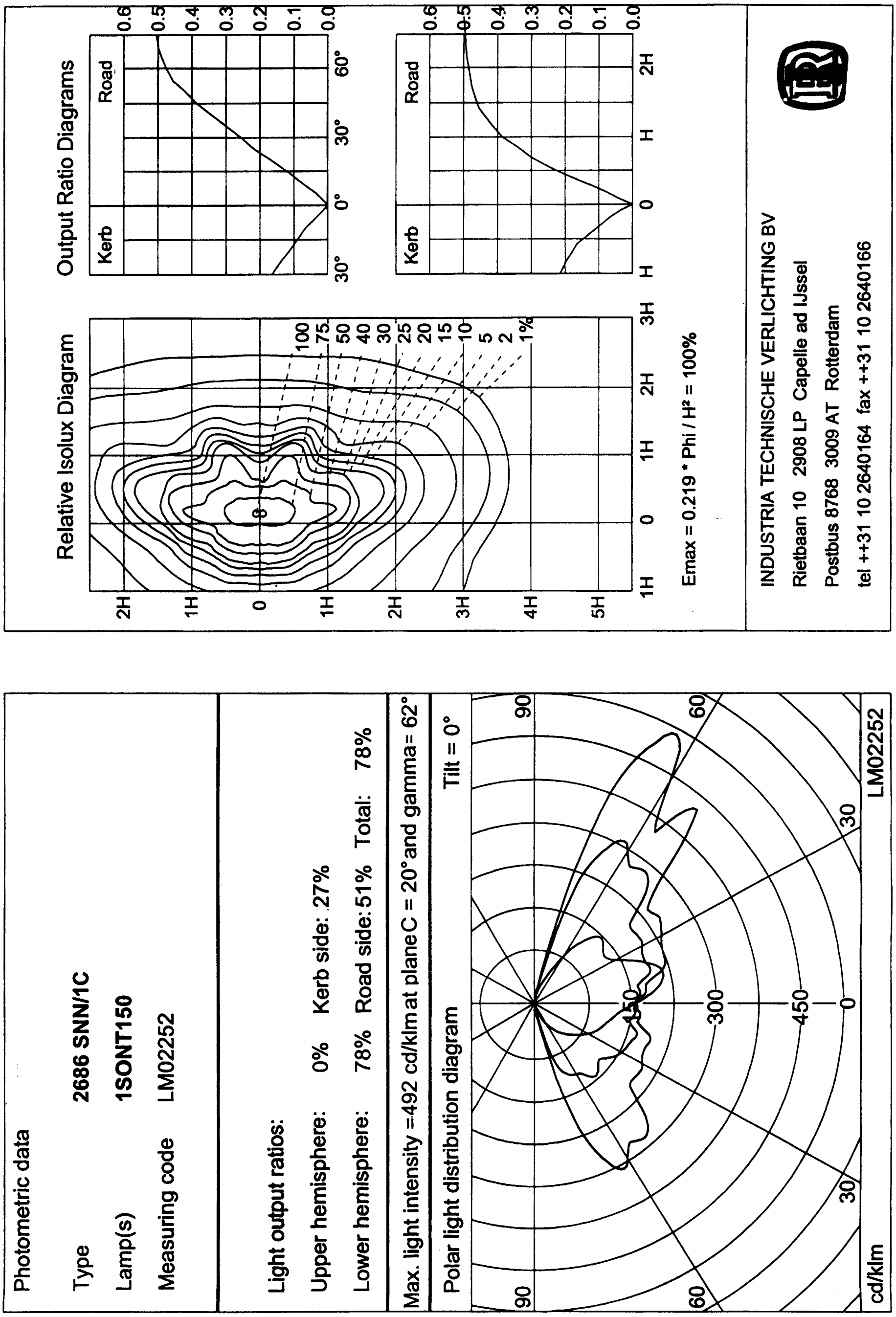

Figure 12.4.4: *Data for the luminaire type ARC with a flat glass cover.*

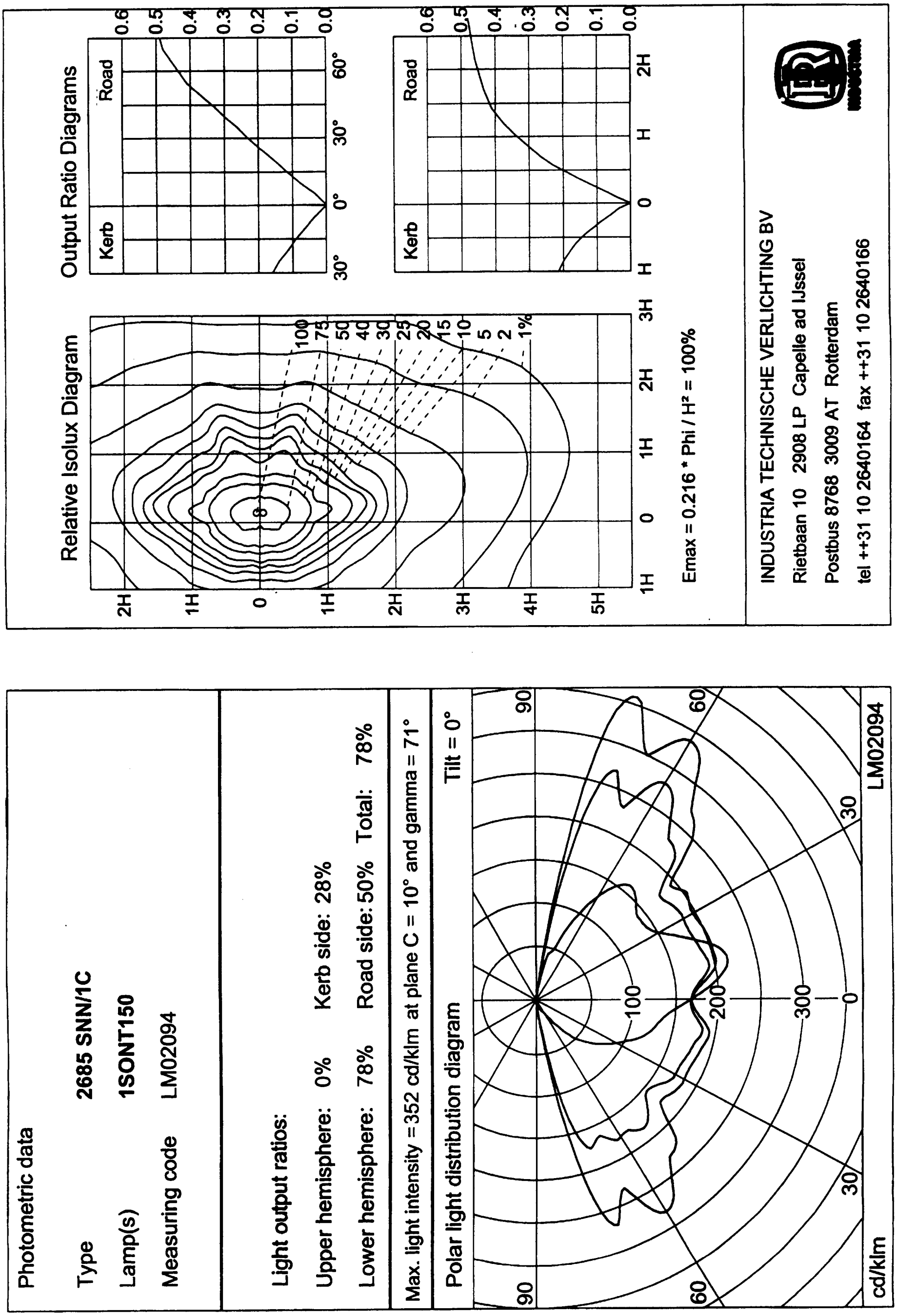

Figure 12.4.5: Data for the luminaire type ARC with a shallow bowl cover.

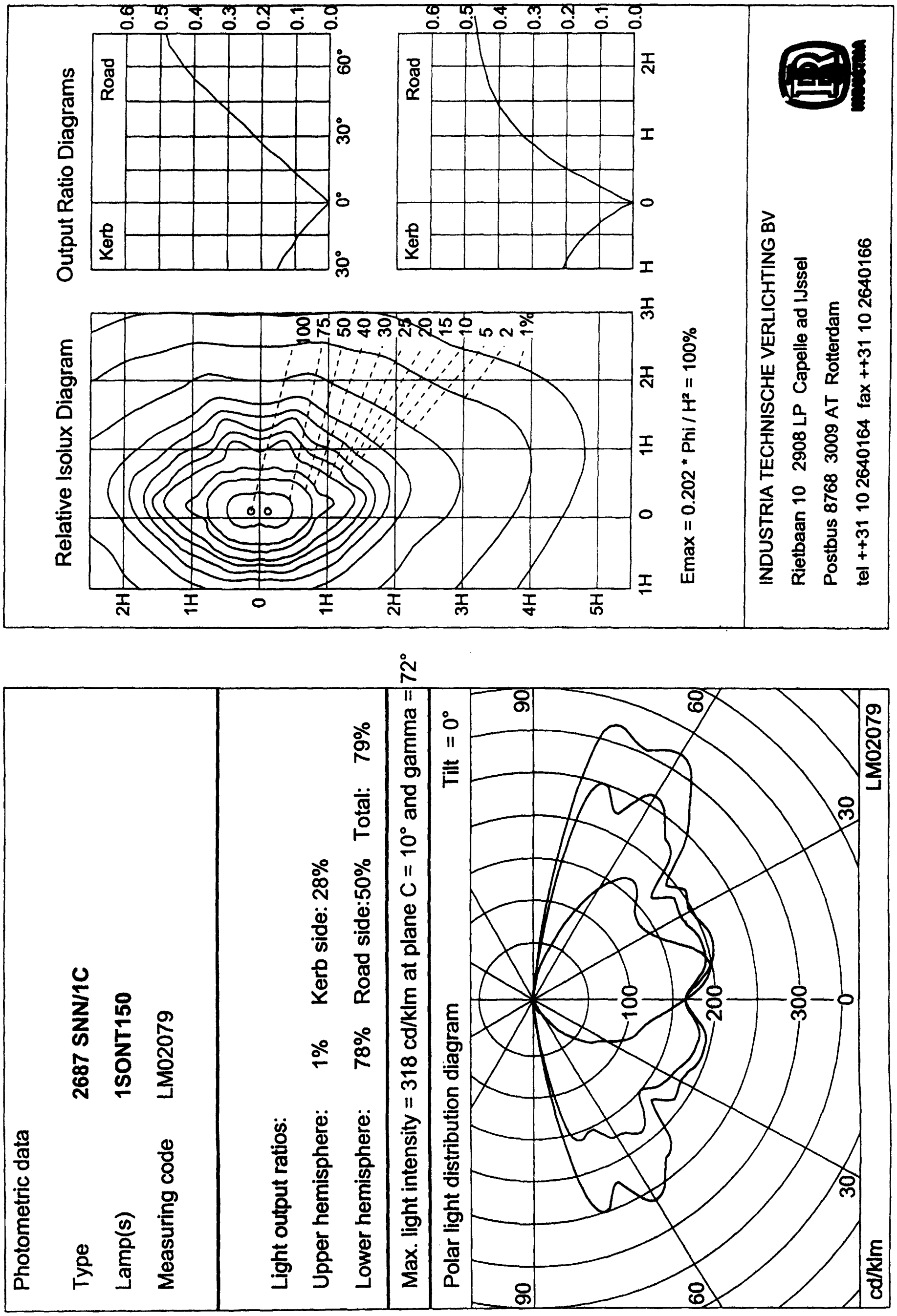

Figure 12.4.6: *Data for the luminaire type ARC with a deep bowl cover.*

12.4.6 Comparisons between installations with luminaires with different cover shapes

(a) Need for comparisons between installations

In most cases, comparisons cannot be made in a straight-forward way, because they involve street lighting luminaires that are not identical, apart from the cover shape. In many cases, the luminaires are members of the same 'family', sometimes even carrying the same type designation. Still, there are differences between the members. Sometimes this has to do with the fact that the cover does restrict the volume that is available inside the luminaire. For a lamp of a certain wattage, a minimum volume is needed in order to avoid overheating. A flat glass leaves less space in the housing than a deep bowl. So, other changes in the design of the luminaire are necessary, that might influence its performance. Another thing is, that, in a flat glass luminaire, as a result of space restrictions, the lamp will be mounted high into the housing. This will automatically lead to a FCO luminaire with a short reach. In order to enlarge the reach, the lamp needs to be installed lower in the housing. With a flat glass cover, this is often impossible, so that a deep bowl, or at least a shallow bowl, is needed. The implication is that not the luminaires themselves, but the installations as a whole are compared. This gives rise to another problem: often, the installations are not fully comparable, because sometimes different lamps, and sometimes even different luminaire arrangements are used. Nevertheless, several comparisons give interesting results that are worth to be mentioned here.

(b) Study in Italy

First, we will summarize a comparison that was made in Italy (Broglino et al., 2000). A number of rather different lighting installations have been compared. The only common characteristics are an average road surface luminance of 1 cd/m^2 and a road reflection of 10 % (Broglino et al., 2000, p. 259). The results are summarized in Table 12.4.8.

Instal. number	Lamp	Cover	Eff.	ULR (%)	Power (W/cd.m^{-2})	Energy rel (%)	Visibility loss (mag)
1	HP Sodium	flat glass	73	0	141	+34	0
2	HP Sodium	curved glass	85	0,1	123	+17	0,01
3	HP Sodium	prism bowl	80	2,8	105	0	0,3
4	HP Sodium	smooth bowl	82	1,8	118	+12	0,2
5	Mercury	smooth bowl	68	1,5	195	+12	0,2
6	LP Sodium	prism bowl	67	3,9	108	+3	0,5

Table 12.4.8: *Comparison between road lighting installations. After Broglino et al., 2000, Table 1. Based on data from Iacomussi et al., 1997.*

The calculation of the visibility loss of stars that can be seen by the unaided eye as indicated in Table 12.4.8 is summarized briefly in Broglino et al., 2000, sec. 2. This type of assessment is discussed in detail in sec. 14.2.2.

From Table 12.4.8 it can be seen that, from the installations that have been included in the comparison, Installation No 1. is the best as regards the loss in visibility. This is to be expected, although it should be noted that the table only contains relative values. The light that is reflected at the road surface is not taken into account. It can also be seen that, even for a small value of ULR of just under 4 %, the visibility loss is considerable: as is explained in sec. 14.3.2, a loss of say from 5,4 to 4,9 Magnitude corresponds with an increase from 190 10^{-6} cd/m^2 to about 560 10^{-6} cd/m^2, or almost a factor of 3 in sky glow luminance (Garstang, 2002).

From Table 12.4.8 it can also be seen that, from the installations that have been included in the comparison, Installation No 3. is the best as regards the use of energy. The differences between the installations that have been included in the comparison, is considerable. Far out the worst is Installation No. 1, the one with the flat glass. It consumes 34 % more energy than the most efficient one – No 3.

(c) *Study in Belgium A*

The study was made, using calculated road lighting installations, with the aim to assess the proportions of the direct and the reflected upward flux (Gillet & Rombauts, 2001, 2003). For this study, reflection measurements were made on different road surfaces. In this summary, only the data for asphalt are quoted. The study involved one member each of five families of luminaires, each equipped with high-pressure sodium lamps:
No 1. spherical luminaire without optics ('globe');
No 2. sphere type with low-efficiency reflector;
No 3. flat-glass cover with high-efficiency reflector;
No 4. glass bowl cover with high-efficiency reflector;
No 5. polycarbonate bowl cover with high-efficiency reflector;
No 6. high-efficiency refractor.
For each luminaire, the optimum spacing was assessed for a lighting installation with the following characteristics:
- Road width: 7 m;
- Overhang: -1 m;
- Mounting height: 10 m.

The requirements according CIE (1995) must be fulfilled:
- $U_0 > 0{,}4$;
- $U_l > 0{,}6$;
- TI < 15%.

The lamps were, if needed, dimmed so far that the Lave is precisely 0,75 cd/m^2.

Because of the large differences in the efficiency of the different families of luminaires, the lamp lumens needed to fulfill the requirements also were very different. The data are given in Table 12.4.9, expressed in lumens installed per km of road.

Luminaire type	Lumen per km
No 1	789 000
No 2	276 000
No 3	192 000
No 4	171 000
No 5	205 000
No 6	136 000

Table 12.4.9: *Installed lumen per km. After Gillet & Rombauts, 2003, Figure 7.*

For each installation, the total (direct and indirect) upward flux was assessed. Also, the split-up between the direct and the indirect components was assessed. In Table 12.4.10, the total upwards flux per km, as well as the split-up, are given for the different luminaire families.

Luminaire type	Total upward lumen per km	Component direct (lm)*	Component indirect (lm)*
No 1	103 368		
No 2	16 469	7 200	12 300
No 3	8 195	0	8 200
No 4	7 555	500	7 100
No 5	9 193	900	8 300
No 6	9 152	2 600	6 600

Table 12.4.10: *Total upwards flux per km. After Gillet & Rombauts, 2003, Figure 6. Spit-up into direct and indirect components. After Gillet & Rombauts, 2003, Figure 8.*

Note: *) the data for the direct and indirect components are approximations.

It follows from Table 12.4.9. that luminaire No 6, the high-efficiency refractor, is the most efficient luminaire as regards as the total flux to be installed. In this respect, No 3, the flat-glass cover with high-efficiency reflector performs considerably less well. However, from Table 12.4.10. it follows, as is to be expected, that, as regards the upward flux, the roles are reversed. No 6, the high-efficiency refractor, shows by far the highest upward flux from all high-efficiency luminaires. By definition, the upward flux of No 3, the flat-glass cover with high-efficiency reflector, equals zero.

It is concluded that using high-efficiency luminaires and applying dimming systems for the lamps to reach precisely the required illuminance or luminance levels are important tools to reduce light pollution (Gillet & Rombauts, 2003, p. 166).

(d) Study in Belgium B

In Belgium, further studies were made as a follow-up to the earlier studies that are summarized in an earlier part of this section (Gillet & Rombauts, 2003). The extended studies are reported by Laporte & Gillet (2003). For a large number of luminaires, the total upward flux was calculated. Part of the data, related to an unilateral lighting geometry for a two lane asphalt road with grass verges, is represented in Table 12.4.11. The luminaires come from three 'families' of cover shape: flat glass, shallow bowl and deep bowl, as described earlier. The best performance and the average performance of all luminaires in each cover type family are given.

Cover type family	**Upward flux** (lumen/km)	
	average	**best**
Flat lens	21 311	17 276
Shallow bowl	19 583	14 935
Deep bowl	24 085	16 538

Table 12.4.11: *Upward flux for different families of cover shape.*
After Laporte & Gillet, 2003, Figure 6.2.

The influence of the type of the road surface, as well as of the verges, is considerable. This is depicted in Figure 12.4.7.

In Figure 12.4.7, the average is given of all 'best solutions' from Table 12.4.11. Figure 12.4.7. relates to an unilateral lighting geometry for a two lane 7 m wide road. The study gives a detailed comparison between asphalt and concrete road surfaces. It was found that, an asphalt road requires a luminous flux that is 37/30 = 1,23 times larger than a concrete road. In spite of that, a lighting installation on a concrete road surface "produces twice the reflected flux than the asphalt does" (Laporte & Gillet, 2003, p. 7). The publication does not discuss this effect. However, it should be noted that concrete road surfaces usually are much more diffuse than asphalt surfaces (De Graaff, 1967; Schreuder, 1967; SCW, 1974, 1984). As is explained in sec. 14.1.8b, the road luminance is determined primarily by the specular component of the reflection indicatrix (S_1), whereas the illuminance is determined primarily by the diffuse component of the reflection indicatrix (q_0). It is explained sec. 3.3.4, that the diffuse part, being mainly responsible for the illuminance, produces primarily the 'sky glow' near the source of light, whereas the specular part, being mainly responsible for the luminance, produces primarily the interference of the astronomical observations at large distances.

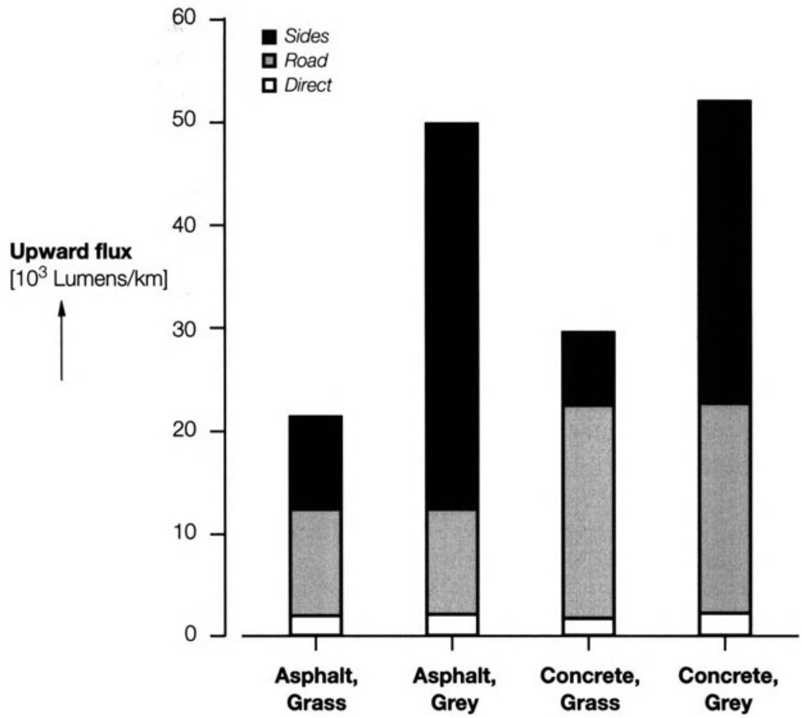

Figure 12.4.7: *The upward flux for different surfaces of road and verge. After Laporte & Gillet, 2003, Figure 7.*

There are two more striking aspects in Figure 12.4.7. First, it is evident that for the conditions chosen here for this comparison, the direct component of the upward flux is very small compared to the indirect component. This is in line with the earlier Belgium study that is summarized earlier in this section (Gillet & Rombauts, 2003). From Table 12.4.10, it is clear that, for all high-efficiency luminaires, the direct upward flux is low, although for reflector luminaires much higher than for flat-glass luminaires. The second striking thing in Figure 12.4.7 is, that the colour or lightness – and probably the texture – of the verges is very important for the total upward flux of the lighting installation.

(e) *Conclusions of the different comparisons.*

When luminaires with different cover shapes are compared directly, it seems that the difference between different cover shapes is marginal. In line with the expectations, the luminaire performance of flat-glass covers is slightly higher, and the upward flux is slightly lower, that those of other cover shapes. Also, it seems that the 'reach' of luminaires with flat-glass covers is slightly smaller than that of other cover shapes. All in all, however, it seems that these differences can be neglected in practice.

When installations with luminaires with different cover shapes are compared, it seems that there may be considerable differences as regards the split-up between the direct and the indirect – or reflected – component of the upward flux. As the different tests were made with installations that differed not only as regards the shape of the cover of the luminaire, it is not possible to assign these differences to the shape alone. It should be noted that, in the comparisons that are described here, the shielding of buildings and trees, nor the glare as experienced by the users of the installations, have been taken into consideration. One may conclude that the shape of the cover of the luminaire has some influence on the performance of the installation, as well as on the total upward flux, but statements that have some general validity, cannot be made. It is sufficient to say that is worth-while to take the shape of the cover of the luminaire into consideration.

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13 Environmental aspects of light pollution

The Earth is heating up. Over the last million years, the average temperature of the Earth varied greatly in what seems a random fashion. In more recent years, there seems, however, to be a systematic, steep rise in temperature. The estimates of the temperature rise are not very precise for three reasons. The first reason is that the data show considerable stochastic differences from one year to the other. The second reason is that the temperature has been measured on a world-wide scale only since the middle of the 20th century and the third reason is that the temperature changes considerably by natural causes. The most dramatic consequence of the global temperature rise is the rise of the sea level. The sea level rise constitutes a severe hazard for the world, particularly in low countries like Bangladesh or parts of China, the USA, and the Netherlands.

It is generally accepted that human activities contribute significantly to the temperature rise. The temperature rise is usually called the 'greenhouse effect'. Quantitative data are available that allow to separate human activities from natural causes like changes in the Sun and from volcanic activity.

Many gasses and vapours contribute to the greenhouse effect. These are often called the 'greenhouse gasses'. The best known, of course, is carbon dioxide (CO_2). The main source of CO_2-emission is the use of fossil fuels. Mass-motorization is a major cause of the increase of CO_2-emission.

CO_2 as such is a harmless gas that favours plant growth and even may be useful to increase crops. However, the increase in CO_2 in the atmosphere leads to an increase of the temperature world-wide. Over the years, several international attempts have been made to curb the greenhouse effect. In 1997, a conference was held in Kyoto, Japan, in which the 'Kyoto Protocol' was adopted. It is agreed that the EU is obliged to reduce in 2008-2012, the greenhouse gas emissions to a level 8% lower than that of 1990. One of the many means that may help to achieve this, is to reduce light pollution.

In order to assess the reach of such a measure, details are given about the use of energy in general, as well as the use of electric energy. Because the generation of electric energy by means of fossil fuels is one of the major contributing factors in the CO_2-emission, considerable attention is devoted to

alternative and non-CO_2-energy sources. Special attention is given to stand alone electric installations, with emphasis to biomass and solar energy sources. At present, solar energy is mainly used to heat water in homes in sunny climates, but solar energy panels are a promising solution, particularly in view of their rapid technical evolution.
The reason for the interest in energy for outdoor lighting, is that, promoting 'clean', non-polluting, lighting has a favourable effect on the emission of CO_2, and thus contributes to the reduction of the greenhouse effect. At the same time. it may reduce power costs. Of course, outdoor lighting uses only a small part of the total electric energy, but little things do help.

13.1 Energy production and energy saving

13.1.1 Greenhouse effect

(a) *Global warming*

The Earth is heating up. Over the last half million years, the average temperature of the Earth varied greatly. A survey is given in Figure 13.1.1.

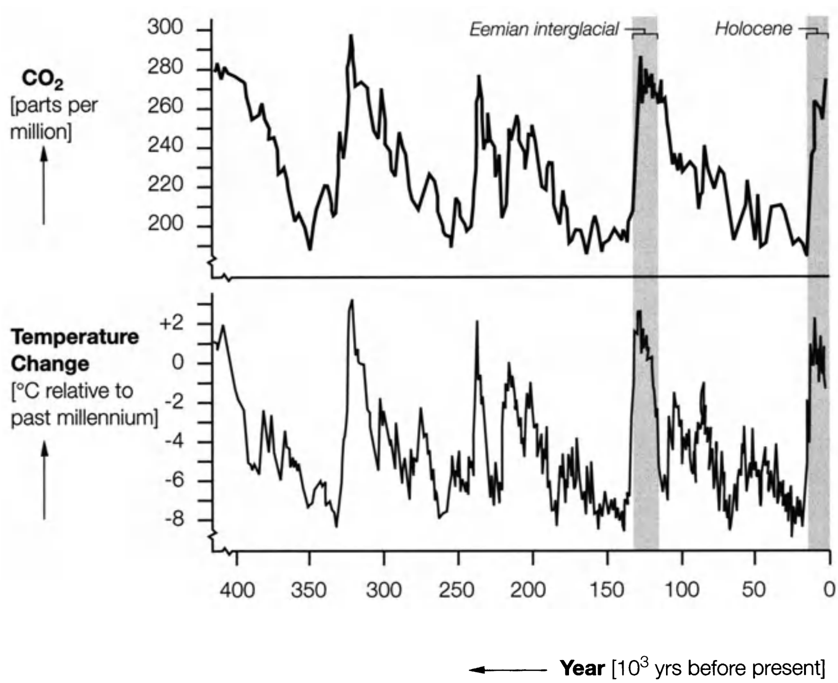

Figure 13.1.1: *Global temperature and CO_2-concentration. The temperature is expressed in the change relative to the past millennium. 'Eemian' and 'Holocene' are interglacial periods. After Hansen, J., 2004, p. 43.*

In more recent years, there seems, however, to be a systematic steep rise in temperature. See Table 13.1.1.

Year	Temperature (°C)	Year	Temperature (°C)
1860	0,00	1940	0,31
1879	0,01	1950	0,31
1880	0,03	1960	0,31
1890	0,05	1970	0,31
1900	0,06	1980	0,31
1910	0,08	1990	0,50
1920	0,18	1995	0,66
1930	0,23	2000	0,83 (extrapolated)

Table 13.1.1: *Average world temperature. Relative scale, 1860 is zero (based on smoothed data from Anon., 1997, p. 8)*

In Table 13.1.2, some other data are given, not relative but in absolute terms (Bradford & Dorfman, 2002).

Year	Temperature (°C)
1880	13,77*
1900	13,8
1920	13,8
1940	14,0
1960	14,0
1980	14,1
2000	14,43*
2020	15,0**
2040	15,5**
2060	16,3**
2080	17,2**
2100	17,5**

Table 13.1.2: *Global annual average temperature. Interpolated from Bradford & Dorfman, 2002, p. 17.*

Notes:
*) actually quoted values
**) average between highest and lowest projection

The estimates of the temperature rise are not very precise for several reasons. The first reason is that the data show considerable differences from one year to the other. The extent of these natural variations is depicted in Figure 13.1.2.

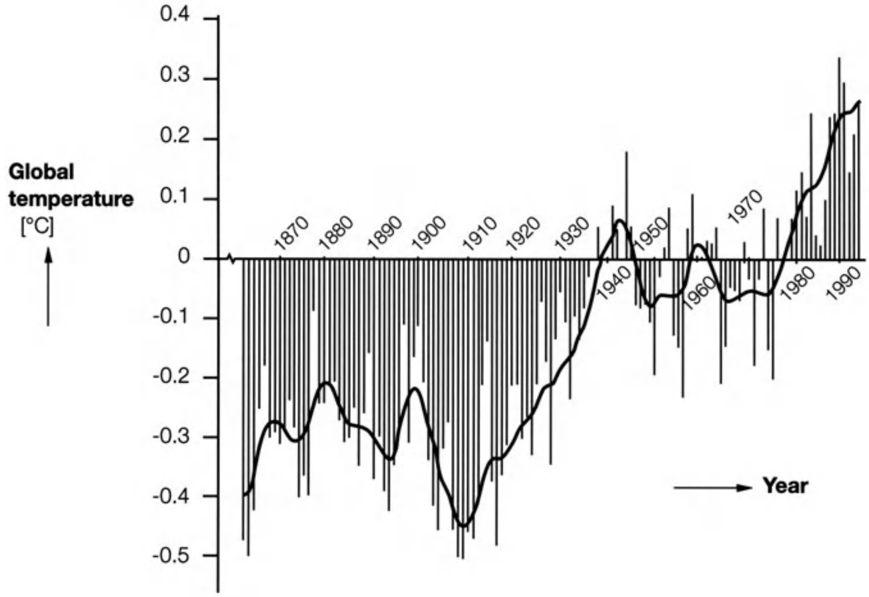

Figure 13.1.2: *The global temperature (in °C) from 1860 to 1995, normalized at the average of years 1961-1995; 1995 equals + 0,4. After Von Baratta, 1996. p. 1121. Based on data from Hadley-Centre, 1996.*

The second reason that the estimates of the temperature rise are not very precise, is that the temperature has been measured on a world-wide scale only since the middle of the 20th century and because the temperature changes considerably by natural causes. A study from 1977 estimates an increase of about 2,5 degrees C in fifty years – ending in 2030 (Anon., 1977, p. 59). Furthermore, any rise in temperature its counteracted by a decrease in temperature due to the dust and smoke in the atmosphere which is, just as the rise in CO_2 an effect of human activities (Anon., 1977). Many other adverse effects are given that might result from a global temperature rise.

More details can be found in Lamb (1995). This book gives a complete overview of the different elements that determine the climate of the Earth and their interactions. particularly in the recent past as well as the consequences for the near future.

More data have been published regarding the changes in global temperature. As they agree roughly, but not in all details, we will quote several more. In one, the measurements of the average temperature made at a number of meteorological stations all over the world are compared. Between 1946 and 1975, 19 stations reported a systematic cooling between 0,2°C and more than 0,3°C per decade at a 5% significance level. At 55 stations, no systematic change was found. In a later period, between 1976 and 1999, 30 stations, almost all in Eastern Europe reported no change, whereas each of 51 stations, an increase of more than 0,3°C per decade was reported. The number od stations involved in this study, obviously changed in that period. The change seems therefore to be of recent times. These data are derived from Klein Tank et al. (2002, p. 21). The number of stations is approximative only.

The first consequence, that is mentioned often, is the rise of the sea level as a result of the global temperature rise. Melting glaciers may contribute to this, but melting sea ice does not, because it is floating: if part of the sea ice melts, it will only, according to Archimedes's principle, decrease the amount of ice sticking out over the sea surface. It is often assumed that the major contribution to the rise in sea level is a result of the thermal expansion of the sea water itself. Some estimated values of the sea level rise are given in Table 13.1.3.

Year	**Sea level** (cm)
1700	0
1750	0
1800	1
1850	5
1900	11
1950	17
1990	25
2000	27 (extrapolated)

Table 13.1.3: *Sea level at Amsterdam and Den Helder in cm. Relative scale. 1700 is zero (based on Anon., 1997, p. 11)*

It should be noted that these values are well in line with several of the most common estimates of the sea level rise world-wide. See Anon. (1997, p. 11). The models for the rise in world temperature and the related rise in the sea level show large differences in their outcome. The prognosis according to the two-dimensional IMAU-model is a rise of just over 1,5 cm between 1995 and 2000 and of 4 cm between 1995 and 2020. According to the one-dimensional IPCC-model, the values are 2 cm and 7 cm respectively. No data regarding these models are given (Anon., 1997, p. 21). Some quote a temperatue rise of 0,3 to 0,6°C and a corresponding rise of the sea level of 0,1-0,25 m (Von Baratta, ed., 1996. p. 1121). According to the Intergovernmental Panel on Climate Change IPCC, a rise of the sea level of 0,15-0,95 m is to be expected for the year 2100, the best estimate being 0,5 m (quoted by Von Baratta, ed., 1996. p. 1121).

Whichever model is the best, it is certain that the sea level rises and that this rise constitutes a severe hazard for the world. The rise in sea level will lead to more floods, particularly in low countries like Bangladesh or parts of China, the USA and the Netherlands. It should be noted that the majority of world metropoles are often just a few meters above the mean sea level, like e.g. New York, London, Tokyo, Dhaka, Amsterdam, Hamburg, Shanghai, Rio de Janeiro – just to name a few.

There are positive sides to a rise in temperature. Some of them may be estimated from a book written in 1977, when the main concern was not the heating, but the cooling of the Earth (Anon., 1977). But most effects are considered as having negative results, some even catastrophic. Some refer to the distribution of wet and dry regions on Earth; it is often assumed that the wet parts of the world will get wetter, and the dry parts dryer. This would result in a smaller area for agriculture and thus to an increased risk of famines. Also, a rise in temperature would favour the population of pests like mosquitos to grow, leading to more severe epidemics of malaria etc. It is often stated that a rise in temperature will lead to more natural disasters like storms, floods, droughts, severe winters, and even earthquakes, as these are often triggered by a sudden drop in barometric air pressure near tropical storms (Francis & Hengeveld, 1998; Vellinga & Van Verseveld, 1999; Hansen, 2004).

"Scientists now believe that hazards occur more frequently due to global warming. Swiss studies indicate that Alpine glaciers have receded between 5% and 40% since the early 1970s. It's hard to say how much is due to natural forces and how much human activity is to blame" (Anon., 2002b).

"The climatic system is so complex, that nothing can be proved with certainty. But when scientists say 'uncertainties', in societal terms one should say 'risks'" (Schöne, 2000. p. 17).

(b) Global warming and the greenhouse effect

It is generally accepted that human activities contribute significantly to the temperature rise. The temperature rise is usually called the greenhouse effect. As such, the greenhouse effect is essential for life on Earth as we know it today (Anon, 2000a, p.11). Without it, the average temperature on the surface of Earth would be about 33°C lower (Anon. 2000a, p.15). It is generally assumed that the greenhouse effect is caused by emitting several greenhouse gasses into the atmosphere.

The greenhouse effect got its name because the Earth atmosphere, just like the glass roof in a greenhouse, allows the incoming solar radiation to pass through, but the outgoing radiation is trapped. The result is predictable: the greenhouse heats up. The physical basis for this is discussed in a further part of this section.

It must be noted, that the clarity of the atmosphere is important. If the atmosphere contains more aerosols like dirt, or more water vapour in the form of clouds, its reflection – or 'albedo' as astronomers use to call it – increases. Although dirty clouds with aerosols like soot absorb more light, they reflect more sunlight as well. After the fall of the Berlin Wall, most of the dirty Eastern European industry was closed down, removing the dirty clouds. The light reflection of the clouds diminished by 2,8%, resulting in an increase of the irradiance of 1,5 Watt per square meter at ground level. This is based on a study of the Max Planck Institute in Germany (Anon., 2002, p. 13). No further references are given. This is just over 2% of the average solar irradiance at sea level, which is about 700 W/m^2 (Herrmann, 1993, p. 105).

The greenhouse effect can be described as follows. See also sec. 11.1. The temperature of any physical body is determined by the difference between the incoming and outgoing energy flow. It reaches an equilibrium value when the two flows are equal. In the case of the Earth, the incoming energy comes from the Sun; the Earth loses energy because it radiates heat. When the heat radiation from Earth into space is diminished as a result of the greenhouse effect, the temperature rises. At the higher temperature, the Earth emits more radiant energy, so a new equilibrium will be reached, where the incoming and outgoing energy flows are again equal. To get a feeling for the order of magnitude, the total energy of the sun that hits the Earth corresponds to 230 trillion horsepower; or 2,8 million Watt per acre at the top of the atmosphere. In ISO-measures this is $169 \cdot 10^{15}$ kW or 691 W/m^2 respectively. 53% of the energy at the top of the atmosphere reaches the surface of he Earth (Anon., 1990).

It is interesting to note, that in a country at a rather high latitude like the Netherlands at 53 degrees Northern latitude, the total energy consumption represents only 0,2% of the solar energy that hits the surface of the Earth. Closing the CO_2-cycle by planting trees is not feasible; the total area required would be 130 times the total national area – obviously out of the question. This review article is a plea for the use of solar energy. Unfortunately, it is not added how this could be realized (Anon., 2002, p. 44).

In physical terms, the greenhouse effect is basically a result of Wien's Law, or the Displacement Law, that is explained in sec. 11.1.1. The atmosphere is transparent for the short-wavelength visible light, but not transparent for long-wave radiation like infrared radiation. This implies that sunlight can pass through the atmosphere, and hit the surface of the Earth. The surface will be heated up, and will begin to act as an blackbody radiator. In sec. 11.1.1d, it is explained that the electromagnetic radiation from a blackbody radiator depends in two ways on the temperature of the radiator.

(1) As the temperature increases, the total energy that is emitted, increases rapidly with the fourth power of the temperature. This is the Stefan-Boltzman Law.
(2) As the temperature increases, the wavelength where the maximum energy is emitted, shifts towards the short wavelength. This is Wien's Law.

The second effect is the basis for the greenhouse effect, that has been described earlier. The sun has a temperature if some 6 000 K. The wavelength of maximum energy emission is about 500 nm. The Earth, heated by the sun, will reach a temperature of about 300 K. For that temperature, the wavelength of maximum energy emission is in the far infrared.

The first passes through the atmosphere, the second not. So, the sun's energy is trapped in the Earth's atmosphere. Some farmers may like it in their greenhouses. For the world as a whole this effect may be disastrous.

In another study, a critical evaluation is given about the scientific basis of climatic changes and the human influence on it. Also, a survey of the atmospheric models that were used at that time, is given, as well as an assessment of the results (Crutzen & Graedel, 1996). Since 1900, the global average temperature did rise between 0,3°C and 0,6°C. According to the models prevailing at that time, it was expected that in the year 2100, the temperature would be between 1°C to 4°C degrees higher, which would lead to a rise in the sea level of 15 to 95 cm (Crutzen & Graedel, 1996, p. 130). These data are probably the same that have been quoted earlier in this section (Von Baratta, ed., 1996. p. 1121).

"During the years of their research, scientists are attacked on their theories, and they still are. The readers know better since, but still we list the most important objections, followed by a critical comment" (Crutzen & Graedel, 1996, p. 157). When comparing the quotations from Calder (1997) and Crutzen & Graedel (1996), there seems to be a real risk that the important discussion on the influence of human activities on the climate and on the conditions for life on Earth, will bog down in some in-fighting between professors and journalists. More recent results, however, seem to indicate that the 'warners' are right and the 'do-as-you-pleasers' are wrong.

We mentioned Calder. Nigel Calder is a well-known journalist who published several influential popular-scientific books in which he critically assessed a number of items in modern physics. One of his more recent books is about the greenhouse effect. He is among the few left over who do not believe in the greenhouse effect. His point of view is that, after proving the greenhouse theory as wrong, "the ordinary citizen was delivered from the threat of a greenhouse catastrophe" (Calder, 1997, p. 195). Environmental activists should focus on saving endangered species, although they should take care "of the dangers of too enthusiast meddling in other's businesses" (Calder, 1997, p. 195). Furthermore, he asserts that: "The error was restricted to a small, but determined minority who pretended to speak for the whole scientific discipline" (Calder, 1997, p. 196). In short, the whole last section of that interesting book is just a compilation of the standard arguments that are used by the oil and coal lobby to defend the sales of fossil fuels (Calder, 1997, p. 195-199). In his own words, the environmentalists want that: "the world should be saved from the claws of the oil and coal producers" (Calder, 1997, p. 197). Needless to say that the majority of modern scientists agree with this, and do not agree with Calder. According to Calder, the greenhouse theories have collapsed: "Thanks to a couple of scientists from Copenhagen who, in their spare time, fiddled about with their pc's, and booked laudable progress" (Calder, 1997, p. 195-196).

In contrast, an equally influential book (Anon., 1981) devotes a whole chapter to the dangers of the greenhouse effect (Ayensy, 1981). Together with human activities like deforestation: "Mix this with man's apparent destruction of the ozone layer and you have a recipe for global disaster" (Ayensy, 1981, p. 134). This is, of course a qualitative expression dating from 1981; since then, plenty of quantitative data are available that also allow to separate human activities from natural causes like changes in the sun and volcanic activity.

An independent 'think tank' in the Netherlands has published a report on environmental policies (Anon., 2000a). Although this report is primarily aimed at the issues as they are relevant for the Government of the Netherlands, many more general aspects of the problems related to climate changes, are covered. We will present several interesting quotes from this report.

It should be noted, that not all man-made emissions into the atmosphere cause a rise in temperature. Some emissions, notably aerosols like e.g dust and sulfuric aerosols, have a cooling effect on the surface of the Earth (Anon., 2000a, p. 16). This effect is mentioned in an earlier part of this section, when discussing the opinions about climatic changes as they were prevalent in the 1970s (Anon., 1977). Also, solar activities have an influence on atmospheric phenomena on the Earth (Anon., 2000a, p. 17). The overall effect of these three influences is depicted in Figure 13.1.3.

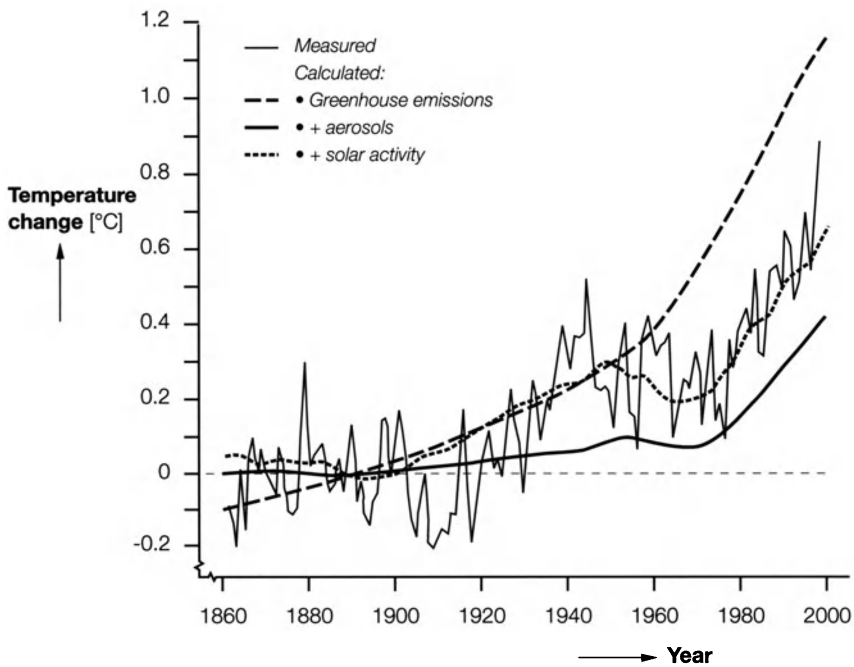

Figure 13.1.3: *The temperature of the atmosphere between 1860 and 2000, (a) as measured, and as calculated, when considering respectively greenhouse emissions (b); greenhouse emissions and aerosols (c), and greenhouse emissions, aerosols an solar activities (d). After Anon., 2000a, Figure 5. Based on Wigley, 1999.*

The Kyoto Agreement, that was mentioned earlier, gives requirements only for the so-called Annex-1 countries. These countries include the OECD-countries, Eastern Europe and the former Soviet Union (Anon., 2000a, p. 29). For industrialised countries, the Kyoto Agreement states that in total the ceiling of the CO_2-emission in 2008-2012 must be 5,2% lower than emission in 1990 (Anon., 2000a, p. 30). For the 'non-Annex-1 countries', no limits are given. These countries include most developing countries in Asia, Africa, and Latin America, but also big, rapidly developing countries like China and India. Furthermore, international aviation and shipping are exempt (Anon., 2000a, p. 31 and Figure 7). The different sources provide slightly different values for the Kyoto Agreement, maybe because the data refer to different groups of countries.

In conclusion, we may state that it is generally accepted that the temperature of the world is increasing at a pace unprecedented in history, and probably also in prehistory. Also, it is generally accepted that this temperature rise is caused by a greenhouse effect, where the transmission of infrared radiation into space is hindered by greenhouse gasses. In the following parts of this section, it will discussed the increase of the abundance of greenhouse gasses, as well as the possible influence of human activities in this increase.

(c) Greenhouse gasses

Many gasses and vapours contribute to the greenhouse effect. These are often called the 'greenhouse gasses'. The best known, of course, is Carbon Dioxide (CO_2). It is, however, not the only greenhouse gas, and not even the most hazardous. See Table 13.1.4.

Gas	Name	Greenhouse effect
CO_2	carbon dioxide	1
CH_4	methane	30
N_2O	di-nitrogen oxide	150
O_3	ozone	2.000
CFK	chloreflurohydrocarbon	15.000

Table 13.1.4: *Hazards of greenhouse gasses. Relative values, based on CO_2 = 1. After Schreuder, 1998, Table 14.3.1, based on data from Kuhn (1990, Abb. 27).*

However, its abundance makes CO_2 the most serious greenhouse gas in absolute terms. See Table 13.1.5.

Gas		Greenhouse contribution (%)
CO_2	carbon dioxide	55
CH_4	methane	15
N_2O	di-nitrogen oxide	6
CFK	chloreflurohydrocarbon	24

Table 13.1.5: *The greenhouse effect in absolute terms.*
After Schreuder, 1998, Table 14.3.2, based on data from Anon. (1990a)

All do increase, but not at the same pace. Some data are given in Table 13.1.6.

Gas	Before industrial revolution	1994	Increase (%)
carbon dioxide (ppm)	280	360	28,6
methane (ppb)	700	1666	138
di-nitrogen oxide (ppb)	285	309	6,4

Table 13.1.6: *Increase in concentration in several greenhouse gasses. After Von Baratta, ed., 1996. p. 1122. Based on data from the World Resource Institute and of the World Meteorological Organization. See also Figure 13.1.1.*

Note to Table 13.1.6:
- ppm (parts per million) 1/1 000 000;
- ppb (parts per billion) 1/1 000 000 000.

Another way to represent the severity of the situation, as well as the differences between the influence of the different greenhouse gasses is given in Table 13.1.7.

Greenhouse gas		Relative disturbance (%)
CO_2	carbon dioxide	55
CH_4	methane	17
O_3	tropospherical ozone	14
CFK	chloreflurohydrocarbon	9
N_2O	di-nitrogen oxide	5

Table 13.1.7: *Relative disturbance of the man-made influence of the radiation balance of the Earth (in %) since the year 1750. After Von Baratta, ed., 1996. p. 1123. Based on data from IPCC, 1995.*

When considering the data from the Tables 13.1.4 to 13.1.7, some of the criticism of the Kyoto Agreements is easy to understand. We will come back to the Kyoto Agreement in a further part of this section. The Kyoto Agreement deals in principle with all greenhouse gasses, but quantitative goals are given only for CO_2. When combatting the climate changes that are triggered by the greenhouse effect, it seems to be short-sighted to focus all attention, all efforts and all money exclusively on CO_2. True, its contribution is the largest, but methane and CFKs are very important as well. CFKs, although important, seem to be more or less under control now. Methane is a waste product of drilling for oil and of raising cattle. One might suspect that the oil and beef industries will not easily cooperate in the realization that their waste is almost as dangerous as the waste of individuals who drive around in cars and utility vans! However, as CO_2 contributes, at least for the moment, most to the greenhouse effect, we will follow the trend to focus on that gas.

13.1.2 CO_2-emission

(a) *The carbon content of the atmosphere*

The CO_2 content of the atmosphere has not been constant. Over last 140 000 years it did vary between 200 to 300 ppm (1000 ppm equals 0,1%). Over the last 10 000 years, between 275 to 300 ppm. Around 1900 is was 280 ppm, whereas in 1995 it was 360 ppm (Anon., 1997, p. 6). Thus, during the last 140 000 years it was never as high as at present. These data agree with those given in Figure 13.1.1.

A more detailed representation of the steep increase in CO_2-abundance is given in Figure 13.1.4.

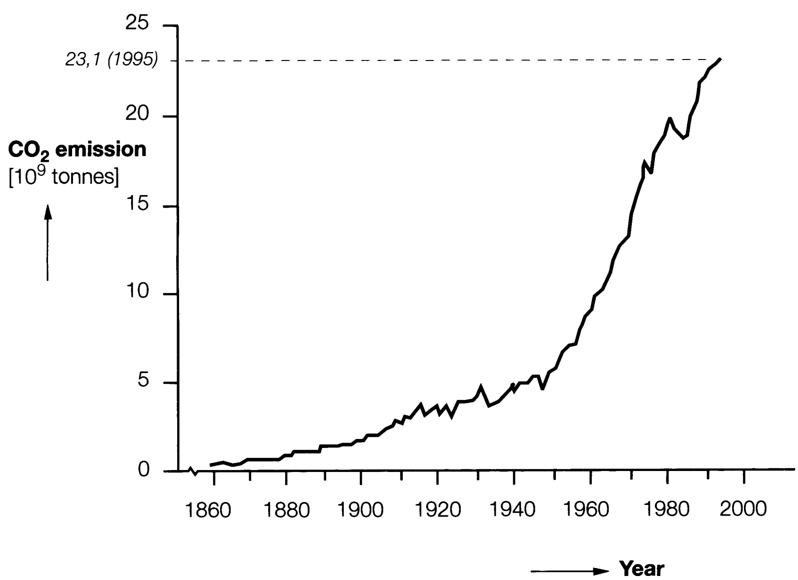

Figure 13.1.4: *Global CO_2-emission between 1860 and 1995. After Von Baratta, ed., 1996. p. 1123. Based on data from the Carbon Dioxide Information Analysis Center and the World Energy Council.*

Regarding the world-wide emission of CO_2, a recent report did show that, as is well-known, the USA are by far the greatest culprits. See Table 13.1.8. The report was shown on Dutch television on 19 July 2001 without further reference.

Country	Relative CO_2-emission (%)
USA	34
Canada	2
Australia	2
Japan	8
Europe	24
Rest	30

Table 13.1.8: *Relative CO_2 emission per country (no reference)*

The use in absolute terms, per nation, and per capita, are given in Table 13.1.9.

Country	CO_2-emission (10^9 tonnes)	Per capita (tonnes)
USA	4,88	19,1
China	2,67	2,3
Russia	2,1	14,1
Japan	1,09	8,8
Germany	0,88	11,0
India	0,77	0,9
Ukraine	0,61	11,8
United Kingdom	0,57	9,8
Canada	0,41	15
Italy	0,41	7
for comparison:		
Egypt	0,083	1,5
Philippines	0,0498	0,77
Kenya	0,005	0,2
Cambodia	0,0004	0,04

Table 13.1.9: *The top-ten countries in CO_2-emission, with some other countries as a comparison. After Von Baratta, ed., 1996. p. 1124. Based on data from the Carbon Dioxide Information Center.*

Another report quotes different figures. This should warn us not to put too much trust in these reports. It is not always easy to compare the data from different sources, because they are given in different ways. Most are only summaries of more extensive – and probably more precise – reports. It should be noted that, as was suggested earlier in this section, the reports are sometimes quoted to 'make a political point'. This might shed some doubt on the validity of the data as they are quoted in the popular press. Probably, the differences are just a matter of different definitions, but one never can be certain about that. "The USA, with 5% of the world population, is responsible for more than 25% of the CO_2-emission, that is $5{,}6 \cdot 10^9$ tonnes per year" (Anon., 2002c).

Still another report gives another split-up of the different countries (Anon., 1994). See Table 13.1.10.

Group of countries	Energy use total (10^{15} J)	Energy use per capita (10^9 J)	CO_2-emission total (10^6 tonnes)	CO_2-emission per capita (tonnes)
OECD	166 809	199	10 385	12,4
Eastern Europe*	74 481	175	4 989	11,7
other countries**	100 621	24	6 754	1,6

Table 13.1.10: *CO_2-emission in 1990. (Anon., 1994, p. 97).*

Notes:
*) Russia included
**) Non-OECD and Non-Eastern Europe means, in practice, the developing countries

In still another study, the worldwide CO_2-emission is given by region. See Table 13.1.11.

Year	Developing countries	Europe Western	Europe Eastern	USA	Japan
1900	0,005	0,03	0,01	0,02	0,005
1910	0,005	0,035	0,01	0,03	0,005
1920	0,006	0,04	0,008	0,04	0,005
1930	0,007	0,04	0,01	0,05	0,005
1940	0,008	0,035	0,015	0,04	0,008
1950	0,01	0,03	0,015	0,065	0,005
1960	0,035	0,055	0,035	0,075	0,007
1970	0,5	0,07	0,07	1,05	0,015
1980	1,15	0,08	1,15	1,2	0,02
1990	1,95	0,075	1,25	1,05	0,02
2000	2,45	0,07	0,07	1,4	0,025

Table 13.1.11: *Carbon emission per year per country, 10^9 metric tonnes (after Doyle, 2002, p. 17)*

The world carbon emission from fossil fuels is given in Table 13.1.12. (Anon., 2002d).

Country	Percent of world emission	Emission per capita (metric tonnes)
USA	24	5,4
China	14	0,7
Russia	6	2,7
Japan	5	2,5
India	5	0,3
Germany	4	2,8
Canada	2	4,2
UK	2	2,5
South Korea	2	2,2
Italy	2	2,0
France	2	1,7
Mexico	2	1,1

Table 13.1.12: *World carbon emission from fossil fuels (After Anon, 2002, p. 17).*

For the Netherlands, the relevant data are given in Table 13.1.13 (Oliver et al., 2002)

Year	CO_2		Total greenhouse gasses	
	emission	index	emission	index
1990	158	100	208	100
1991	166	105	220	105
1992	164	104	217	104
1993	166	105	219	105
1994	167	106	221	106
1995	171	108	222	106
1996	178	113	233	111
1997	167	106	223	107
1998	174	110	225	108
1999	171	108	217	104
2000[1]	172	108	216	103

Table 13.1.13: *Greenhouse emission in the Netherlands 1990-2000 (in Tg CO_2-equivalent; 1 Tg equals 1000 kiloton). After Oliver et al., 2002. table 3.1. (rounded off values).*

Note: 1): preliminary numbers.

(b) *Trends in CO_2-emission*

For Europe, the following data are quoted (Anon., 1996). See Table 13.1.14.

Country	**CO_2-emission** (million tonnes) **1990**	**1994**	**Difference 1990-1994** (%)
EUR 15	3188	3103	-2,7
EUR 12	3025	2929	-3,2
Austria	58	57	-1,6
Belgium	111	117	+5,9
Denmark	53	63	+18,9
Finland	53	61	+13,9
France	368	349	-5,0
Germany	992	897	-9,5
Greece	73	78	+6,7
Ireland	31	32	+3,3
Italy	402	393	-2,2
Luxembourg	12	12	-2,8
Netherlands	157	164	+4,9
Portugal	40	45	+13,8
Spain	209	229	+9,5
Sweden	52	56	+7,5
U.K.	579	550	-5,0

Table 13.1.14: *CO_2-emission in Europe (after Anon. 1996, p. 6).*

These data are split up for different sectors, See Table 13.1.15.

Sector	**CO_2-emission difference 1990-1994** (%)
EU total	-2,7
thermal power stations	-4,4
industry and energy	-7,7
transportation	+7,6
road traffic	+7,2
air traffic	+13,3
residential etc	-8,3

Table 13.1.15: *CO_2-emission, difference 1990-1994 per sector (after Anon. 1996, p. 6,7).*

There are more statistics to be given. In 1990, the atmosphere did contains 25% more CO_2 as at the beginning of the industrial revolution (Schreuder, 1998; Seager, ed., 1991, p. 61). Per year, 22 thousand million tonnes of CO_2 are added (Seager, ed., 1991, p. 116).

Mass-motorization is a major cause of the increase of CO_2-emission. Around 1990, the number of passenger cars world-wide was about 400 million. The distribution of them over the world is given in Table 13.1.16.

Country	Percentage of cars
USA	35
Western Europe	32
Japan	7
Latin America	7
Eastern Europe (including DDR)	4
Soviet Union	3
Canada	3
Australia, Oceania	2
Africa	1
Rest of the world	6
Total	100

Table 13.1.16: *Distribution of the 400 million passenger cars per country expressed as percent of he world population of cars, 1990. Data from Seager, ed., 1991, p. 77).*

For the Netherlands, some corresponding data, as well as the trend in time, are given in Table 13.1.17.

Mode of transport	1990 (Tg)	2000 (Tg)	Increase (%)
road transport	25,4	31,5	24
off-road transport	2,3	2,3	0
internal navigation	0,9	1,0	14
civil aviation	0,5	0,3	-43
railways	0,1	0,1	26
total	29,1	35,1	21

Table 13.1.17: *$C0_2$-emission for the Netherlands. After Oliver et al., 2002, table 8.11.*

However, there are also positive signs. In the Netherlands, since 1980 the number of cars on the road did grow by almost 40% from 4,2 million to 6,9 million in 2002. The NOX-emission did decrease in the same period to 20% in 2002, with 100% for 1980, whereas the CO-emission did decrease to 30% in 2002, also with 100% for 1980. It is assumed that the use of cleaner fuels and particularly the obligatory use of catalysts is responsible for this. Also the emission of CO_2, did decrease in the same period, although catalysts have no influence on this emission. It is assumed that using more efficient cars with better designed engines is responsible for this (Anon., 2003f).

(c) *The Kyoto-agreement*

CO_2 as such is a harmless gas that favours plant growth and even may be useful to increase crops. However, it is, as indicated earlier, a greenhouse gas; the increase in CO_2 in the atmosphere leads to an increase of the temperature world-wide. The scientific community is, however, convinced that the temperature rise can be attributed directly to the greenhouse effect of CO_2 and other gasses. What is more, it seems that earlier prognoses were too lenient. It is estimated now that the global warming towards the end of the 21st century will be 5,3 degrees centigrade, according to recent UN forecasts – twice what was predicted in 1995 (Anon., 2001).

Over the years, several international attempts have been made to curb the greenhouse effect. Its influence is at any rate very serious, and may be even catastrophic for the whole Earth in the future. Some of these activities have been triggered by the influential book of Al Gore, at that time US Senator (Gore, 1992). It is very disturbing to note that this interest did lead to nothing, after the same Al Gore was elected to Vice-President of the United States. Since the change of the administration, the last hope that the United States would take the greenhouse effect, or any environmental effect for that matter, light pollution included, seriously, is completely evaporated. Fortunately, though, there are other influential books that stress the need to be careful with the natural environments, and that are optimistic in tone, provided some international agreements are made (Goodenough, 1998; Goodal, 1999; Van Lawick-Goodal, 1971).

The first major effort was made at the Rio de Janeiro-conference in 1992. Here, a principal decision was made to reduce the greenhouse effect (Anon., 2000a, p. 29). This convention was, in July 1996, ratified by 159 sates (Von Baratta, ed., 1996. p. 1125). The next major conference was held in 1997 in Kyoto, Japan, in which the so-called Kyoto-protocol was adopted. As mentioned earlier, the protocol refers to all greenhouse gases but concentrates on the reduction of CO_2-emission. As a general guideline, it has been stated that each country should aim to reduce the CO_2-emission by 5%, compared to the level of 1990.

As is mentioned in an earlier part of this section, the Kyoto Agreement gives requirements only for the so-called Annex-1 countries. These countries include the OECD-countries, Eastern Europe and the former Soviet Union (Anon., 2000a, p. 29). For industrialized countries, the Kyoto Agreement states that, in total, the ceiling of the CO_2-emission in 2008-2012 must be 5,2% lower than emission in 1990 (Anon., 2000a, p. 30). For the non-Annex-1 countries, no limits are given. As mentioned earlier in this section, these countries include most developing countries in Asia, Africa and Latin America, but also big, fast-developing countries like China and India. Furthermore, international aviation and shipping are exempt (Anon., 2000a, p. 31 and Figure 7).

More specifically, it was agreed that the EU is obliged to reduce, in 2008-2012, the greenhouse gas emissions to a level that is 8% lower than that of 1990 (Schöne, 2000. p. 17). The Netherlands agreed to reduce the CO_2-emission by 6% (Anon, 2003a). One might meet slightly different values for the Kyoto Agreement requirements. This probably results from the fact that different groups of countries are considered.

For Belgium, the policy goal is a 7,5% reduction of the emission of greenhouse gasses in 2010, as agreed in the Kyoto Protocol. One of the proposals to reach that goal it to construct, at sea, a wind turbine fleet that is planned to produce 6 to 10% of the demand of electric energy in Belgium (Anon., 2003, p.5).

In Table 13.1.18, the national CO_2-emission for 1990 is given, together with the average reduction factor and the targeted emissions for 2012. After FAIR, 2003, table 5.

Region	Emission 1990	Reduction Factor	Targeted emission 2012
Canada	125 795	0,94	118 248
USA	1 344 245	0,93	1 250 148
Western Europe	932 263	0,92	858 651
Eastern Europe	258 748	0,93	240 515
Former Soviet Union	935 617	0,92	864 553
Oceania	81 978	1,07	87 985
Japan	306 691	0,94	288 289
Total	3 916 500	0,95	3 708 390

Table 13.1.18: *CO_2-emission targets (in 10^9 gram Carbon). After FAIR, 2003, table 5.*

It should be noted that Table 13.1.18 refers only to the countries that agreed to the Rio Standards, not necessarily to the Kyoto Agreement. So, the USA still appears in the table. It is clearly stated that the CO_2-emission in other countries – more in particular the developing countries of Africa, Asia and Latin America, that include a.o. India and China – is allowed to increase. Futhermore, it should be noted that the Kyoto Agreement has been, up to the beginning of 2002, ratified by only 15 of the required 55 countries (Anon., 2003a). Finally, it should be stressed that the IPCC has stated that in 2050, the industrialized countries ought to reduce greenhouse gas emission by no less than 80% (Anon., 2003a). So, even if the Kyoto Agreement would survive, it is nothing more than a first, minor, but important step. The Kyoto Agreement still might fall completely apart, because the USA refuse to ratify it, a standpoint that is likely to be shared by some large industrialized counties like Japan and Russia. No one can predict the future of the Kyoto Protocol.

In spite of these negative signals, the government of the Netherlands maintains its standpoint, that the Kyoto Agreement should be implemented as far as possible. It seems that this standpoint is shares by many other countries.

Based on the data from the central statistics agency of the Netherlands, the CO_2-emission for the Netherlands was 148 million tonnes in 1991 and 142 million tonnes in 1990, corresponding to an increase of 4,5%. It is assumed that this means a triplication of the CO_2-emission over the total of the 1980s.

"It is the aim of the Government of the Netherlands to stabilize the CO_2-emission in 1994-1995 to the level of 1989-1990. Another aim is to reduce the CO_2-emission by 2000 to a level 3 to 5% lower than that of 1989-1990" (Anon., 1990, p. 34). This prognosis is made in 1989. It is clear that in fact the aims were not reached at all. As 'all little things may help', even a small contribution that leads to the reduction of light pollution may be useful.

In the EU, the emission of the six most important greenhouse gasses did increase from 2000 to 2001 with 1%. The agreement, according to the Kyoto norm, was to reduce the emission by 8% between 2008-2012. Between 1990 and 1999, the emission decreased by 4%. In the Netherlands, the emission in 2001 was 1,3% higher than in 2000 and 4,1% higher than in 1990. According to the Kyoto norm, the emission in the period 2008-2012 must be 6% lower than in 1990. These statements are based on data from the European Environmental Agency EEA (Anon., 2003).

In an earlier part of this section, the study of Oliver et al. (2002) was mentioned. This study also considered policy aspects of the problem: "Without policy measures, the emissions in 2000 would have been 10% higher. The uncertainty in the total annual CO_2-equivalent emissions is estimated at 5%" (Oliver et al., 2002., Abstract, p. 2). It has been decided that in the EU, the CO_2-emission in 2010 shall be 8% less that in 1990; for the Netherlands it has been decided that this shall be 5% less than in 1990, corresponding with 150 10^{12} grammes CO_2-equivalent annually. So far, it is unlikely that this goal will be reached; in 2000, the level of CO_2-emission is 8% higher than in 1990 (See Table 12.4.13). It has been noted that without policy measures, the situation would have been much worse.

As regards policy attitudes in general, it is interesting to note that, in an interview, the former Minister of the Environment in the Netherlands, Jan Pronk, complains that the environmental movement in the Netherlands is too 'provincial', and has the wrong priorities. Instead of focussing on world problems like climatic changes, they concentrate on marginal, local problems like stench and noise. (Van Der Meer & Ham, 2002, p. 13). What he meant is the stench from the oil industry near Rotterdam, the noise of the Schiphol Airport, and the noise of motorway traffic. Although these types of pollution may cause severe hindrance, and sometimes even health hazards to people living close by, stench and noise are hardly world-wide environmental problems. The same incorrect selection of priorities seems to apply to the environmental movements world-wide. Political issues, like the anti-globalization fad, seem to overshadow the major problems like climatic changes, sea level rise, etc., and, on a smaller scale, light pollution.

In conclusion, one may state that, although in recent years some improvement has been made in which the Kyoto Agreement seems to have played a favourable role, the total abundance of greenhouse gasses did not decrease at all, as envisaged, but it did increase. Although the data that are quoted here, differ considerably, it is evident that transportation, and notably air and road transport, had a negative effect on this. The generation of electricity seems, however, to decrease, in spite of the increase of the number of electrical home appliances.

The fact that greatest pollutant of all, the USA, did not even bother to sign the Kyoto Agreement, does not help. Many other countries threaten to follow the USA. Furthermore, many developing countries consider the greenhouse effect to be a result of the energy waste in the industrialized world – a statement that is not completely correct – and, therefore, request that the industrialized countries solve the problem – a distinctly short-sighted standpoint, because global warming is a global problem. Nevertheless, they are, as indicated earlier, exempted from the targets of the Kyoto Protocol.

Finally, the standpoint of the US Government that "adhering to the Kyoto Agreement is bad for the US economy", is not true. It is the experience in many European countries, that adhering to strict environmental regulations stimulates the economy, because more sophisticated processes and products are developed. This effect has been clearly noted by many lighting companies, when recommendations to reduce light pollution were proposed. It might, however, be unpopular for the common citizen, who wants to have his house warm in the winter and cool in the summer, whilst traveling around in oversized, gas-guzzling vehicles. These points frequently turn up in newspaper and TV reports, but are difficult to support by unambiguous quotes.

One aspects that is important in considering the effects of the Kyoto Agreement, is the use of 'sinks'. It is suggested that forest could act as a sink for CO_2-emission. The CO_2 is supposed to disappear in the wood (Schöne, 2000. p. 18). This is, of course, the case for newly planted forests. As soon as the forest is fully grown, however, an equilibrium state is reached (Anon., 2000, p. 43). The CO_2 absorbed by the forest equals the CO_2 emitted by it. Proposing forests as sinks is therefore a very crude and cheap political trick. It would allow the USA to increase its CO_2-emission by 15%, in stead of reducing it by 6%. Canada is even worse: it would be allowed to double the CO_2-emission and still adhere to the Kyoto-norm! (Schöne, 2000. p. 18).

Most measures that are implemented to protect nature, to improve the environment for all living creatures, and to reduce negative impact of human interference with nature, cost money – some of them cost a great deal of money. Most governments, many non-governmental organizations and institutions, and a fair number of private companies, have accepted this. Many companies spend a lot of money in the research for improved alternative energy and for the development of sources of renewable energy. It goes without saying, that many of these companies expect to make, on the long run, a profit on these investments. In this respect, one point must be made. As is mentioned in different sections of this book, reduction of light pollution may be one of the few exceptions to this rule: reducing stray light – the main component of light pollution – may, in the end, result in more efficient lighting installations, because reducing stray light usually also reduces energy consumption, and thus energy costs.

13.1.3 Trends in energy usage

(a) *Energy use in general*

It is a well-known fact, that the energy use per capita is, in different countries, closely related to the per capita Gross National Product. However, this relation is not a straight-forward one; there are indications that, when the per capita GNP does increase, the per capita energy use reaches a plateau of saturation. This is depicted in Figure 13.1.5.

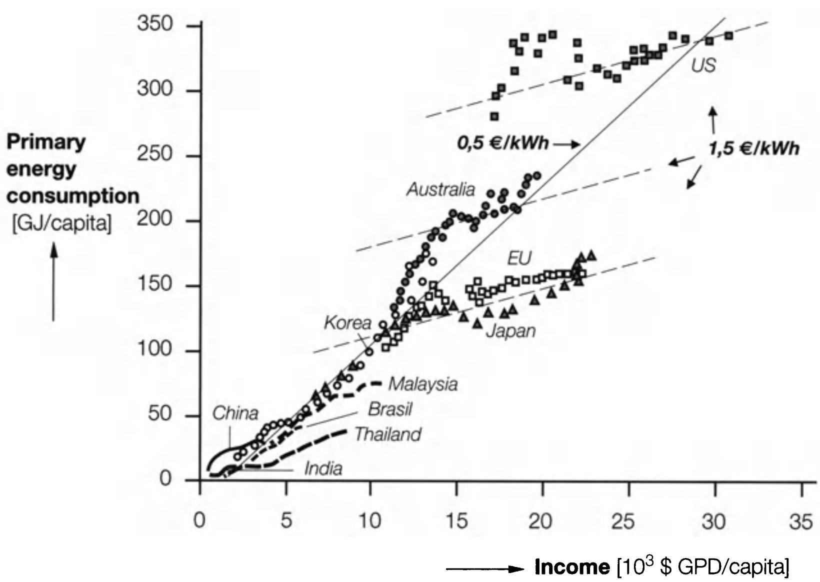

Figure 13.1.5: *The per capita energy use in relation to the per capita GNP for different countries and for different periods of time. After Anon., 2001a, p. 11 and Lopes Cardozo, 2004.*

There are signs of saturation beyond US$ 25 000. Crudely speaking, one might assume that people can use only a certain amount of energy. You can drive only one car at the time, and the heating and cooling of your house have some sort of natural limits, ruled by requirements of comfort.

Transportation, and notably air and road transport, had a negative effect on this. The generation of electricity seems, however, to decrease, in spite of the increase of the number of electrical home appliances. See Table 13.1.15.

It is not easy to get data for the energy use in different segments of human society. We will quote here data from 1983. In view of what was indicated in Table 13.1.15, one may wonder in how far these data can still be used. They are quoted here, however, because one may assume that the order of magnitude is still valid. See Table 13.1.19.

Ares of application	North America	Western Europe	Japan	Developing countries
transport	8,7	4,6	1,3	4,5
industry	5,1	5,1	1,8	4,5
households	7,3	6,1	1,3	2,1
loss	10,2	6,5	1,9	5,7
total	31,3	22,3	6,3	17,0

Table 13.1.19: *Energy use in 1983. In millions of barrels of oil equivalent daily. After Schreuder, 1998, Table 14.2.3. Based on data from Anon., 1984.*

Notes to Table 13.1.19:
- One barrel of oil equivalent (boe) corresponds to 5,8 G (Anon., 2001a, glossary, p. 60).
- It may be assumed that North America does not include Mexico.

It should be noted that Table 13.1.19 does not cover the whole world. Notably, Eastern Europe is not included. It is interesting to note that the contribution of 'losses' is very high: on the average, well over 30%! One might assume that reducing these losses would be a very promising energy saving measure. It seems that some companies have had similar thoughts – at least similar plans. In Figure 13.1.6, some data are given about waste and about the targets for the years ahead.

It should be noted that a considerable part of the spills result from sabotage.

For the world as a whole, fossil fuel is the most important source of energy. Some data are given in Table 13.1.20.

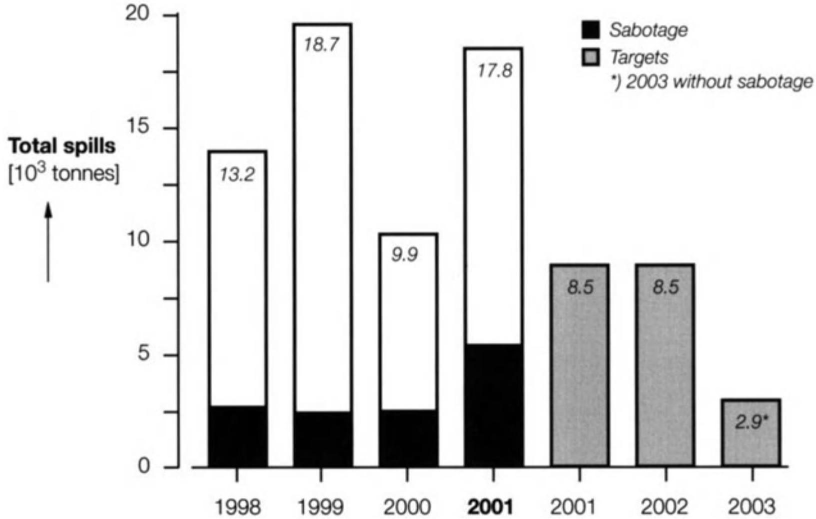

Figure 13.1.6: *Total spills in thousands of tonnes. After Anon., 2002f, figure 8.*

Energy source	**Percentage worldwide in:** **1973**		**1999**	
oil		45		35
coal		24,9		23,5
natural gas		16,2		20,7
fossil, total	86,1		79,2	
renewables, waste	11,1		11,1	
CO_2, total	**97,2**		**90,3**	
hydroelectric		1,8		2,3
nuclear		0,9		6,8
other (incl. solar and wind)		0,1		0,5
non-CO_2, total	**2,8**		**9,6**	

Table 13.1.20: *Sources of energy worldwide (after Bradford & Dorfman, 2002, p. 17).*

Note to Table 13.1.20: the data do not always add up to 100%; this may the result of the rounding off of data.

Table 13.1.20 shows that the contribution of oil did decrease markedly, but that the contribution of fossil fuel did not change too much. The total of non-CO_2-sources of energy did increase, mainly because of the increase of nuclear fission power, for about 340% – well above a factor of 3! It should be added here that nuclear fusion proves to be very promising. The 'power multiplication factor' that describes the overall efficiency of a fusion generator, doubles every 1,8 years (Lopes Cardozo, 2004).

(b) Electric energy

The reason to discuss the greenhouse effect in some detail is, that a considerable part – albeit not all of it – is caused by the generation of electricity. At present, most electric energy is generated by means of thermal power stations, that work on fossil or renewable fuel. Renewable fuel, like biomass, may have considerable advantages for the environment in general, but it causes just as much CO_2 as fossil fuel. The generation of electricity results therefore in the emission on CO_2. As is discussed also in sec. 1.1.2, for what Slater indicates as 'typical UK conditions', the generation of 1 KWh results in the production of just over half a kilogramme of CO_2 (Slater, 2000). We will come back to this point later.

In industrialized countries, only electric energy is used for lighting. That this is not always the case, is explained in a further part of this section, where it is mentioned that at least 2 000 000 000 people live without having access to electricity (Mills, 2002, p. 376). They pay 20% of the total bill for lighting, but receive only 1% of the benefits (Mills, 2002, p. 371). See also Mills (1999). These people do not contribute much to light pollution in general. Their situation must urgently be improved, but not for the reasons that are covered in this book. See e.g. Schreuder (2001).

The production of electric energy in the European Union is given in Table 13.1.21.

Source of electric energy	1980		1990	
thermal power stations	75,8		56,9	
of these (%):				
– natural gas		10,3		11,9
– oil		28,7		17,7
– coal		55,6		65,0
– other		5,4		5,4
hydropower	12,4		8,1	
nuclear energy	11,8		35,0	
total	100%		100%	
	1403 TWh		1805 TWh	

Table 13.1.21: *The production of electric energy in the European Union (in %; in TWh). After Schreuder, 1998, Table 14.2.1. Based on data from NOVEM, 1994, table 1.09.*

Notes to Table 13.1.21:

(1) The data refer to the membership of the EU in the years indicated.

(2) Alternative energy sources, like solar or wind, are not mentioned. This is noteworthy because, as is indicated in Table 12.4.20, these sources represent about 0,5% of the total energy produced. One should expect that they would represent about 5% of the electric energy. One may assume that they are included in one of the other items in Table 12.4.21. We will come back to these energy sources.

(3) Several European countries do not use nuclear energy at all.

(4) It should be pointed out that large river dams have, just as nuclear power plants, considerable environmental draw-backs (Schöne, 2000. p. 18). This is often overlooked, when hydropower is promotes as 'clean power'.

In Table 13.1.22, data are given about the energy consumption of the Netherlands. as well as some data concerning the split of energy in the Netherlands. The data are based on an unpublished report of EnergieNed (1992). Although the data stem from 1991 and concern only one densely populated and affluent country, they are given here as an indication of what one may expect. It is most interesting to note from this table, that about 10% of all energy is electric energy, and that about 0,8% of all electric energy is used for public lighting – or about 0,08% of all energy!

Energy source	Annual energy use	
total energy	2 872 10^{15} J	
electric energy		
– mains network	246 10^{15} J	(68 340 GWh)
– proprietary generation	36 10^{15} J	(10 000 GWh)
total electric energy	282 10^{15} J	(78 340 GWh)
use for public lighting	2,29 10^{15} J	(635 GWh)

Table 13.1.22: *Energy use in the Netherlands; 1991. After Schreuder, 1998, Table 14.2.3. Based on data from EnergieNed.*

In a rather old American study, the ways to reduce energy consumption are discussed for traffic lighting, more in particular for fixed road lighting and for vehicle lighting (Anon., 1981). About the energy use, the following is mentioned. In 1976, in the USA, electric energy amounted to 28% of the total gross energy use, amounting to $1800 \cdot 10^9$ kWh. From this, $14{,}4 \cdot 10^9$ kWh was used for fixed road lighting, less than 0,8% of electric energy, and less than 0,2% of all energy. These data are almost in line with more recent data that are given in Table 12.4.2 (Schreuder, 1998, sec. 14.2.2). Expressed in barrels of oil, the energy used daily in the USA for fixed lighting was 18 032 bbls in 1976.

(c) *Alternative and non-CO_2-energy*

First, a remark about terminology. The term alternative energy sources is often used as a synonym to sustainable energy sources. They are, however, completely different in principle, even if their practical application might seem similar. Particularly when discussing light pollution, it is important to make a clear distinction between the two.

Sustainable energy means energy that does not make use of fossil energy sources, like oil, coal, natural gas, etc. The sources of energy are renewable. Some renewable energy sources produce, however, CO_2. Of course, on the long run, also these energy sources are renewable, but in the short term they are likely to increase the carbon content of the atmosphere. It depends on the type of source for the energy, how long the turnover time will be. For forests, it may take at least half a century. Therefore, forests are sometimes included in the 'CO_2-sinks' that are discussed in an earlier pat of this section. Using chicken manure, the turnover time is likely to be more like one or two years. We will come back to this point when discussing biomass energy sources.

In industrialized countries, most electric energy is generated in large scale thermal power plants, fed by the traditional fossil fuel: oil, coal or natural gas. In this respect, it is worth mentioning, that the World Wildlife Fund, in its 'Living Planet' report, has pointed out (again!) that the natural resources are being depleted at an alarming rate. In the last three decades, about one-third of the natural resources has disappeared. It warns (again!) that the patterns of consumption need drastically be changed (Anon., 2002, p. 1). All fossil fuels are sources of CO_2-emission. Nuclear power based on fission processes, does not lead to CO_2-emission, but is has severe environmential disadvantages. Political pressure, based on a complete lack of knowledge of physical processes, and on poor judgement, has prevented a healthy development of the pollution-free nuclear fusion power stations. So, far the greatest majority of large-scale power plants cause considerable CO_2-emission.

There are a number of alternative power sources, that can be applied. Some of them do create just as much CO_2 as the traditional power stations, but, by using biomass as the primary source of energy, they do not deplete the stocks of fossil fuel.

Biomass is often considered as an important 'alternative' energy source. When the turnover time is short, like e.g. when using waste, or chicken manure, the net CO_2-emission is kept within limits, as is mentioned earlier in this section. It is expected that, in the Netherlands, in the year 2040, about 30% of the total energy consumption will be from biomass. In order to reach that goal, the supply of biomass-fed energy must rise by 7% to 8% over the overall energy demand. In the year 2002, the contribution of biomass-fed energy was between 2,1 and 2,3% of the total. It should be noted that, although it is not stated, one must assume that 'total energy use' means 'total electric energy use'.

There are more possibilities to generate electricity. Just like most biomass generating systems, they are more suitable for small-scale generation than for the traditional large-scale power plants. These systems are more suitable for developing countries than for industrialized countries, particularly for the densely populated centres of these countries (Schreuder, 2001). However, large or small, with or without CO_2-emission, they generate electricity that, if used for outdoor lighting, may cause light pollution. Still, we will pay some attention to the alternative energy sources, and in particular to the smaller, stand-alone systems, because, given their reduced scale, it may be more feasible to avoid light pollution of the outdoor lighting.

In most developing countries, the national grid is hardly sufficient to support the key industries; in many countries there is simply not enough capacity to serve all households – or even a considerable part of them. Local communities have to rely on local power supply. Local supply networks are of a completely different size. Some include a whole village, whereas others only serve one single home or one single street light. They are all typical 'stand-alone' generation installations.

(d) Stand-alone electric generation

Stationary stand-alone electric generation installations can be powered by any one of the following primary energy sources. Some of them have been mentioned already:

- batteries
- water
- wind
- biomass
- solar
- (diesel) engines.

Each of these 'prime movers' has a set of very specific characteristics. Sometimes, human or animal muscle power is added to this list. See for details Schreuder (2001).

Beside stand-alone installations, 'Co-Generation' systems need to be mentioned. In the system, a normal diesel or gasoline engine generator of relatively small size is used. The advantage of the system is to be able to utilize the hot water for cooling of engine as a source of heat energy, such as for air-conditioning or heating. The system efficiency is higher than that of a large power station, from which cooling water is wasted in the sea or the river. Many do not stand 'alone' completely, because any surplus electric energy is fed into the main electric grid.

Stand-alone installations usually are quite small, serving only one household at the time, or maybe a small village. Some stand-alone installations are still smaller; many are used in areas where there is no lack of energy suppliers, and where the distance to the grid is quite small. As an example, all parking meters in the city of Berlin each have their own solar panel. But sometimes, stand-alone installations are somewhat larger. "In most agricultural developments around the San Pedro Martir National Park – that houses the National Astronomical Observatory of Mexico – the only electricity supply available is yielded by private power plants" (Costero, 1991, p. 46-47)

A few words on batteries and biomass electric generation. Dry batteries are probably the main energy source for small electrical appliances. However, they are expensive and they are one of the most serious sources of pollution in developing countries. They present a severe public health hazards, particularly if people try to 'recycle' them. Biomass as an energy source is promoted for grid use and for stand-alone installations. It was shown in an extensive programme in Nepal that an effective installation could be delivered for about US$ 350 – of which half was subsidized. The numbers increase at a rate of 20 percent per year; the total potential in Nepal is estimated at 1,5 million installations (Hessing, 2000). Wood is the most common biomass. As many countries are virtually logged clean, it is not feasible any more as a general source of energy. Dung is sometimes used in its place e.g. for cooking. There are, however, considerable public health consequences. "Recent studies in Mexico, Nepal and South Africa, have shown that non-smoking women who cook on biomass stoves or open fires in the home have seven times more chance of contracting obstructive lung diseases than those who use other heat sources. Children from such homes are also at an increased risk of acute and other respiratory infections" (Zaffran, 1993, p. 10). So, in conclusion, neither batteries nor dung-based biomass are to be recommended for stand alone energy schemes.

In a further part of this section, some data are given in the contribution of wind energy to the total energy production (Roggenkamp, 2003; Schreuder, 1990). The plans from Belgium have been already mentioned (Anon., 2003). In Europe, wind energy grew by 39,6 % over the last 10 years (Knoppers, 2003).

For the Netherlands, the policy goals for energy saving by means of sustainable sources, including wind energy, is illustrated in Table 13.1.23.

Source		**Year**	
	2000	**2007**	**2020**
wind	16	33	45
PV	1	2	10
solar thermal	2	5	10
geothermal	0	0	2
energy addition	2	8	15
heat pumps	7	50	65
hydropower	1	3	34
waste and biomass	54	85	120
hydropower from Norway	0	18	18
total	**83**	**204**	**288**

Table 13.1.23: *Projected energy savings by means of sustainable energy. In PJ. After Verbong et al., 2001, table 4.1., p. 128. Note 1 PJ = 10^{15} Joule = 0,2778 $\cdot 10^{12}$ KWh.*

Note to Table 13.1.23: The terms 'energy addition' and 'hydropower from Norway' have not been explained. One may assume that they are included in this way, because Norway is not an EU-country.

(e) Solar energy

When looking for a source of alternative, non-CO_2-energy, it is most logical to use the direct radiation of the Sun. Solar radiation heats up the Earth. However, deflecting it towards the generation of electricity does not offer a risk that the Earth would cool down, because, in the end – as a result of the famous Second Law of Thermodynamics, all energy will end up as heat anyway. The total solar energy that hits the Earth is about 15 000 times the amount of all energy needed by humanity (Hoagland, 1995). The Sun emits 230 trillion horsepower, correponding to 2,8 million Watt per acre at the top of the atmosphere, of which about 53% reaches the surface of Earth (Anon., 1977, p. 39). In ISO-units, this means $177 \cdot 10^{12}$ W and 692 W/m^2, respectively. Still, there is plenty, even if the prognoses from 1995 will come true, meaning that in 2025 the demand for energy will increase by 30%, and the demand for electrical energy by 265% (Hoagland, 1995).

At present, solar energy is mainly used to heat water in homes in sunny climates. The principle of using solar radiation for heating water is very simple: just let the sun shine on a water vessel and the water gets hot. The heated water itself is a very good means to store the heat until it is needed. The same principle is sometimes used for room heating, where the surplus heat of the summer is stored until it is needed in winter. There seems to be a considerable future for solar-thermal installations. In the past 10 years, installations in Europe grew by 11,7%. In Europe, there is possibly room for $1{,}5 \cdot 10^9\ m^2$, about 100 times as much as is installed at present. This could produce about 6% of the total energy used in Europe (Knoppers, 2003). Some data for the Netherlands are given in Table 13.1.23.

For the generation of electric energy, a different method is used: the photovoltaic method, where solar energy is directly converted into electricity. The physical process is described briefly in a further part of this section. The main reason for its use is, apart from the obvious environmental advantages which it shares with wind and water, the advantages for 'stand-alone' installations, because they are especially suited for small installations up to 100-200 W (Schreuder, 19981, 2001). The performance of solar cells is by convention expressed in 'Wattpeak'. The Wattpeak is a somewhat awkward unit. It describes the output of a panel, when subjected to electromagnetic radiation of specified spectral composition at a specified temperature. It is a laboratory unit. Koornstra (2000) suggested the following rule of thumb: A solar panel of 0,5 square meter gives 50 Wattpeak nominal. In tropical regions that is enough for 180 Wh useful energy per day.

Solar energy panels for generating electricity are rare, particularly in countries like the Netherlands, that lay at a rather high latitude (some 53 degrees North, corresponding to Labrador, or Patagonia!). It is expected by some that, at some moment in the future, solar radiation can provide 60% of the electricity and 40% of the fuel for heating (Hoagland, 1995).

In 2002, about 23 000 family homes in the Netherlands use solar power for electricity. Without subsidy, it still is a costly affair. A panel of some 450 Wattpeak costs, without subsidy, between 2300 and 2700 Euro. If the installation is put in place by an expert, 500 Euro needs to be added. A panel of 600 Wattpeak can deliver about 450 KWh per year – about 15% of the average family use per year. The savings are about 90 Euro per year. The pay-back time is about 15 year, on the base of the 2002 subsidy. It is not certain whether the subsidies will be continued in 2003 and beyond (Anon., 2003).

The solar panels installed in the Netherlands are given in Table 13.1.24.

It should be noted that one MWp (Megawattpeak) corresponds to about one hectare, or 10 000 m^2 of panels.

Year	MWp
1989	0,351
1990	0,765
1991	1,02
1992	1,27
1993	1,641
1994	1,963
1995	2,4
1996	3,257
1997	4,036
1998	6,48
1999	9,195
2000	12,535
2001	20,509
2002	26,326

Table 13.1.24: *Installed Wattage in the Netherlands. Data from Ecofys, 6 October 2003.*

Presently, there are three main types of solar cells:
(1) Monocrystalline cells.
(2) Polycrystalline cells.
(2) Amorphous cells.
All are made with silicium as their main constituent, as is explained earlier in this section. Monocrystalline and polycrystalline cells are stiff, whereas amorphous cells can be produced in a flexible way. They can be bent, which is an advantage in many applications. Monocrystalline cells perform best, followed by the polycrystalline cells and the amorphous cells, in that order. However, prices follow the same trends: monocrystalline cells are the most expensive, followed by the polycrystalline cells and the amorphous cells, again in that order. At present, the developments, both in technology as in prices, are very rapid. Therefore, it is not very useful to quote numbers regarding the performance nor regarding prices.

The systems efficiency is understood as the energy output (electric power) as a fraction of the energy input (solar radiation). According to data from the Siemens-company, as given on the Internet, the system efficiency is as follows:

(1) Monocristalline cells	13-14%
(2) Polycristalline cells	11-12%
(3) Thin film CIS	8-9%
(3) Amorphous cells	about 2%.

The world production of solar cells is given in Table 13.1.25.

Year	USA	Japan	Europe	Rest world	Total	Cumulative
1993	22	17	17	4	60	60
1994	26	17	22	6	70	130
1995	35	16	20	6	78	207
1996	39	21	19	10	89	296
1997	51	35	30	9	126	422
1998	54	49	34	19	155	576
1999	61	80	40	21	201	778
2000	79	117	59	24	278	1056
2001	100	171	86	33	391	1446
2002	121	251	135	54	560	2006

Table 13.1.25: *World production of solar panels, rounded off values (in MWp). After Maycock, 2003.*

In physical terms, present-day solar panels produce about 150-180 Wattpeak per m^2. Further improvements for solar panels are possible. At present, the best solution seems to be the polycristalline layer on glass. The theoretical maximum efficiency is 73,7%; at the moment, of which only about 20% is reached (Knoppers, 2003). Laser application in the manufacture of solar panels brings another improvement. The new type cells are just 37 micrometer thick, which makes them flexible. Their efficiency is 20,2%. Present-day solar cells are usually about 300 micrometer thick and have an efficiency of only 16%. Further advantages ages are short production time which makes the process suitable for mass production. Also the prices may go down, because very little crystalline silicium is used (Knoppers, 2003).

Solar cells are essentially barrier-layer cells, where solar energy (light quanta) are trapped within the semiconducting barrier layer of silica crystals, and converted in electricity. The physics are described in detail in Green (1986) and Würfel (1995). On the average, the maximum solar irradiance is about 1000 Watt per m^2 at sea level (NOVEM, 1996, p. 9). It may be noted that in an earlier part of this section, other values have been quoted. The differences are probably due to the fact that not always the same conditions have been taken into account. They are, however, of the same order of magnitude. Taking 13% as the efficiency of the panel (Van Zolingen, 1997), the peak is 130 W/m^2. Usually this is designated as 130 Wp ('Wattpeak'). In the Netherlands, at about 53 degrees Northern latitude, the solar irradiation is equivalent to 1000 hours of full sunshine a year (NOVEM, 1996, p. 6). The yearly yield is 130 000 Wh/year or just under 360 Wh per day per m^2.

For almost all lighting purposes, the energy that is generated during the day must be stored for nighttime use. Thus, a stand-alone solar energy lighting device consist of four components:
(1) The solar panel (to convert solar photons into electricity);
(2) The battery (to store the energy for future use);

(3) The switching and control gear;
(4) And, of course, the light source (lamp, ballast, luminaire, support).

Usually, each lamp has its own support, control gear, battery and solar panel. The costs of such light points are obviously higher than those of a traditional light point 'as such'. When, however, the cable and grid costs are taken into account, it turns out that photovoltaic ('stand-alone PV') lighting often is considerably less costly. The results of an approximative calculation by Schreuder (1998a) are given in Table 13.1.26.

Average daily load wH/day	**Distance to grid** (m)
20	6
40	22
80	50
160	100

Table 13.1.26: *Break-even points of cost equality of PV and grid distance. Based on data from De Gooijer, 1998, Fig. 1.*

In conclusion, one may state that stand-alone PV road lighting installations seem to be cost-effective in many isolated, sparsely populated rural areas as regards installation costs. This statement holds both for industrialized countries as for developing countries, because the costs are in all cases directly related to world-market prices, both for materials and for oil. It is not easy to say if this is the case for annual costs: the life of PV-installations is shorter (as regards the batteries even considerably shorter) than that of cables. However, energy costs are absent. Further, grid connection restrictions – a common problem in many rapidly developing countries – are absent as well; however, theft of equipment is often a major problem, and so are aesthetic considerations. One thing is clear: stand-alone PV road lighting installations are worth-while considering seriously (Schreuder, 1998a,b; 2001).

In the Netherlands, the total of alternative energy sources did amount to about 1,5% of the total energy use. A split is given in Table 13.1.27. The savings in fossil fuel would be equivalent to about 1 200 000 000 m^3 natural gas per year.

There are no precise, world-wide, data available for the generation of electricity by means of photovoltaic processes. In Table 13.1.20, it is indicated that, world-wide, solar and wind energy combined did not amount to more than 0,1% in 1973 and 0,5% in 1999 of the total energy (Bradford & Dorfman, 2002, p. 17). In the Netherlands, sustainable energy amounted to about 1,5% of the electric energy generated in the Netherlands in 2002. When imported energy was included, the sustainable energy amounted to 4,2% (NOVEM, 2003). The trends of solar and wind energy are given in Table 13.1.28.

Energy source	Percent of alternative energy
bio-energy (burning of waste)	74
wind	18
water	3
solar	2
heat or cold storage	1
heat pumps	1

Table 13.1.27: *Percentage sustainable energy, the Netherlands, 2000 (data from CBS, Anon., 2001b, p. 1).*

Energy source	Unit	Added in 2001	Added in 2002	Total	Reference
photovoltaic	MWp	7,6	3,6	–	NOVEM (2003a)
wind	MW	38	33	480	NOVEM (2003b)

Table 13.1.28: *Use of photovoltaic and wind energy in the Netherlands.*

As is mentioned earlier, the Netherlands agreed to reduce the CO_2-emission in 2008-2012 by 6% in order to adhere to the Kyoto Protocol. The Government of the Netherlands has decided, in order to comply with this agreement, to rely to a large extent on wind energy. It set the goal of installing in 2020, 7500 MW in wind energy, of which 1500 MW will be placed on land and at least 6000 MW (Roggenkamp, 2003, p. 6). The juridical aspects of installing windmills at sea, are discussed in great detail. This publication is part 7 in a series! It seems, however, that many legal problems are typical for the Netherlands. It is likely that other countries have different legal problems. It is interesting to note that it is expected that, in spite of many delays as a result of legal problems, the goal of 6000 MW at sea indeed will be reached in 2020 (Roggenkamp, 2003, p. 6). Other juridical aspects, together with road safety, and driving comfort aspects of wind turbine parks, are discussed in detail in Schreuder (1990).

In conclusion, it can be stated that most electric energy is generated in ways where CO_2 is emitted; for our purpose it seems to be justified to disregard the nuclear and alterative non-CO_2 energy altogether. It is, of course, an approximation, but we will assume for the assessment of the share of light pollution of the global CO_2-emission that all generation of electric energy involves CO_2 emission.

13.2 Energy for lighting

13.2.1 Outdoor lighting

As has been explained earlier in this section, the link with light pollution is in the fact that all outdoor lighting is electric lighting. Many measures aimed at a reduction of light pollution are based on a reduction of the light itself. So, promoting 'clean', non-polluting, lighting has a favourable effect on the emission of CO_2, and thus contributes to the reduction of the greenhouse effect. It may reduce power costs at the same time. Of course, outdoor lighting uses only a small part of the total electric energy, but little things do help.

In this respect, we come back here to the survey that has been mentioned in sec. 13.1.3b (Mills, 2002). It is claimed that this publication is: "the first global estimate of lighting energy use, costs and the associated greenhouse-gas emissions" (Mills, 2002, p. 369). However, light pollution is not mentioned. The report is based on a survey in 38 countries with 63% of world population. Their energy use in 1997 was 2016 TWh, which is equivalent to about 1000 power plants. The total energy costs in these countries are 185 10^9 US$ per year; the CO_2-emission amounts to 1,775 10^9 metric tonnes per year. It is difficult to compare these data with the data from other reports, because only little more than half of the world population is included in the survey. It is not indicated which countries are included, and which not. Within the countries of the survey, 28% of the energy is used in the residential sector, 48% in the service sector, 16% in the industrial sector, and 8% for street and other lighting (Mills, 2002, p. 369). It is explained in sec. 11.2, most lighting is indoor lighting. It should be taken into consideration that road and street lighting represents only a fraction of all outdoor lighting.

When considering the amount – the small amount – of energy that is used for road lighting it is interesting to compare the energy of road lighting with that used by vehicle headlighting. Take a 4-lane motorway with 2000 veh/hour – heavy traffic. At 100 km/h, there will be 80 vehicles per km. Usually there are two 55 Watt headlamps per car. In view of what is mentioned in sec. 12.2.5, this is a modest estimate. The total vehicle headlighting uses 4,4 kW per km. If we assume a lighting installation with two SON 250 W at a distance of 40 m, an overall road width of 35 m, an overall system efficiency of 0,4 and 14 lux per cd/m^2, the average road luminance would be about 1 cd/m^2. For this, one would need 12,5 kW per km. So, vehicle lighting would require a considerable amount of energy, but less than road lighting. Using different assumptions, the outcome of such comparisons would be different as well (Narisada, 1996, as quoted by Narisada & Kawakami, 1997, table 4). Because, however, the use of vehicle low beams is mandatory in almost all countries, also on well-lit streets, the exercise has little practical implications.

13.2.2 Energy use for street lighting

First we will discuss street lighting. Not because it is the largest source of light pollution, but because most is known on this subject. In another part of this section, it is explained that only a small part of all energy is used for street lighting. In Table 13.1.22, it is indicated that in the Netherlands, about 10% of all energy is electric energy, and that about 0,8% of all electric energy is used for public lighting – or about 0,08% of all energy.

In order to find out the precise energy use, and particularly the possibilities to save on energy, in the 1980s, a comprehensive study has been made about the energy used in street lighting in the Netherlands. See Table 13.2.1.

	Urban streets	Rural roads	Motorways
number of luminaires	2 000 000	331 000	29 000
lit roads (km)	41 000	10 000	875
lumen value (Mlm)	13 750		
power (kW)	211 700		
energy use per year (MWh)	712 600		

Table 13.2.1: *Public lighting in the Netherlands in 1991. After Schreuder, 1998, Table 14.2.4. Based on data from Fernhout, 1990.*

It is interesting to note the distribution of the different lamp types for public lighting. In total, about 2 860 000 lamps were used in road and street lighting. A split-up is given in Table 13.2.2. The total number of luminaires was smaller, because at the time, quite a few luminaires did house more than one lamp. In 1990, about 2 360 000 luminaires were used in road and street lighting. For a population of about 15,5 million, this means, per inhabitant, just over 47,5 KWh per year and over 0,15 luminaires per inhabitant.

Lamp type	Urban	Rural	Motorways	Total
incandescent	50 000	3 000	–	53 000
fluorescent tubes	1 225 000	116 000	–	1 341 000
high-pressure mercury	475 000	36 000	–	511 000
low-pressure sodium	500 000	106 000	29 000	635 000
high-pressure sodium	250 000	70 000	–	320 000
total	2 500 000	331 000	29 000	2 860 000

Table 13.2.2: *Number of lamps in use on different types of road in 1990. After Schreuder, 1998, Table 14.2.5. Based on data from Fernhout, 1990.*

It should be noted that since 1990, the split-up has changed considerably. High-pressure mercury lamps are hardly used in new installations any more, whereas for residential streets, compact fluorescent lamps are quite common (Schreuder, 1998). It is not precisely known in how far this reflects the experience in other countries. Casual inspection would suggest, however, that the wide use of compact fluorescent lamps in residential areas is typical for the Netherlands.

13.2.3 Luminous flux per inhabitant

(a) The 'Garstang number'

The reason to look into these figures, is the fact that the luminous flux, installed in road and street lighting, is considered as an important quantity. It is supposed to be a general value that can be used throughout the industrialized world in order to estimate the extent of light pollution, as well as the trends in this of the pollution. In a way, it is considered as an indicator of social development as well as of the relative or absolute wealth of a country or a region. In sec. 5.4, the increase of light pollution in recent years is discussed. There seems to be a relation between the per capita installed luminous flux for outdoor lighting in a city, and the number of inhabitants. In that section, the Garstang-model is discussed. This model states a value of 1000 lumen per capita (Cinzano et al., 2000; Garstang, 1991). We have coined that number the 'Garstang number', although 'Walker-number' could have been regarded as appropriate as well. Walker has, however, already his 'Law'. A simple figure of 1000 lumen per capita would mean a relation with an exponent of 1. An exponent of 0,8 seems to fit the measured data better (Walker, 1973, 1977).

In the past, several studies have been published regarding the luminous flux per inhabitant. As mentioned already, Garstang (1989, 1991) did conclude it was 1000 lm per capita, although recent measurements quoted in sec. 5.2.1 suggest a higher value. In the following, we will call the 1000 lumen par capita mark as the 'traditional value of the Garstang Number'. Finch et al. (1979) suggested a value between 500 and 1000, whereas Schreuder (1986, 1991) did find values as low as 50. We will come back to this point. These data are quoted in Schreuder (1994. p. 35). See also Schreuder (1986, 1987); CIE (1997).

(b) Studies in the Netherlands

Since 1990, a lot changed in the public lighting in the Netherlands and elsewhere. The urban road network did increase considerably. Most cities and towns did spread out over the countryside, although the number of inhabitants did not increase very much. It is usually stated that this is mostly a result of the spectacular economic growth over the last decades, so that many more people could afford to live in spacious suburban houses instead of in cramped apartments in city outskirts. Although the rural road network did not increase very much, the percentage of lit roads did. It is likely, that this trend did contribute considerably to the increase of light pollution in the Netherlands over the last few decades. At present, there are 3 200 000 lighting columns in the Netherlands (Anon., 2003b, p. 16). Earlier in this section, we quoted that, in 1990, there were 2 360 000 luminaires. Because some lighting columns carry more than one luminaire, we may estimate for 1990 a number of 2 100 000 columns. This would imply an increase of over 65% in just about 10 years! Because the optics of luminaires is much better now than 10 years ago, it does not automatically imply that the light pollution from street lighting did increase with 65% as well.

These numbers can be compared to more recent form an unpublished study in Zoetermeer, a 'new town' of about 100 000 inhabitants in the central area of the Netherlands. The data refer to 1998. See Table 13.2.3.

Lamp type	Wattage (W)	Number of lamps	Lumen	Total lumen (lm)	Total wattage (KW)
HPLN	50	1 800	1 375	2 475 000	90
SON	50	3 500	1 292	4 522 000	175
SON	70	5 600	1 774	9 934 400	392
TLD	18	1 150	5 029	5 783 350	20,7
TLD	58	4 600	665	3 059 000	266,8
PLL	24	1 800	7 904	14 227 200	189,7
Total			18 039	40 000 950	1 134,1
Rounded off			18 000	40 Mlm	1,13 MW

Table 13.2.3: *Municipality of Zoetermeer, the Netherlands. Public lighting lamps, 1998.*

Note to Table 13.2.3:
- lamp designation according Philip (Anon., a). HPLN: High-pressure mercury; SON: high-pressure sodium; TLD, PLL: fluorescent lamps;
- lumen values after Philip (Anon., a);
- the data have been provided by the Municipality of Zoetermeer.

In Table 13.2.4, some overall data on the municipality of Zoetermeer are given.

area	37,05 km^2
inhabitants	109 936
inhabitants per km^2	2967
lamps	18 039
total Wattage	1,13 MW
total per year	4,54 GWh
per inhabitant	41,3 KWh
total lumen	40 Mlm
lamps per inhabitant	0,164
lumen per inhabitant	364

Table 13.2.4: *Lighting data from Zoetermeer. Data from Table 13.2.3.*

Although Zoetermeer is by no means typical for the Netherlands, and definitely not for the World, the number of 0,164 lamps per inhabitant corresponds closely to the figures of 1990 quoted earlier, even more so because there still are some multi-lamp luminaires to be found in the Netherlands. The value of 364 lumen per capita, however, is lower than the Garstang number, that is quoted earlier.

Another, small scale, study was made in two districts of the town of Leidschendam. The districts are called 'Vogelbuurt' and 'Amstelwijk' respectively. A summary of the data is given in Table 13.2.5.

	'Vogelbuurt'	'Amstelwijk'
zone (CIE, 1997)	E2	E3
road length (m)	5187,5	8850
area (km^2)	0,31	0,4
number of lamps	228	476
total power (KW)	16	84
lumen output (Klm)	1430	7360
lumen per m	275	831
lumen per m^2	4,6	18,4
number dwellings	430	2920
dwellings per m [1]	0,083	0,33
inhabitants[2]	1290	8762
energy per inh. (W)	12,4	10
flux per inh. (lm)	1109	840

Table 13.2.5: *Public lighting in Leidschendam. Data from 14 December 2001.*

Notes to Table 12.4.30:
1) Amstelwijk estimated;
2) Estimated; 3 inhabitants per dwelling.

The Leidschendam-numbers are higher than the Zoetermeer-numbers, viz. 1109 and 840 lumen per capita. They are very close to the traditional value of the Garstang number.

One must be careful to use data from one municipality for the whole country, let alone for the whole world. As a further example, some data form the city of Apeldoorn, the Netherlands, are given. These data are part of a survey that covers the whole of the outdoor lighting in the Netherlands (Schmidt, 2003). It should be mentioned, that the survey focusses on the amount of light that is emitted upwards by the different types of outdoor lighting. In Table 12.4.31, the data are given for road and street lighting. Other areas of outdoor lighting are discussed in a further part of this section. In the Netherlands, there are three main authorities that operate road and street lighting, viz.: the municipalities, the provincets, and the Central Government. For municipal road and street lighting, the municipality of Apeldoorn is taken as being representative for the urban streets in the Netherlands. The Province of Noord-Holland is taken as being representative for the rural roads that are lit under the authority of the Provinces. The national roads are those under the authority of the Central Government.

Example	Municipality Apeldoorn	Road authority Province Noord-Holland	Central Government	Total
inhabitants	155 000	2 474 800	n.a.	16 000 000
energy use (GWh)	5,33	5,1	70	
energy use per inh (W)	8,6	0,52	1,09	10,71
flux per inh (lm)	732	62	159	1 003

Table 13.2.6: *Energy for public lighting. Based on data from Schmidt, 2003, table 1.*

Only the numbers for municipalities can be compared with the traditional value of the Garstang number, because the other numbers refer to roads that are maintained by distinct authorities. These data are in no way related to the number of inhabitants. If we make this comparison, it shows that, at least Apeldoorn, is well below the traditional Garstang number; this municipality has only 732 lumen per capita.

It seems that, at least for a number of cases in the Netherlands, the Garstang number is on the high side, and not on the low side. From Table 13.2.14., that is presented in a further part of this section, it can be seen that in the city of Turin (Italy), with a population of about 1 million, 922 Mlm is installed in public lighting (Broglino et al., 2000, Table II). This corresponds with 922 lumen per capita – slightly under the Garstang number.

As mentioned earlier, the luminous flux per inhabitant for a large number of cities in the Netherlands as well as in several other countries was collected by Schreuder in the context of activities of IAU Commission 50 and of CIE TC 4.21. The list was never published. Only summary data were given (Schreuder, 1991, 1994). It seems worth-while to include the full data here. First we will list the data for the Netherlands. See Table 13.2.7.a.

For a small, homogeneous country on may assume that there are no major differences in affluence between the regions or cities. Also, the data are collected in a systematic way, using national statistical banks. Still, the variations are very significant. There is no obvious reason for this. One may assume that the ideas of the municipality are important. Also, it should be understood that the data refer to municipalities, and that the municipalities in the Netherlands differ considerably as regards their proportion of urban and rural area. It should be mentioned that these data are from around 1986. At that time, lighting master plans where not common (sec. 11.7). Still the table may have its value. It refers to about

4,4 million people, that is about 28% of the population op of the whole country. Most major municipalities are included. The weighted average amounts to 936,8 lumen per capita, just a fraction under the Garstang number of 1000. It should be noted, however, that this 'weighted average' must be handled with care, because the municipatities mentioned in Table 13.2.7a do not represent a random sample from all municipalities, that numbered some 600-plus at that time.

City	Inhabitants	lumen/inh
Wervershof	7 324	465,6
Hellendoorn	33 967	532,9
Breda	120 000	573,3
Emmen	92 018	576,0
Eibergen	16 086	596,8
Schiedam	69 349	601,3
Franekerdeel	21 074	631,1
Delft	87 752	635,9
Meersen	20 375	667,5
Den Haag	445 097	676,3
Castricum	22 658	684,1
Maastricht	113 951	690,6
Zaanstad	128 388	697,7
Assen	47 350	705,4
Ridderkerk	46 247	726,5
Dordrecht	106 999	729,9
Nieuwegein	55 000	752,7
Lisse	20 449	782,4
Leeuwarden	85 181	798,3
Haarlem	149 099	816,4
Beverwijk	35 000	857,1
Roermond	38 297	861,7
Enschede	144 226	911,8
Amsterdam	682 779	959,3
Rotterdam	572 642	978,1
Tilburg	153 294	1098,1
Nijmegen	146 651	1100,0
Utrecht	229 285	1109,2
Eindhoven	191 023	1185,7
Oss	50 636	1204,7
Heerlen	71 088	1211,2
Den Bosch	89 749	1291,4
Groningen	140 000	1509,9
Almere	51 200	1570,3
Arnhem	127 671	1595,9

Table 13.2.7a: *Luminous flux per capita for a number of cities in the Netherlands, listed in increasing number of lumen per inhabitant.*

For comparison, we will list the data that were collected for several other countries as well. See Table 13.12.7b. The data in that table have only some anecdotal value. The data refer to 1986 or maybe somewhat earlier. It should be stressed that the data are the result of an unofficial enquiry under IAU and CIE committee members. There is no system as regards the people who took the trouble to answer the enquiry, and there is no check whether they all used the same definition. But still, the data are considered as interesting.

Country	City	Inhabitants	lumen/inh
China	Canton	3 000 000	53,3
China	Bejing	6 000 000	59,4
China	Wuhan	3 200 000	66,1
China	Qindao	1 100 000	71,6
China	Hangzhou	800 000	74,5
China	Yangzhou	300 000	87,0
China	Shanghai	6 500 000	88,0
China	Shashi	240 000	218,0
Switzerland	Elsau	2 640	322,0
Switzerland	Langnau	9 500	336,8
Switzerland	Saanen	7 250	358,1
Argentina	Zarate	65 000	593,8
Argentina	L. de Zamora	500 000	623,4
Switzerland	Trubschachen	1 700	647,1
Argentina	Buenos Aires	2 900 000	660,7
Argentina	Mar del Plata	400 000	826,5
Csechoslovakia	Prinovske	600	833,3
Switzerland	Dietikon	20 700	840,1
Switzerland	Zurich	362 000	994,5
Csechoslovakia	Mirosov	1 800	1000,0
Csechoslovakia	Plzen	170 000	1032,9
Csechoslovakia	Brno	344 000	1053,2
Csechoslovakia	Kosice	203 000	1091,1
Csechoslovakia	Opava	50 000	1150,0
Csechoslovakia	Roznava	18 000	1177,8
Switzerland	Bern	145 000	1206,9
Csechoslovakia	Tabor	26 000	1319,2
Csechoslovakia	Praha	1 195 000	1327,9
Csechoslovakia	Bystrica	66 000	1648,5
Csechoslovakia	Liberec	72 000	1656,9
Csechoslovakia	Ostrava	279 000	1809,0
Csechoslovakia	Sliac	3 000	2000,0
Csechoslovakia	Bratislava	380 000	2008,9

Table 13.2.7b: *Luminous flux per capita for a number of cities in different countries, listed in increasing number of lumen per inhabitant.*

(c) Studies in Japan

In 1995 and 1996, a large survey was made in Japan. The results are summarized in Narisada & Kawakami (1998). In seven districts of a number of different cities and towns in Japan, a complete survey was made of all outdoor lighting equipment. The main purpose was to establish what part of the luminous flux is emitted upwards. The seven districts are listed in Table 13.2.8.

District	Location
A	a shopping centre in Nagoya
B	outskirts of a town in Saitama
C	suburbs of a town in Saitama
D	a residential area in Tokyo
E	a commercial area in Tokyo
F	a business centre in Nagoya
G	a shopping centre in Nagoya

Table 13.2.8: *Districts in the Japanese study. After Narisada & Kawakami, 1998, Tables 8-1-1 to 8-2-6.*

In Table 13.2.9, the results of the study are summarized. The districts are as given in Table 13.2.8.

District	Number luminaires	Total energy (KW)	Total flux (Mlm)	Average ULOR (%)
		Source		
	8-1-1	8-1-3	8-1-4	8-1-6
A	423	62,2	2,63	17,8
B	824	67,5	2,79	12,0
C	2 493	84,1	2,98	9,5
D	1 960	131,8	4,60	9,7
E	23 138	1333,5	60,30	18,9
F	3 900	762,2	73,30	17,9
G	26 316	2456,2	146,60	19,6

Table 13.2.9: *Results of Japanese survey. After Narisada & Kawakami, 1998.*

Note to Table 13.2.9: ‘Source’ means table number in Narisada & Kawakami, 1998.

District	Road lighting	Business centres	Residential streets	Signs	Total
A	11,4	22,5	–	–	17,8
B	9,1	12,2	16,8	16,9	12,0
C	12,7	2,1	5,0	27,3	9,5
D	2,1	32,7	24,0	22,3	9,7
E	4,1	21,2	23,4	19,3	18,9
F	28,2	7,1	16,4	27,2	17,9
G	18,1	34,8	–	21,8	19,6
Average	12,2	19,0	17,1	22,5	15,0

Table 13.2.10: *Values of ULOR for different areas and different lighting classes. After Narisada & Kawakami, 1998, table 8-1-6.*

It is interesting to note from this survey, that, in Japan, the ULOR usually is quite high. The overall average is 15,0%. Of course, this survey does not include all lighting installations of Japan, but it includes most common lighting classes; therefore, it is likely to be a rather good representation of the outdoor lighting of the whole country. Also it may be noted, that the ULOR is not only very different for different lighting classes – which is to be expected – but also for the same lighting class in different locations. There seems to be a case for more standardization.

Another survey was made in Japan in 1996. Here, the use of different types of luminaires was studied for different environmental zones (Narisada & Kawakami, 1998a). In Table 13.2.11, the extent of the survey is given. The results of the survey are given in Table 13.2.12 and Table 13.2.13.

Zone	Land use	Area (hectares)
E1	national park (Kyushu)	78,0
E2b	rural area (Saitama)	17,6
E3a	suburban area (Saitama)	14,2
E3b	urban residential area (Tokyo)	10,6
E4a	urban city area (Tokyo)	5,8
E4b	big city business area (Nagoya)	7,9
E4b	big city commercial area (Nagoya)	15,0
Total		149,1

Table 13.2.11: *Areas surveyed. After Narisada & Kawakami, 1998a, Table 1.*

Zone	Traffic roads	Resident streets	Decor. lighting	Projectors	Signs	Other	Total
E1	49	26	159	68	0	121	423
E2b	63	153	108	91	290	80	785
E3a	87	373	80	40	107	1640	2327
E3b	547	415	321	160	189	1707	3339
E4a	250	367	1983	2117	12 817	800	18 334
E4b business	193	100	1100	893	727	887	3900
E4b shopping	734	0	7000	1331	16 380	620	26 065
Total	1923	1434	10 751	4700	30 510	5855	55 173

Table 13.2.12: *Number of luminaires per zone per 100 hectares. After Narisada & Kawakami, 1998a, Table 2.*

Zone	Traffic roads	Resident streets	Decor. lighting	Projectors	Signs	Other	Total
E1	1	1	50	38	0	8	100
E2b	3	5	44	6	41	2	100
E3a	3	25	27	1	30	14	100
E3b	7	9	27	9	15	32	100
E4a	0	0	24	5	63	6	100
E4b business	1	0	16	74	4	3	100
E4b shopping	2	0	40	21	34	2	100

Table 13.2.13: *Proportion (in %) of upward flux per zone per 100 hectares. After Narisada & Kawakami, 1998a, Table 3.*

(d) Studies in Italy

In Italy, a survey is made in two cities (Broglino et al., 2000). The study relates to Turin and Treviso. "Turin is a heavily industrialized town with a population of about 1 million. The local electrical energy distributor prepared a public lighting plan that, for each type of road, specifies luminance and illuminance levels, the type of lamp and the colour of the light, and also the maximum ULR" (Broglino et al., 2000, p. 261). The lighting data for Turin are summarized in Table 13.2.14.

"Treviso is a town in North-East Italy, characterised by numerous small industries and businesses, distributed over a territory that still retains the features of intensive agriculture. Is a medium sized town with about 80 000 inhabitants. It is situated in the Veneto region, where a local law from July 1997 establishes certain restrictions on the use of public lighting, in order to restrict the upward luminous flux (Anon., 1997b). That is why Treviso was chosen for a 'sample' assessment of present-day light pollution levels (Medusa, 1998)" (Broglino et al., 2000, p. 265). The data of the Treviso survey are given in Table 13.2.15.

Luminaire type	Number	Power (MW)	Flux (Mlm)	Rel. flux (%)	ULR (%)
post, road	42 593	8,3	635	68,8	6
suspension, road	2113	0,4	33,8	3,7	6
diffusor	9761	1,6	105	11,4	20
lantern type	2952	0,6	33,5	3,6	33
sphere type	1101	0,1	10,1	1,1	50
garden lamps	5027	0,9	50,4	5,5	33
other	3888	0,8	54,5	5,9	6
total	67 435	12,7	922	100	10,5

Table 13.2.14: *Public lighting installations in Turin. After Broglino et al., 2000, Table II.*

Luminaire type	Number	Power (KW)	Flux (Mlm)	Rel. flux (%)	ULR (%)
road (open type)	3953	323,7	10,4	32,4	10,3
road (with diffusor)	1513	177,9	8,5	26,5	2,9
road (flat glass)	1409	180,2	10,6	32,9	1,2
lantern type	117	12,6	0,6	1,9	39,7
sphere type	486	52,1	2,0	6,3	42,0
total	7478	746,5	32,1	100	7,94

Table 13.2.15: *Public lighting installations in Treviso. After Broglino et al., 2000, Table III.*

Notes to Table 13.2.15.
- The original publication makes a distinction between 'historical town centre' and 'suburbs'. Here, only the 'global values' are quoted;
- 35 'unclassified' luminaires are disregarded here.

It is concluded that the use of luminaires with a prismatic bowl and with high-pressure sodium lamps provide the most cost-effective lighting. The use of flat-glass luminaires would lead to an increase of between 20% and 30% in energy use. As a result of the contribution to the stray-light from the reflections by the ground surface, the improvement in the visibility of stars would be not more than only 0,15 magnitudes (Broglino et al., 2000, p. 268-269). Flat-glass luminaires as well as the influence of the reflections by the ground surface are discussed in sec. 12.4.

(e) Studies in The Netherlands for outdoor lighting in general

The final report that will be discussed in this context is the survey that is made to assess the upwards light flux in the Netherlands for different types of outdoor lighting (Schmidt, 2003). Some data from this report have been mentioned already in an earlier part of this section, more in particular the data regarding the luminous flux per inhabitant that is used in street lighting. These data have been presented in Table 13.2.6. Now, the upward light flux will be discussed, and also the other areas of outdoor lighting. As regards road lighting, Table 13.2.6 will be extended to include the upwards flux. See Table 13.2.16.

Example	Road authority Municipality Apeldoorn	Province Noord-Holland	Central Government	Total
inhabitants	155 000	2 474 800	n.a.	16 000 000
energy use (GWh)	5,33	5,1	70	
energy use per inh (W)	8,6	0,52	1,09	10,71
flux per inh (lm)	732	62	159	1003
direct upwards flux (est.)	5%	5%	5%	
reflected upwards flux (est.)	5%	10%	15%	
total upwards flux per inh (lm)	78,2	9,15	31,6	118,95

Table 13.2.16: *Upwards flux for public lighting. After Schmidt, 2003, table 1.*

As regards the lighting of greenhouses ('assimilation lighting'), it is assumed that the lighting installations are 'state-of-the-art', meaning that the direct upward flux is 0%. As the light falls on soil and on plants, the reflection is considerable. For full-grown plants is it about 5% to 10% and for young plants between 10% and 30%. Of this, about 25% is absorbed by the glass and the roof construction of the greenhouse. The net value of the reflected upward flux is estimated at 10%. On the average, assimilation lighting is used 3000 hours per year, of which about 20% during the day. The data on the assimilation lighting are given in Table 13.2.17.

Greenhouse lighting	Total for the Netherlands	Per inhabitant
area of greenhouses (m^2)	17 000 000	1,06
energy (34 W/m^2)	5780 MW	36 W
luminous flux (130 lm/W)	751 10^9 lm	4685 lm
direct component upward flux	0%	0%
indirect component upward flux	10%	10%
upward flux (lm)	75 10^9	469

Table 13.2.17: *Upwards flux for assimilation lighting. After Schmidt, 2003, table 1.*

For the lighting of outdoor sports, the following data are given in the report (Schmidt, 2003). In the Netherlands, there are about 60 000 masts for the lighting of sports fields. Most of them are equipped with two lamps of 2000 W each. These lamps yield 100 lm/W. The total flux is $24 \cdot 10^9$ lumen., that is about 1500 lumen per inhabitant. It is assumed that 5% is emitted upwards directly and 10% indirectly. This means 225 upwards lumen per inhabitant. Furthermore, it is assumed that, on the average, the installations are used 400 hours per year.

No reliable comparable data for the Netherlands exist for other sources of outdoor lighting (floodlighting, advertising and area lighting). Therefore, some preliminary estimates have been made (Schmidt, 2003). The following assumptions are made:
(1) One building on every 2500 inhabitants is flood-lit, using 10 lamps of 150 W each.
(2) For every 2500 inhabitants, 10 signs of 1 m^2 are lit with 10 000 cd/m^2.
(2) For every 2500 inhabitants, 2 hectares of area are lit to a level of 10 lux.
All this would result in 140 lumen per inhabitant, of which 50% is emitted upwards, either directly or indirectly. Most lighting is in operation all night, or 4000 hours per year.

It should be noted that most of these data cannot be checked at the moment. "All assumptions seem to be at the high side" (Schmidt, 2003).

Table 13.2.18 gives the summary data of this study.

	Lighting for:			
	Roads	**Greenhouses**	**Sports**	**Other**
per capita (lm)	1002	4685	1500	140
upwards per capita (lm)	118	468	225	70
operation per year	4000	2400	400	4000
upwards lumen · hour per capita	472 000	1 123 200	90 000	280 000
% of total	24,0	57,1	4,6	14,3

Table 13.2.18: *Upwards flux; summary of data. After Schmidt, 2003, table 3.*

13.3 Energy losses as a result of light pollution

Although only a small part of the energy that is used by humanity is emitted as light into the atmosphere where it may cause light pollution, the amounts are staggering when looked at in absolute terms. As an example, the energy emitted upwards by a number of cities in Turkey, as well as in the rest of the world is given in Table 13.3.1. The table is based on data from the Defence Meteorological Satellite Program DMSP and relates to the year 1997. In fact, it is based on the same data-set as the 'First World Atlas' that is explained in sec.5.3. The total energy emitted from Turkey amounts to 120 million kWh per year, which corresponds to about 10 million US dollars per year (Aslan & Isobe, 2000). As mentioned already, these values should be seen as an example only.

City	Energy emitted (kWh/yr/km^2)
Istanbul	4850
Izmir	3080
Bursa	2370
Ankara	3880
Antalya	1730
London	11200
Belfast	1620
Paris	10700
New York	15000
Vienna	6660

Table 13.3.1: *Energy emitted upwards by a number of cities (Aslan & Isobe, 2000)*

Data for the total energy (expressed in lumen·hours), that is emitted upward for different types of outdoor lighting installations, have been given in Table 13.3.2. When considering the fact that almost all lamps in use for outdoor lighting have are gas discharge lamps that usually have a luminous efficacy of about 100 lumen per Watt, the energy loss as a result of the upwards light emission can be assessed. It should be taken into account that, in road lighting, some lamps, like e.g. compact fluorescent lamps have a lower efficacy, but also that low-pressure sodium lamps have a considerable higher efficacy. So, it seems to be justified to use the overall figure of 100 lm/W also for road and street lighting.

Now we will use these data to estimate the total energy loss 'into space' as a result of outdoor lighting, considering that in an earlier part of this chapter, in Table 13.1.22, the total energy use in the Netherlands in 1991 is mentioned, based on data from EnergieNed. See Table 13.3.2.

	Unit	Energy	From Table
upwards energy total per capita	KWh	19,6	13.2.17
upwards energy total, whole country	KWh	$313{,}6 \cdot 10^6$	13.2.17
total energy, whole country	10^{15} J	2872	13.1.22
	KWh	$797{,}4 \cdot 10^{12}$	
total electric energy, whole country	10^{15} J	282	13.1.22
	KWh	$78{,}3 \cdot 10^{12}$	

Table 13.3.2: *Total energy lost 'into space' in the Netherlands.*

These data can be compared to the data that are given in sec. 1.2.3. The annual energy consumption for road lighting in the Netherlands was 635 GWh in 1990. For 15,5 million inhabitants, the total power consumption for road lighting was about 41 KWh per person per year. Assuming that road lighting represents about 70% of the total outdoor lighting – a high estimate –, the total yearly consumption is about 59 KWh per person. Taking into account that most lighting installations are not too well maintained, one may assume that about 65% of the light will leave the luminaires. This figure is a rough estimate of the system efficiency of the lighting installation. This corresponds to 38 KWh per year per person. Taking into account that most lighting installations are not too well designed, on may assume that about 50% of the light will reach its goal. This means that half of the light is 'wasted', corresponding to 19 KWh per year per person. This amount is almost identical to the value given in Table 13.3.2.

As is explained in some detail in sec. 1.2.3, this estimate is compared to other studies on this subject, a considerable discrepancy is found. Crawford calculated on the basis of a number of 'rule of thumb' assumptions the loss of one thousand million dollars annually in the USA alone (Crawford, 1991, 1997a). This is about three times the amount estimated here. Isobe has given similar data but then more detailed for specific towns and locations (Isobe, 1999). The main reason seems to be the fact that Crawford and Isobe did include the reflected light as part of the 'wasted' light. In sec. 1.2.3, it is explained what is the reason for this discrepancy.

From Table 13.3.2, it can be seen, that only a fraction as small as $0{,}393 \cdot 10^{-6}$ from the total energy is lost into space. From the total electric energy, the fraction is, of course, larger. It amounts to $4 \cdot 10^{-6}$, or 0,000 04%. When we assume that an optimum design of lighting equipment and lighting installations, as well an optimum lighting management, cold reduce the upward flux by the – be it rather optimistic – value of 20%, the reduction in upward emission, and consequently the reduction of CO_2-emission into the atmosphere, would be not more than 0,000 008%. A word of caution: we have not always be very consistent in the preceding discussion, when using the distinction between 'road lighting' and 'outdoor lighting' in general.

13.4 Conclusions about environmental aspects

As a conclusion we may state that reducing the upward luminous flux of lighting installations proves to have a major benefit in the reduction of light pollution. As a measure to reduce the CO_2-emission into the atmosphere, the effect is beneficial, but very small. However, the old Dutch saying states that 'all little things matter'.

There is, however, a more important reason to stress the beneficial – be it small – effect of reducing light pollution on the CO_2-emission. Although the amount is small in quantitative terms, the political impact may be considerable: amongst other things, it is always a task of the Government to set a 'good example'. We will come back to this point in sec. 15.2, when discussing the promotion of 'public awareness'.

Another reason to stress the beneficial effect of reducing light pollution, is that, although the reduction of the CO_2-emission is small, still here are considerable sums of money involved. In sec. 1.2.3, a summary estimation of the costs is made. It was estimated that, at a price of 0,125 Euro per KWh, the Netherlands would loose about 2,38 Euro per year per person. For the whole country, the loss is about 36,7 million Euro per year. In the USA, energy is much cheaper. If we assume a price of 0,08 Euro per KWh, this would mean about 1,52 Euro per year per person in the USA. With 250 million inhabitants, the total yearly loss will be about 380 million Euro for the whole USA. Although the amounts of money are somewhat smaller than was estimated by Crawford, Isobe and others, it is still a sizeable sum of money!

As a conclusion we may state that reducing the upward luminous flux of lighting installations proves to have a major benefit in the reduction of light pollution. As a measure to reduce the CO_2-emission into the atmosphere, the effect is beneficial, but very small. However, the old Dutch saying states that 'all little things matter'. Also, contrary to another old Dutch saying, 'a droplet on a hot stove really cools down'.

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14 Photometry

Both in engineering and in astronomy, photometry is essential. Photometry makes it possible to express lighting and vision phenomena in a quantitative way, to define them, and to compare results with those of other researchers or of other laboratories. Photometry is a branch of experimental natural science. To deal with matters of lighting and vision in a scientific way, the first thing is to quantify light. For this purpose, the quantities of and the units of the light are strictly and precisely defined and described in the International Lighting Vocabulary that is published by CIE. This vocabulary is based on the ISO-Standards of weights and measures.

When light strikes the eye, a sensation of light is provoked. The intensity of the light stimulus is called the photometric quantity, and the sensation produced by the stimulus is called brightness. The energy of electric radiation can be expressed in Watt. However, only the wavelength range between about 400 nm and 800 nm can produce a sensation of light and colour. Fundamentally, photometry is nothing else but photon counting. Each photon is counted, and weighted according to the photopic spectral luminous efficiency curve. In this chapter, the different photometric quantities and units are described, and so is their measurement. We begin with the luminous flux, followed by the luminous intensity, the illuminance, and the luminance. Special attention is given to the eerie subject of the luminance of virtual objects, like the night sky. Also, the luminance factor is discussed, more in particular the way, light is reflected by road surfaces.

Astronomy faces problems that differ from the problems engineers have to deal with. In astronomy, both subjective and objective photometry are used. The conspicuity of heavenly objects is described in the, essentially subjective, scale of magnitudes. Objective photometry is more like radiometry, because different types of detectors are used, not only the light-adapted human eye. There is no real difference in the way photometry is used in engineering and in astronomy. It is mainly a difference in the nomenclature that is used. The conversion from the one into the other is, however, not straight-forward, because engineers use only the light adapted human eye as a detector, whereas astronomers use all sorts of different detectors, each having a *different spectral response. The only true comparison is therefore in 'power' (in Watts, that is).*

Further, this chapter deals with the measurement of light. First, the different detectors are discussed, with emphasis on photodiodes and CCDs. Finally, the measurement of the sky luminance is discussed in some detail, as that is the main constituent of light pollution. Simple area surveys are described, as well as means to monitor the sky luminance. The selection of observational sites is determined to a large degree on the level of light disturbance one may expect. Measurements for site selection are important. Further, the most important of the recent developments gets considerable attention: 'The first world atlas of the artificial night sky brightness'. Finally, a special case is the fact that, at present, no standardized methods for the measurement and the description of the sky luminance are available. In this chapter, a proposal is made for a standard measuring method for the sky luminance.

14.1 Photometry in engineering and in astronomy

14.1.1 General aspects

(a) *The CIE Vocabulary*

The principal aim of outdoor lighting is to make objects, the area, or the visual environment sufficiently light during the time that the level of natural daylight, is not enough for human activities. To deal with the matters of lighting in a scientific way, the quantity – the strength – of the light has to be measured, calculated, and expressed in a consistent and numerical way. For this purpose, the quantities of and the units of the light are strictly and precisely defined and described in the CIE International Lighting Vocabulary (CIE, 1987). In this chapter, some more simplified explanations will be given, to make them easier for practical applications. They are still based on the CIE. Before the explanation of the quantities and the units, some general aspects will be discussed. Several items have been discussed, sometimes in detail, sometimes briefly, in other chapters of this book. When needed, references will be made.

There is one important general aspect, that must be pointed out right at the outset. As mentioned earlier, illuminating engineering makes use of the quantities and the units as described in the CIE Vocabulary, which, in its turn, is based on the ISO-Standards of weights and measures. In observational astronomy, however, many non-ISO quantities and units are used. This deviation is the cause for many misunderstandings. In sec. 14.3.6, the discrepancies and the methods to convert the different units into each other, are discussed in detail. It should be mentioned that, contrary to observational astronomy, astrophysics, being closer to the experimental natural sciences that are discussed in sec. 10.1.2, usually follow the ISO-Standards.

(b) Stimulus and sensation of the eye

When light strikes, through the ocular media, the retina of the eye, a sensation of light – or brightness – is provoked. As all the sensations of human being, such as the hotness, the loudness, the smelliness, etc., the sensation of brightness cannot be measured directly by means of physical measuring devices. To be able to deal with the sensation in a technological or engineering way, the strength of the physical stimulus that produced the sensation, in stead of the strength of sensation, is measured, calculated and expressed as required.

(c) Photometric quantities of light as stimuli producing the brightness

The intensity of the light stimulus is called the photometric quantity, and the sensation produced by the stimulus is called brightness. The sensations of human being other than brightness, such as the hotness, the loudness, the smelliness, etc. are produced by physical, mechanical or chemical stimuli. The sensation of brightness, however, is not produced by a simple physical, mechanical or chemical stimulus, but by a psychophysical stimulus.

(d) Photometric quantities as the psychophysical stimuli

Light is an electromagnetic wave – or it can at least be described in terms of electromagnetic waves. Electromagnetic waves have a wide variety of functions and possibilities of applications, depending on the wavelength. As is explained in sec. 11.1.1, the wavelength of electromagnetic waves that are used in different fields of application, vary between about 10^6 m, and 10^{-14} m (Hentschel, 1994). They are used, for example, in order of decreasing wavelength, as electric power, radio and television broadcasting, telecommunications, digital information transmission, computers, radars, heating, lighting, signalling, photo-chemical applications, X-ray applications, radio-active radiations, etc. Radiation can be measured. The process is called radiometry. The energy of the radiation can directly be expressed in Watt. The definition of the unit 'Watt', and that of the other ISO-units are discussed in sec. 14.1.2a.

Only the wavelength range between about 400 nm and 800 nm can produce a sensation of light and colours in the human eyes. The electromagnetic wave with a wavelength within this range, is called light or optical radiation, and the wavelengths within this range are called visible wavelengths.

Obviously, in order to measure the stimulus of light, the visible wavelength range has to be extracted. However, the photometric quantities do not simply correspond to the electromagnetic radiation within the visible wavelength range, the energy of which is measured in W. More in particular, it is not always true that the same amount of energy of optical radiation that strikes the retina (measured in Watt or Watt/m^2), does not produce always the same sensation of brightness.

The sensitivity of the human retina for the optical radiation is different according to the wavelength of the light striking the retina. The curve, which shows the variations of the sensitivity for the light of the retina for different wavelengths of the optical radiation, is called the 'spectral luminous efficiency curve' of the human visual system. As an alternative term, one may speak of the spectral sensitivity curve. The relevant ISO-Standard specifies the detailed numerical values of the relative spectral efficiency for different wavelength. As is explained in more detail in sec. 8.2.2, the 'Standard Visibility Curve' is usually presented in two ways:

(1) As a curve, depicting the relative sensitivity versus the wavelength. The curve, called the 'V_λ-curve', this is shown in Figure 8.2.1.
(2) As a table, giving the same relation. A shortened version is given in Table 8.2.1. CIE has produced a certified version of the table that gives the value of the sensitivity up to intervals of 1 nm.

It should be stressed that, as explained in sec. 8.2.3d, other receptors have other response curves. In sec. 14.1.2.b, we will come back to this point when discussing the measurement of light. Examples of other detectors are given in Sterken & Manfroid (1992, sec. 1.16, Figure 1.17).

The spectral luminous efficiency curves have been derived by means of psychophysical experiments regarding the stimuli of the light and the sensation of brightness. Therefore, the photometric quantities are called the psychophysical quantities. This means that all – simple or sophisticated – measuring devices for photometric quantities are based on the psychophysical observations. This is also the reason that, as is explained in sec. 14.2.1a, a psychophysical quantity – the candela – is added as one of the fundamental quantities of the International System of Weight and Measures, as defined by ISO.

Photometric quantities can be measured by a photo-electric device with a spectral sensitivity corresponding to the spectral luminous efficiency curve, specified by the ISO-Standard. If the spectral sensitivity of the photo-electric device deviates from the ISO-Standard, the measuring results with such a device are invalid for lighting purposes where the human eye is the 'end user'. Such devices may have their use, of course, in other, non-visual, areas of radiometry. See also the examples that have been mentioned earlier in this section (Sterken & Manfroid, 1992, sec. 1.16, Figure 1.17).

As is described in detail in sec. 8.1.4, there are two different kinds of photoreceptors in the retina: the cones, that are active in bright conditions, and the rods, that are active in very dark conditions. Visual conditions under which the cones are active, are called the conditions of photopic vision. The visual conditions under which the rods are active, are called the conditions of scotopic vision. Both photopic vision and scotopic vision have their own standard spectral luminous efficiency curve. The curve for cone-vision – or daytime vision – is, as is indicated earlier, called the V_λ-curve. The curve for rod-vision – or nighttime vision – is, in analogy, called the V'_λ-curve. The tabulated values of the V_λ-curve and the V'_λ-curve are given in Table 14.1.1.

λ (nm)	V_λ	V'_λ
380	0,0000	0,0006
390	0,0001	0,0022
400	0,0004	0,0092
410	0,0012	0,0348
420	0,0040	0,0966
430	0,0116	0,1998
440	0,023	0,3281
450	0,038	0,455
460	0,060	0,567
470	0,091	0,676
480	0,139	0,793
490	0,208	0,904
500	0,323	0,982
510	0,503	0,997
520	0,710	0,935
530	0,862	0,811
540	0,954	0,650
550	0,995	0,481
560	0,995	0,3288
570	0,952	0,2076
580	0,870	0,1212
590	0,757	0,0655
600	0,631	0,0332
610	0,503	0,0159
620	0,381	0,0074
630	0,265	0,0033
640	0,175	0,0015
650	0,107	0,0007
660	0,061	0,0003
670	0,032	0,0001
680	0,017	0,0001
690	0,0082	0,0000
700	0,0041	0,0000
710	0,0021	0,0000
720	0,0010	0,0000
730	0,0005	0,0000
740	0,0002	0,0000
750	0,0001	0,0000
760	0,0001	0,0000
770	0,0000	0,0000
780	0,0000	0,0000

Table 14.1.1: *The relative standard spectral luminous efficiency curve for V_λ and V'_λ. The maximum values of V_λ and V'_λ are taken as 1. After Hentschel, 1994, Table 2.2, p. 3. Based on data from CIE, 1924, 1951. See also Table 8.2.1.*

In between the ranges of cone-vision and of rod-vision, where the visual conditions are called mesopic vision. Sometimes, a separate curve, similar to the V_λ-curve, is identified for mesopic vision. As is explained in sec. 8.3.4c, it is probably better to speak of a 'family' of mesopic spectral sensitivity curves. For photopic vision, the wavelength at which the spectral sensitivity reaches its maximum is 555 nm, while, for scotopic vision, the maximum is 507 nm. As is explained in sec. 14.1.2b, all photometric quantities are, according to the ISO-Standards, defined according to the spectral sensitivity curve belonging to the photopic vision. The definitions according to the photopic curve, do not pose problems for most areas of illuminating engineering, because usually, the lighting levels are in the region of daylight vision. This is also the case or a large part of outdoor applications that function at night. This is, however, not always the case. In several, still quite numerous, nighttime outdoor lighting applications, the lighting levels fall in the range of mesopic vision, rather than in that of photopic vision. In sec. 8.3.5, the consequences of this fact are discussed in detail.

14.1.2 The ISO-photometry

(a) The SI-units

In 1960, at the 11th General Conference of Measures and Weight, the Système International d'Unités (the International System of Unities or SI) was adopted. It is based on seven basic unities:

(1) The meter (m) as the unity for length;
(2) The kilogram (kg) as the unity of mass;
(3) The second (s) as the unity of time;
(4) The Ampère (A) as the unity of electric current;
(5) The Kelvin (K) as the unity for thermodynamic temperature;
(6) The mol (mol) as unity of amount of matter;
(7) The candela (cd) as the unity of luminous intensity.

From these basic unities, all sorts of derived unities have been defined. The definitions of the basic unities are given – in German – in Anon. (2001a). The definitions themselves are, however, sometimes a little strange – to say the least. We will give a few examples:

- The meter – a word that, in many languages also means a measuring device – is defined in terms of time (the length that light travels in vacuum in 1/299 792 458 seconds);
- The kilogram used the prefix kilo – which would mean 1000 basic units, not one;
- The second is, as the word says, a unit of the second level. The hour would be more appropriate;
- The candela is defined in terms of luminance. This gives rise to a fundamental problem, because the mathematical expressions, such as those that are discussed in sec. 14.1.4, are valid only for a point source, whereas luminance only makes sense for a source larger than a point – a source with a measurable surface area. "Mathematically, a solid angle must have a point at its apex; the definition of luminous intensity therefore applies strictly only to a point source" (Moon, 1961, p. 556, quoting Anon., 1932). Furthermore, the whole idea of defining the photometric units and quantities while using the V_λ-curve is reduced to the introduction of the constant 1/683. As is explained in sec. 8.2.2,

this constant follows from the integration of the V_λ-curve (Hentschel, 1994, p. 32). It corresponds to the ratio between the 'Watt' and the 'light watt' or 'luminous watt' (Schreuder, 1998, sec. 5.2., p. 467).

As is explained in more detail in sec. 8.2.2, the standard visibility curve is sometimes written as a function: $V = f(\lambda)$. See e.g. Hentschel (1994. equation 2.44). As is to be expected, there is a third way to represent the Standard Visibility Curve. For this, a mathematical approximation is given. The function is very complex and not very accurate. It should be noted that the integral of the function gives the conversion from lightwatts into lumens. After a new definition of the candela was introduced in 1979, it determines automatically that one Watt corresponds to 683 lumen (Schreuder, 1998, p. 73). For the scotopic observer, the corresponding value is 1699, as given by Wyszecki & Stiles (1967). The value of 683 is sometimes called the radiometric equivalence. A more detailed description of that ratio is the 'photometric equivalent of radiation' (Hentschel, 1994, p. 32). Further details are given in Bischoff & Metzdorf (2001). These comments are more or less 'official', as they are given by the German Agency for Physics and Technology, which might be loosely translated as the National Bureau of Standards of Germany. More unofficial, but often more clear, comments are given in recent textbooks like e.g. Baer (1990, sec. 1.2.1.1; Hentschel, 1994; Schreuder, 1998, sec. 5.2 and sec. 5.3; p. 46-58).

(b) The photometric units

Fundamentally, photometry is nothing else but photon counting. Each photon is counted, and weighted according to a weighing function. This weighing function is, of course, the spectral luminous efficiency curve that was described earlier. As we deal with 'official', or photopic photometry, the spectral luminous efficiency curve that we need is the one for the human visual system, viz. the V_λ-curve.

In sec. 8.2.1, when discussing visual functions, photons are briefly mentioned. "A photon is a quantum of electromagnetic radiation. It has an energy of $h \cdot \nu$, where h is the Planck-constant and ν the frequency of the radiation" (Illingworth, 1991, p. 350). "Planck constant is a universal constant, having the value of $6{,}626\ 076 \cdot 10^{-34}$ J·s" (Illingworth, 1991, p. 354). A quantum represents energy. "Energy is the quantity that is the measure of the capacity of a body or a system for doing 'work'. When a body does work, its energy decreases by an equal amount" (Illingworth, 1991, p. 151). The unit of energy is joule (J). A Joule equals a Watt · second (Ws; Kuchling, 1995, p. 106). Thus, n photons represent the energy of $n \cdot h \cdot \nu$. What interests lighting engineers and astronomers alike is usually not the number of photons, but rather the number of photons that are emitted – or that pass – per second. So, the logical basic unit of photometry is the energy flux. When we discuss 'light', it is the energy flux weighted according to the spectral luminous efficiency curve for the human photopic visual system. This is, for obvious reasons, called the luminous flux. So, in spite of the fact that SI considers the candela as the basic unit for photometry, we will begin our description with the luminous flux, and the related concepts of transmission, reflection, and absorption. From that, the luminous intensity follows in a natural way. This leads to the illuminance, and from there on, the different derivatives are described.

14.1.3 The luminous flux

(a) Definition

The luminous flux is the quantity or the amount of the light. The unit is lumen (lm). Its dimension is, as is explained in sec 14.1.2, that of the Watt. It is indicated by the symbol Φ. Since, the luminous flux under normal lighting conditions cannot accumulate as water, and proceeds a velocity of about 300 000 km/h and instantaneously transformed into heat, the quantity of the light, therefore, is not the quantity of the accumulated amount of the light but a rate of the stream flow of the light per second. The quantity of the accumulated amount of the light is the exposure. The exposure is described as "the product of the illuminance or irradiance and the time for which the material is illuminated or irradiated" (Illingworth, ed., 1991, p. 63). The exposure is an important quantity to take into account when discussing photographic emulsions (sec. 14.5.1b) or CCDs (sec. 14.5.2).

As has been mentioned in an earlier part of this section, the integration of the V_λ-curve gives the photometric equivalent of radiation (Hentschel, 1994, p. 32). The numerical value is 1/683. This indicates that it is theoretically not possible to construct any light source that produces more than 683 lumens for each watt; in other words, the maximum value of the luminous efficacy of any light source is 683 lm/W (Schreuder, 1998, sec. 5.2., p. 46). The concept of the luminous efficacy is explained in sec. 11.3.2b. If one wants to express the maximum luminous efficacy in terms of the, non-standardized, scotopic photometry, the number would be 1699 lm'/W (Hentschel, 1994, p. 32). This does not imply that lamps would be more efficient in scotopic vision, only that the scotopic lumen (lm') has a different value from the photopic lumen. This difference, of course, results from the differences between the V_λ-curve and the V'_λ-curve.

(b) Reflectance, transmittance

When a quantity of the luminous flux flows into any surface, a part of it is reflected, a part is transmitted, and the rest is absorbed. For an opaque surface, the transmission is, of course, zero. The reflectance is a ratio of the reflected luminous flux to the incident luminous flux under the given conditions. The transmittance is a ratio of the transmitted luminous flux through the optical medium to the incident luminous flux in the given conditions. The optical phenomena of reflection and transmission of the light are not simple. They are influenced by the configuration of inflowing luminous flux and the optical media through which the light passes. The physical phenomena and the mathematical description of reflection and transmission are discussed in considerable detail in sec. 14.1.8a.

14.1.4 The luminous intensity

Almost all light sources, both natural and man-made, emit light at different rates in different directions. Even the Sun, which approaches an ideal emitter of light, shines differently in different directions, for one reason because it is flattened, and not spherical. For all common man-made light sources, this is very much the case, because they all require a lead into the actual source to provide its energy – gas, wax, or electricity. Furthermore, they have to be supported. So there is an urgent need to be able to make a clear distinction for the action of the source into different directions. For this, the luminous intensity is introduced.

The luminous intensity of a light source signifies, therefore, the intensity of the light that is emitted from the source itself. As is described in sec. 14.1.2, the ISO uses the unit of luminous intensity (the candela) as the basic unit for all photometry. We have pointed out the mathematical, physical and practical difficulties that arise when doing so.

In practical photometry, a rather different definition is used. This definition follows directly from the description we have given earlier in this section. Essentially, it means the luminous flux in a certain direction. Thus, the luminous intensity (designated as I) is defined in the following way:

$$I = \frac{\delta\Phi}{\delta\Omega} \qquad [14.1.1]$$

in which Φ means the luminous flux emitted within the solid angle Ω.

In this relation the concept solid angle is introduced. The solid angle is defined as the surface (in m^2), cut out of a sphere with a radius of 1 m. Such a sphere is called an unit sphere. For a different sphere radius, the same solid angle cuts out a different area. The area is proportional to the square of the sphere radius. This is depicted in Figure 14.1.1. In this figure, a solid angle with a unity value, is depicted as it cuts out a surface area of r^2 (m^2) out of a sphere with a radius of r (m).

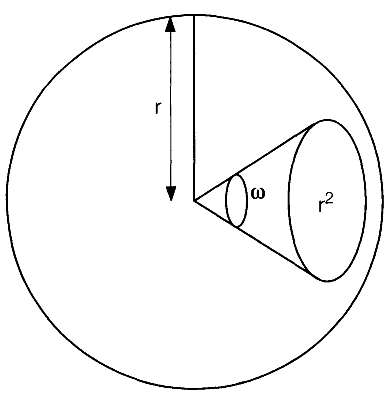

Figure 14.1.1: *The solid angle. After Schreuder, 1998, Figure 5.2.3.*

Using this description of the solid angle, the relation [14.1.1] can be depicted as in Figure 14.1.2.

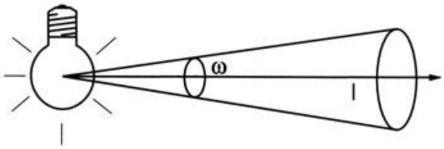

Figure 14.1.2: *The luminous flux emitted within a solid angle. After Schreuder, 1998, Figure 5.2.2.*

Based on the relation [14.1.1], the luminous intensity is defined as the luminous flux in a certain direction. But as the concept 'directions' essentially is a line only, the limit transition from the 'difference-quotient' [14.1.1] into a 'differential-quotient' is required. The formal definition of the luminous intensity is given in the relation [14.1.2].

$$I = \lim_{\delta\Omega \to 0} \frac{\delta\Phi}{\delta\Omega} = \frac{d\Phi}{d\Omega} \qquad [14.1.2]$$

14.1.5 The illuminance

(a) Definition

When light strikes a surface steadily, an amount of the luminous flux is incident on the surface. If the surface is evenly lit, the illuminance is expressed as an areal density of the luminous flux incident the surface. The unit of the illuminance is lux. Sometimes, 'lux' is abbreviated into 'lx'. The illuminance of an area A (in m^2) is:

$$E = \frac{\Phi}{A} \qquad [14.1.3]$$

The dimension of the illuminance is therefore lm/m^2.

It is, of course, possible to define E for a mathematical plane, through which the light shines. No physical phenomenon can be detected, and the term 'illuminance' can be somewhat misleading. It might seem better to call it the density of the luminous flux (Schreuder, 1998, p. 46). It is interesting to mention, that it has been proposed to base a general theory of illuminating engineering on the concept of flux density (Moon & Spencer, 1981, based on Gershun, 1939). The proposals led to nothing, mainly because Moon and Spencer wanted to introduce, at the same time, a completely different, new terminology (Moon, 1961, preface to the Dover edition, p. v-vii). However, from theoretical point of view, their attempts deserve more attention than they have ever received. See Moon (1961); Schreuder (1998, p. 46-47)

(b) Horizontal, vertical and semicylindrical illuminance

For obvious reasons, if the surface is located horizontally, the illuminance is called the horizontal illuminance (E_h). If it is located vertically, the illuminance on the surface is called the vertical illuminance (E_v).

The illuminance on the flat surface is not suitable to express the brightness of spherical or cylindrical object, such as the face of pedestrians. In such cases, the semicylindrical illuminance is used. The semicylindrical illuminance (Esc) is defined as the average value of illuminances on the surface of a cylinder. As one can see only one side of a cylinder at the time, the definition is limited to half a cylinder. The semicylindrical illuminance can be described as follows:

$$E_{semicil} = \frac{I}{\pi \cdot h^2} \cdot \sin\alpha \cdot \cos^3\alpha \cdot (1 + \cos\beta) \qquad [14.1.4]$$

The relation [14.1.4] is illustrated in Figure 14.1.3. In this figure, I signifies the luminous intensity, as described in sec. 14.1.4. The figure also gives the meaning of α, β and h.

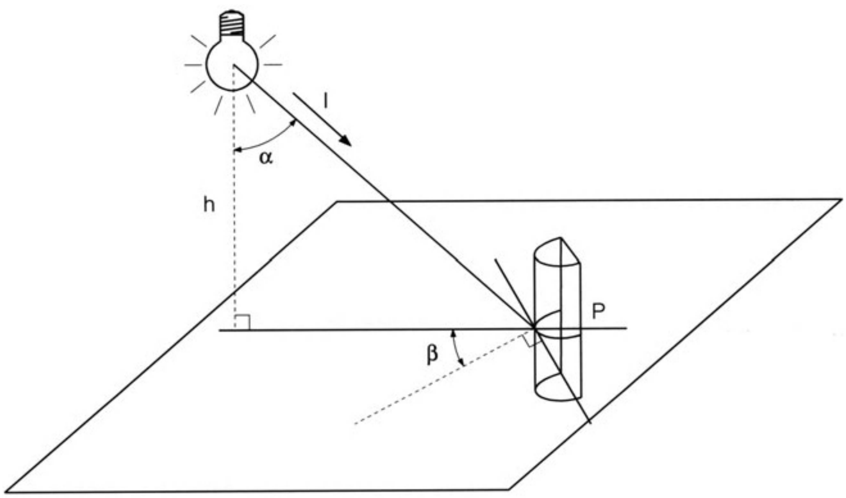

Figure 14.1.3: *The semicylindrical illuminance. After Schreuder, 1998, Figure 5.2.1.*

(c) *The average illuminance and the non-uniformity*

For the characterization of many aspects of outdoor lighting installations, the average illuminance is often crucial parameter. Although the description of the average as such is obvious, we will spend a few words on it.

When the illuminance distributions over any area, horizontal or vertical, or the incident luminous flux is not uniform, the average illuminance is often, as indicated above, an important characteristic. It can be assessed as follows:

$$E_{ave} = \frac{\Phi_{tot}}{A} \qquad [14.1.5]$$

with:

Φ_{tot}: the total luminous flux (in lumens) incident in the area;

A: the surface area on which the luminous flux is falling (in m^2).

If the distribution of the illuminance is extraordinarily non-uniform, sometimes, the average illuminance is not sufficient to characterize the lighting installation. Therefore, almost all standards or recommendations on lighting installations, both indoor and outdoor, give, apart from requirements about the average illuminance, also requirements about the degree non-uniformity that is acceptable. These requirements are given in different fashion, like e.g. as the minimum divided by the average (E_{min}/E_{ave}), or as the minimum divided by the maximum (E_{min}/E_{max}). In this way, the degrees of non-uniformity are always numbers smaller than one, which is convenient for calculations, and which avoids difficulties when the minimum is zero. Very similar definition of the average and the non-uniformity are used, when using the luminance as a design quality criterion. In sec. 14.1.6, the luminance is discussed in detail.

A practical point must be added. When measuring illuminances, e.g. on a road, the procedure is that one places the illuminance meter – the luxmeter – on the ground, takes all necessary precautions to avoid disturbances, and makes the measurement. Thus, the illuminance in one point on the road is measured. In this respects, there are no uncertainties other than the usual measuring errors. However, if the average road illuminance must be assessed, the point measurements must be repeated in different locations. It is essential to be very clear about the measuring grid that is going to be used. If not, severe errors may be the result, particularly if the illuminance is unevenly distributed. Obviously, such repeated point measurements are needed as well in order to assess the non-uniformity. Details about the measuring grids are given in sec. 14.5.3e.

(d) The inverse square law

From the definition of the luminous intensity, that is given in sec. 14.1.4, it can be concluded that the illuminance decreases with the square of the distance between the light source and the receiving plane. This relation is called, for obvious reasons, the inverse square law:

$$E = k \cdot \left(\frac{I}{r^2} \right) \qquad [14.1.6]$$

with:
E: the illuminance;
I: the luminous intensity of the source;
r: the distance;
k: a constant, depending on the units that are used).

This formulation is from Schreuder (1998, p. 52), based on data from Breuer (1994, p. 175). This is depicted in Figure 14.1.4.

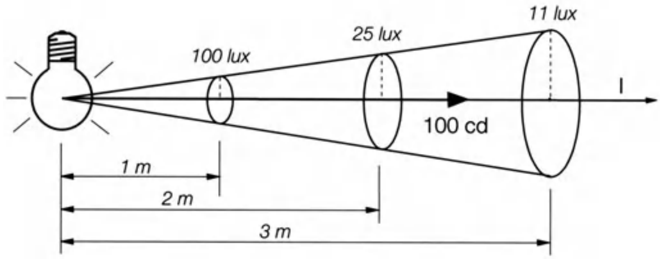

Figure 14.1.4: *The inverse square law. After Schreuder, 1998, Figure 5.3.1.*

(e) The distance law for large sources

As can be seen directly from the definition of the luminous intensity, relation [14.1.6] is valid only for point sources. When the source is small in relation to the distance, relation [14.1.6] can still be used a an approximation. For large sources, like rows of fluorescent tubes in tunnels or in office interiors, this is not possible. Of course, one can always regard a long source as a chain of many, short sources, do the exercise for each small part separately, and add up the results. This is done in most software programmes that are used in the design of the lighting of tunnels and offices. In pre-pc times, mathematical methods were needed. Elegant descriptions are given in Bean & Simons (1968, Chapters 2; 8); Moon, 1961, Chapters 8, 9, 10); Zijl (1951).

The discrepancy between the actual measured value, and the value that would be found if the source were a true point source, is given in the relation [14.1.7].

$$\frac{I}{I'} = \frac{\left(r^2 + R^2\right)}{r^2} \qquad [14.1.7]$$

in which:
I: the actual luminous intensity as measured;
I': the approximated luminous intensity, assuming that the inverse square law is valid.
r: the distance between the light source and the measuring point;
R: the radius of the light source, assumed to be circular.

The derivation of relation [14.1.7] is given in Helbig (1972, p. 47-48). The relation is depicted in Figure 14.1.5.

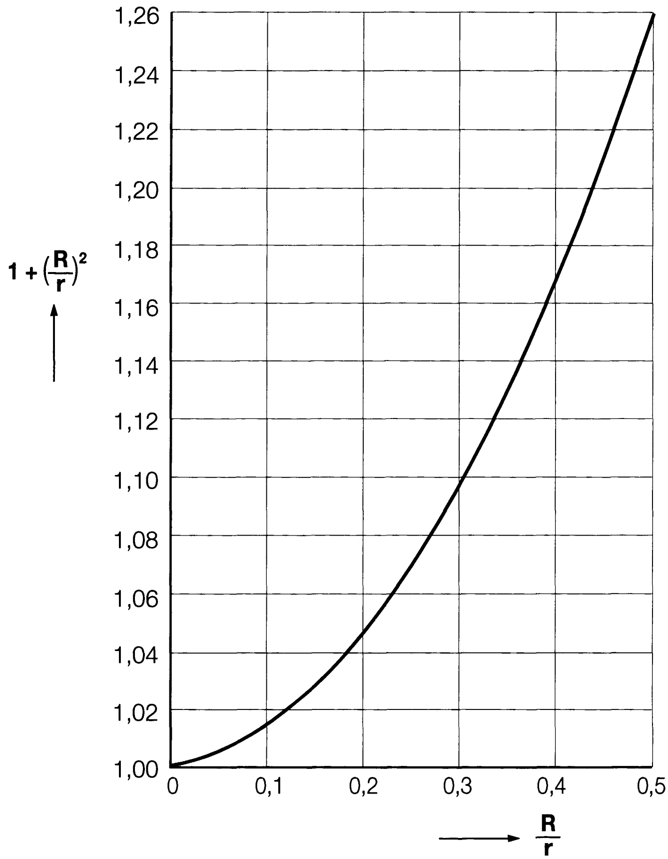

Figure 14.1.5: *Deviations from the inverse square law for non-point sources.*
After Schreuder, 1998, Figure 5.3.2. Based on Helbig, 1972, p. 48.
The meaning of the letters correspond to those used in relation [14.1.7]

For easy reference, a few data are given in Table 14.1.2.

Size (R/r)	Deviation (I/I')
1/2	1,250
1/4	1,062
1/6	1,028
1/8	1,016
1/10	1,010

Table 14.1.2: *Deviations from the inverse square law for non-point sources.*
After Schreuder, 1998, Table 5.3.1. Based on Helbig, 1972, p. 48.
The meaning of the letters correspond to those used in relation [14.1.7].

Table 14.1.2 shows that the deviations soon become 'acceptable', particularly if we take into account that R is the radius of the light source. Usually, that corresponds with half the luminaire length. If we consider that a deviation of 1% is still acceptable – a rather stiff requirement – the distance needs to be only 5 times the length of the luminaire. Sometimes, this distance is called the photometric threshold distance (Schreuder, 1998, p. 53). See also Keitz (1967, p. 187); Walsh (1958).

(f) The distance law for bundled light

The inverse square law, as well as the approximations that have been discussed in earlier parts of this section, are valid only for diffuse ('Lambertian') light sources (Helbig, 1972, sec. 5.2). For bundled light sources, like e.g. search lights, hand-held torches, and vehicle headlamps, the inverse square law is only applicable if the distance is measured, not from the actual light source, but from its optical image. For this, one has to take into account that bundled light sources are made by placing the actual light source – e.g. the filament – in or near the focal point of a hollow mirror or a convex lens. In sec. 12.2.4, several examples are given, when discussing the optical principles of low-beam vehicle headlamps. If the mirror is a parabola and the light source is placed in the exact focal point, the beam is parallel. In optical terms, the (virtual) source is at a distance of minus infinity from the measuring point. As regards the inverse square law, it would mean that any finite change in the distance between the lamp and the measuring point would have no effect as 'an infinite distance plus a finite stretch is still infinite'. In practical terms, it means that the illuminance is equal at any distance from the lamp. Of course, this is precisely the reason why bundled lights, particularly if they have a parallel beam, are so useful in may applications. One example is the high beam of vehicle headlamps. It is, however, also the reason why it is so difficult to reduce the light pollution effects from bundled lights. Not only are they mostly very intense; it also does not help to go away from them. This is depicted in Figure 14.1.6.

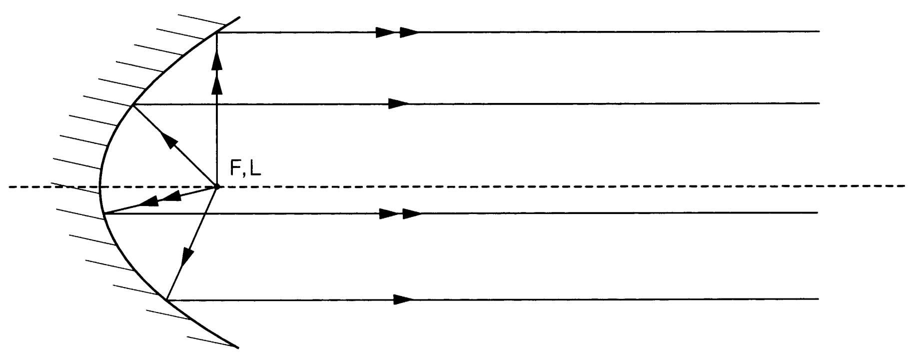

Figure 14.1.6: *The beam of a bundled light with a nearly parallel bundle. F is the focus of the parabola, L the light source. After Schreuder, 1998, Figure 5.3.3.*

A completely different situation is met, when the light source is placed further away than the focal point from the mirror. Here, the optical image is real, and it is located at a certain, often a large, distance before the lamp. The beam is a converging one. This is depicted in Figure 14.1.7.

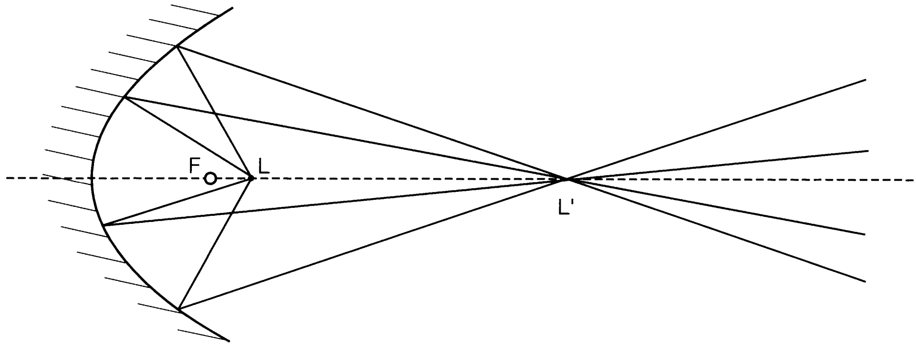

Figure 14.1.7: *The beam of a bundled light with a converging bundle. F is the focus of the parabola, L the light source, L' the optical image of the light source. After Schreuder, 1998, Figure 5.3.4.*

When assessing the influence of the distance on the illuminance, the assessments must begin at the real optical image. This often implies that, when the distance increases, the illuminance is reduced much more steeply than the inverse square of the distance between the lamp and the measuring point.

(g) The cosine law

If the surface, on which the light falls, is tilted, the area on which the luminous flux is falling increases and, consequently, the illuminance decreases. The illuminance decreases in proportion to the cosine of the incident angle. This is called the cosine law. The law follows directly from the definition of the cosine. It can be described as follows:

$$E = \frac{I}{d^2} \cos \gamma \qquad [14.1.8]$$

in which:
E: the illuminance;
I: the luminous intensity of the light source;
d: the distance;
γ: the angle with the normal.

The relation [14.1.8] is illustrated in Figure 14.1.8.

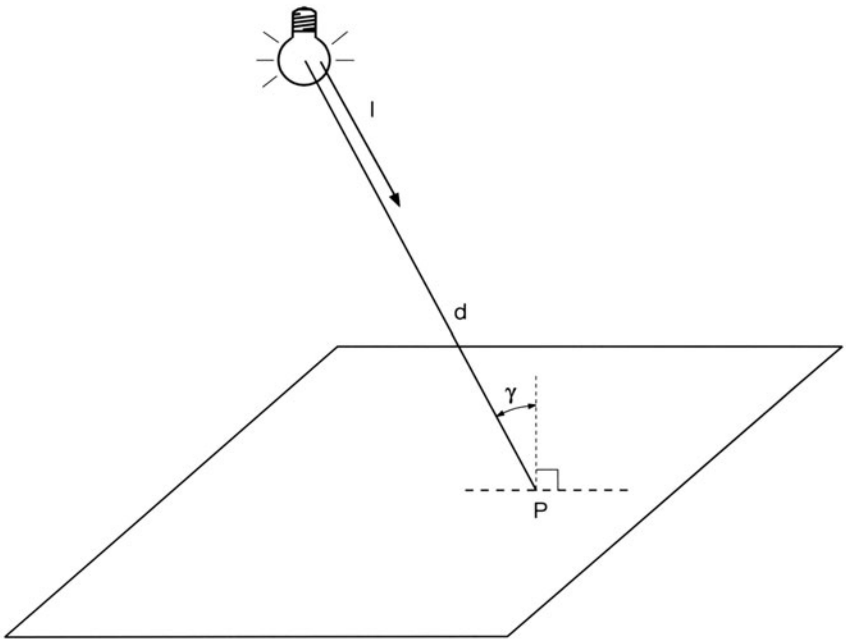

Figure 14.1.8: *The cosine law. The letters are explained in the text. After Schreuder, 1998, Figure 5.3.5.*

(h) The cosine to the third law

A combination of the inverse square law and the cosine law produces the third important law in photometry: the cosine to the third law. It described the illuminance at different points in a plane. It can be described as follows:

$$E = \frac{I}{h^2} \cos^3 \gamma \qquad [14.1.9]$$

in which:
E: the illuminance;
I: the luminous intensity of the light source;
h: the mounting height of the luminaries (analogous to the distance in [14.1.8];
γ: the angle with the normal.

The relation [14.1.9] is illustrated in Figure 14.1.9.

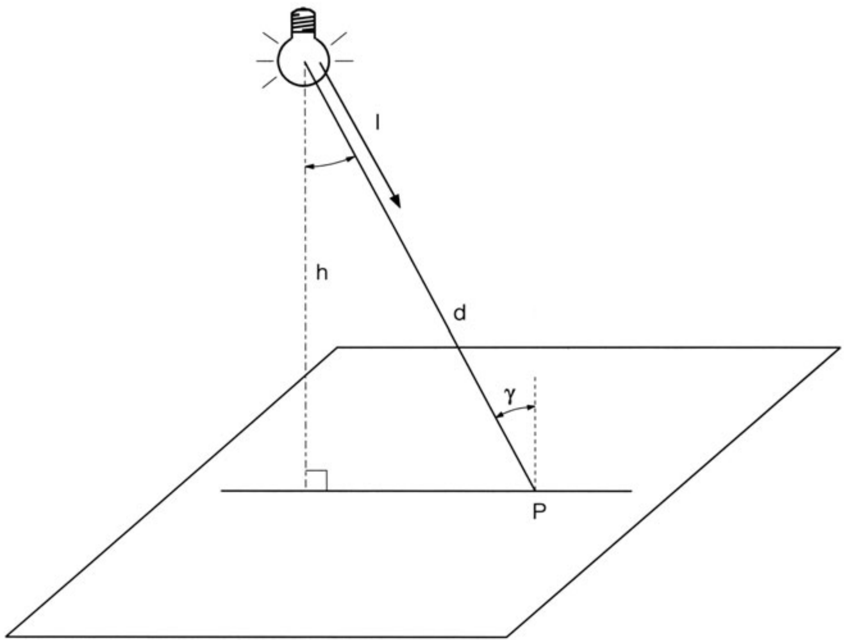

Figure 14.1.9: *The cosine to the third law. The letters are explained in the text. After Schreuder, 1998, Figure 5.3.6.*

One may think about the cosine to the third law as follows: one cosine comes from the cosine law, and two cosines come from the inverse square law. The law has many applications in outdoor lighting, particularly if the area under consideration is flat and horizontal, and the luminaries to be used are identical.

14.1.6 The luminance

(a) General definition

Light only has a perceivable effect when the visual system is activated in one way or another. In other, simpler words, light is only visible once it falls on the eye. These phenomena are describes in a more philosophical way in Wright (1967).

Light is seen as the brightness of the observed object. In order to arrive at a better definition, as well as a concept that is easier to measure, luminance, indicated by L, was introduced. Luminance can be said to be the objective, measurable measure of brightness. In illuminating engineering, the concept of brightness is used in two distinct ways. The first is the colloquial equivalent of the luminance. The second is the subjective experience of the light impression. Details are given in secs. 8.2.3 and 8.3.5.

The definition that is given by ISO for the photometric units, is not applicable to measuring or calculating luminances in practice. As is mentioned in sect. 14.1.2a, the only function of the ISO-unit is to establish the numerical value of the unit of luminous intensity, the candela. For other purposes, a different definition of the luminance is needed. We will follow here, by means of some quotations, the theoretical treatise given in Baer (1990, p. 21).

The general definition of the luminance, as based on the CIE Standard Spectral Sensitivity Curve is:

$$L_v = K_m \int_{360\ nm}^{830\ nm} L_{e,\lambda a} \cdot V_{\lambda,\alpha} \cdot d_{\lambda,\alpha} \qquad [14.1.10]$$

In a similar way, the 'scotopic' luminance could be defined as:

$$L'_v = K'_m \int_{360\ nm}^{830\ nm} L'_{e,\lambda a} \cdot V'_{\lambda,\alpha} \cdot d_{\lambda,\alpha} \qquad [14.1.11]$$

in which:
L_v and L'_v: the photopic and the scotopic luminance;
$L_{e,\lambda a}$ and $L'_{e,\lambda a}$: the spectral radiance for photopic and scotopic vision;
$V_{\lambda,\alpha}$ and $V'_{\lambda,\alpha}$: the CIE Standard Spectral Sensitivity Curves for photopic and scotopic vision;
K_m: 683 lm/W;
K'_m: 1699 lm/W.
These expressions are quoted from Schreuder (1998, p. 49-50) and are based on Hentschel (1994, p. 29). It should be noted, however, that the 'scotopic' luminance is not an ISO-unit.

It only makes sense to speak of the luminance of an object, if the object itself emits light. Otherwise, it is just dark and invisible, and the brightness – and the luminance – will be zero. In a literary sense, this statement would mean that a non-object, like the open night sky, could have no luminance. In sec. 14.1.7, it is explained in which way the luminance of the sky will be defined.

(b) The luminance of light-reflecting objects

As mentioned earlier, a surface that does not emit light itself is invisible when no light falls on it, and the illuminance is zero. However, it is also invisible when all incident light is absorbed, so that there is no light left over to be reflected – and thus, to be observed. Only if, at least part of, the light is reflected, the object can be perceived. When more light is reflected, the object is brighter. This can be the result of two factors.

(1) When more light falls on the object – when the illuminance increases – the brightness increases proportionally.
(2) When, the illuminance being unchanged, the reflection is higher, also the brightness increases. The brightness will increase proportionally to the reflection.

These two factors lead to the simple relation:

$$L = R \cdot E \qquad [14.1.12]$$

in which: R is the luminance factor.

It should be noted that the common ISO-unit for luminance refers, as is mentioned earlier, to a surface. It is expressed in the unit candela per square meter, which is strange, because the candela is defined for a point source only. The definition given earlier in this section in relation [14.1.10], does not circumvent this problem. In relation [14.1.10], the luminous flux is considered, that is emitted by the small element dA_1 of the luminous plane A_1. The element dA_1 is small, but not zero; relation [14.1.10] is not applicable to a point source. It should be mentioned that, actually, two planes are included in the definition: the plane A_1, from where the light is emitted – or seems to be emitted, hence the word 'virtual' in the definition – and the plane A_2, on which the light is falling. In sec. 14.1.7, when defining the luminance of the night sky, the significance of these two planes will be explained.

It might seem that the ancient UK system, that, incidently, still is used extensively in the USA, is simpler in this respect. This is not really true, however. The factor π does not show up in the formulae, because it is incorporated in the definition of the Lambert (De Boer, ed., 1967, Appendix II). So there is, somewhere, a hidden solid angle. Neither the square meter shows up, because it is incorporated in the foot-Lambert – meaning, exactly, a lumen per square foot (De Boer, ed., 1967, Appendix II).

(c) The luminance of light emitting objects

The luminance is defined as the part of the luminous flux $d\Phi$, that is emitted from the virtually luminous plane $(dA_1 \cdot \cos\gamma_1)$, in a prescribed direction within a solid angle element $d\Omega_1$ falls onto a plane. The unit is cd/m^2.

$$L = \frac{d_2\Phi}{dA_1 \cdot \cos\gamma_1 \cdot d\Omega_1} = \frac{I\gamma}{dA_1 \cdot \cos\gamma_1} \qquad [14.1.13]$$

The relation [14.1.13] is illustrated in Figure 14.1.10.

This definition can be used to assess the luminance of an object, that emits light itself. It is explained in sec. 14.1.2, that, according to ISO, the luminance is derived from the luminous intensity. This is based on a light emitting surface, that is subdivided into small parts δA, that are so small, that the luminous intensity according to its actual definition may be used. As is explained in sec. 14.1.4, this definition is valid for point sources only. The luminance of that part can be described as the ratio between the luminous intensity and the surface:

$$L = \frac{\delta I}{\delta A} \qquad [14.1.14]$$

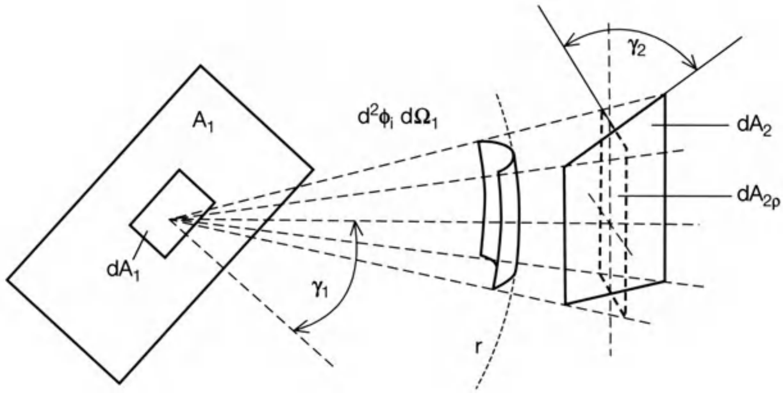

Figure 14.1.10: *The definition of luminance. After Baer, 1990, figure 1.15, p. 21.*

Taking the limit for δA towards zero, the definition of the luminance is:

$$L = \frac{dI}{dA} \qquad [14.1.15]$$

Now it is clear why the luminance is expressed in candela per square meter (cd/m^2).

(d) The relation between luminance and brightness

In sec. 9.1.2, it is explained that impressions and sensations can be scaled (Steyer, 1997). This, in spite of the objections like: "Sensations cannot be measured. Any equation like the Weber-Fechner one is pure nonsense" (Moon, 1961, p. 421-422). A number of different ways to describe subjective brightness are explained.

In sec. 14.1.6, it is stated that light is seen as the brightness of the observed object, and that the concept of luminance is introduced as the objective measure of brightness. It is, therefore, logical to try to assess the relation between luminance and brightness. This relation is similar, but not identical, to the concept of subjective brightness, that is discussed in detail in sec. 9.1.2c.

In a treatise on the design of interior lighting, a method to convert luminance into luminosity, is described in Stevens (1969, p. 147-150). The method is proposed by the legendary J.M. Waldram (1954, 1958). It should be noted that the term 'luminosity' is used here in a different way as is done by Moon (1961, p. 57). Moon used the term 'luminosity' in stead of the generally accepted term 'luminance'. Moon, of course, had a very personal opinion about terminology and nomenclature for illuminating engineering (Moon, 1961, p. v-ix; see also Moon & Spencer, 1981).

Waldram did use a conversion of the figure that was published by Hopkinson and that is depicted in sec. 9.1.2c as Figure 9.1.2 (Hopkinson et al., 1941; Padgham & Saunders, 1966). The difference is that the linear, arbitrary scale of the luminosity is converted into a logarithmic scale. More important is, that the scale is limited to luminosity values of 1 and 100. The relation is depicted in Figure 14.1.11.

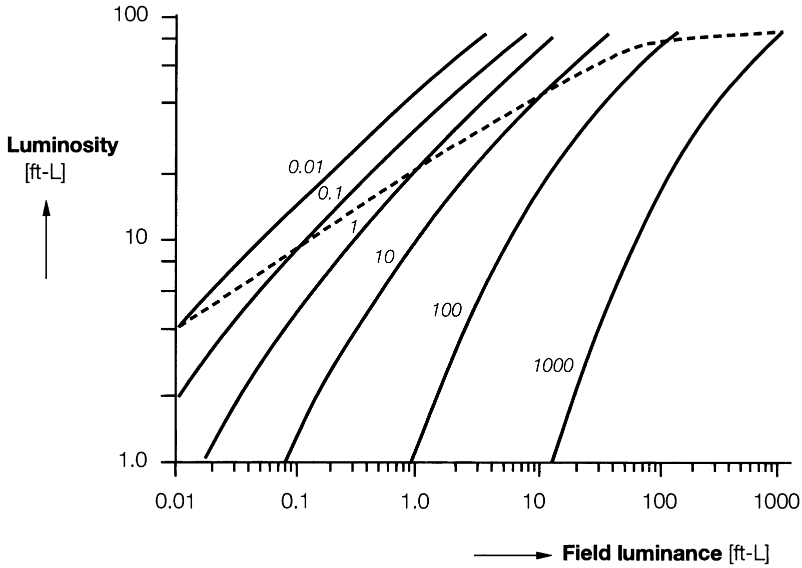

Figure 14.1.11: *Luminosity related to field luminance for a range of adaptation levels. After Stevens, 1969, Fig. 6.3.*

Notes to Figure 14.1.11:

(1) As is usual with older English language publications, the scales are in non-ISO units. A conversion in given in sec. 14.3.6.

(2) The dashed curve connects points at which the field luminance is equal to the adaptation level.

(3) The field luminance is not precisely defined. It seems to mean the luminance of the detail of the field of vision under consideration.

When considering the Waldram conversion as given in Figure 14.1.11, it seems to be implied that 1 means absolute darkness and 100 means blinding glare. The original scale had zero as darkness; there was no upper limit indicated. Although no details are given by Stevens, one might assume that the Waldram transformation is keyed to interior lighting practice, so that 1 would mean 'unacceptable dark' and 100 would mean 'far too bright for an interior'. As said, however, this is just conjecture. The references given by Stevens are very incomplete.

Waldram has combined the luminosity-luminance relation with recommendations for acceptable luminosity values for different activities. This is depicted in Figure 14.1.12.

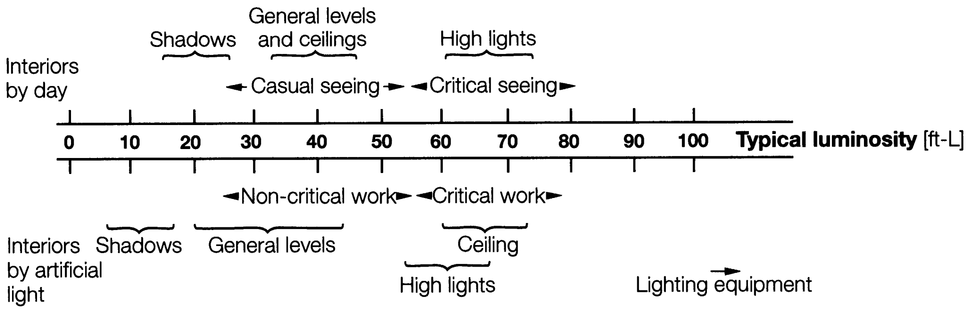

Figure 14.1.12: *Typical luminosity values recommended for interiors. After Stevens, 1969, Fig. 6.2.*

It is interesting to try to apply these graphs to outdoor lighting, in spite of the fact that they are explicitly set up for interior lighting. For casual seeing at night, a luminosity of about 30 to 50 seems to be required (see Figure 14.1.13). At an adaptation level of 0,01 fL, corresponding to about 0,034 cd/m^2, and for casual seeing, the field luminance should be about 0,3 fL, or about 1 cd/m^2. For real dark surroundings of about 0,01 fL (or about 0,034 cd/m^2), the luminosity could not be much more than 5, which is below the values for 'shadows' (Figure 14.1.12).

At the other end of the scale, it is suggested in Figure 14.1.12, that the luminosity of the lighting equipment is far more than 100. Although the mathematics are somewhat blurred, because the scale is supposed to end at 100, it is quite clear that normal luminaires are far too bright to fit in the field of view, without causing hindrance. This is explained in sec. 9.2.3, where discomfort glare is discussed. If this is the case for normal interiors at night and even at day, it is very clear that it will be true outdoors, particularly in rural areas. It is clear once more, that luminaries must be shielded, to avoid excessive hindrance or glare.

We will end this discussion with repeating the remarks made earlier in sec. 9.1.2c. It may be interesting to note that many of the earlier investigations, particularly those of Hopkinson et al. (1941) were made during the Second World War when strict rules about 'black out' did exist in most European countries. It was at that time considered an important matter to establish how much – or how little – one might see in very dim surroundings. In the modern world, people are usually not interested in dim surroundings. What we try to achieve with the battle against light pollution is that the surroundings around astronomical observatories are indeed 'dim'!

(e) Equivalent veiling luminance for glare

The field of view of fixed human eyes has an elliptical shape with horizontal long axis. The angular diameter of the longer axis is about 200 degrees and the shorter axis is about 140 degrees. No one, however, can perceive the details of the full field of view at once. Fine details can be perceived in a very small area around the centre of the line of sight. This area is, as is explained in sec. 8.1.3, the fovea centralis, the macula or the yellow spot. It measures only a few degrees in diameter. The peripheral part of field of view cannot perceive fine details. To pick up important visual information, human beings are moving their line of sight from one direction to another in rapid succession. It has been found, that, when the eyes do not move, the flow of visual information stops after only a few seconds (Cornsweet, 1970; Gregory, 1970; Walraven, 1981).

When objects or areas with a high luminance are visible in the peripheral part of the field of view, however, seeing ability of the eyes at the line of sight is deteriorated. The deterioration of visual performance is caused by the scatter of light, that originates from light sources in the peripheral part of the field of view (Vos, 1963). This phenomenon is called the disability glare. The light source is called the glare source. The phenomena of disability glare are discussed in great detail in sec. 9.2.2.

The scatter of the light in the ocular media increases the luminance of the inside of the eyes fairly uniformly, and the field of view is seen as if a uniform luminance is superimposed over the whole field of view. The intensity of the veil can be expressed in luminance terms. The luminance of the veil is therefore called the (equivalent) veiling luminance. The term 'equivalent' must be added, because the veil is not a physical reality. In sec. 9.2.2, several formulae are given to quantify the veiling luminance, more in particular these of Stiles-Holladay and Vos. See e.g. Adrian (1961, 1969), CIE (1976, 2002), Holladay (1927), Schreuder (1976, 1998); Vos (1999, 2003): IJspeert et al. (1990).

This superimposed uniform luminance decreases the luminance contrast between objects and their background. As is explained in sec. 5.1.1, this contrast reduction causes the disability effects: smaller contrast are more difficult to see.

The veil depends not only on the intensity of the glare source, but also on the angle between the line of sight and the direction from the eye to the glare source. This angle is called the glare angle Θ.

The original formula of Holladay (1927) is still in wide use. It is very simple: the glare depends on the illuminance that hits the eye and on the square of the glare angle. The relation is given in sec. 9.2.2. It is repeated here, written in the way that was proposed by Holladay, Stiles and Crawford. It is usually called the 'Stiles-Holladay relation':

$$L_{seq} = k \cdot \frac{E_e}{\theta^2} \qquad [9.2.3]$$

with:

L_{seq}: equivalent veiling luminance (cd/m^2);

E_e: the illuminance on the plane of the eye pupil (lux);

Θ: the glare angle (degrees); k: a factor that depends on the age and on other parameters. It usually taken as 10. The age dependency is discussed in sec. 9.2.2.

(f) The average luminance and the non-uniformity

In an earlier part of this section, we have explained that, for the characterization of many aspects of outdoor lighting installations, the average illuminance is an important parameter. For many outdoor installations, often the luminance is more important than the illuminance as a quality criterion. Just as for the illuminance, the average and the non-uniformity are important parameters. We will describe them briefly, and it will be noted that this description is very similar to that for the illuminance.

The average luminance can be assessed as follows:

$$L_{ave} = \sum_j L_j \qquad [14.1.16]l$$

The degree of uniformity for street lighting installations is defined in by CIE two ways:

(1) The absolute uniformity $U_0 = L_{min,\ abs}/L_{ave}$, in which $L_{min,\ abs}$ is the smallest point luminance within the relevant area (CIE, 1976, 1990; Schreuder, 1998, p. 150; NSVV, 1990, p. 35)
(2) The lengthwise uniformity $U_l = L_{min} / L_{max}$, in which L_{min} and L_{max} are the smallest and the largest spot luminances along a line parallel to the road axis (CIE, 1976, 1990; Schreuder, 1998, p. 151; NSVV, 1990, p. 36)

Just as with the illuminance requires the assessment of the average luminance, and even more so, the assessment of the non-uniformity, a precise indication of the method of the assessment, both for calculations as for measurements. More in particular, the grid on which the points are located where the calculations or the measurements must be made, must be defined precisely. See also sec. 14.5.3d. It is customary that, both for calculations as for measurements, the same grid points are used for the illuminance as for the luminance. A more theoretical point is the dimension of the area that still can be regarded as a 'point'. The relevant considerations are discussed in detail in Schreuder (1998, sec. 5.4.6, p. 68-89).

When discussing the actual value of the road surface luminance, there are a few points that need to be clarified. A careful consideration shows, that the present definitions of luminances and illuminances that are used in CIE and CEN, are not fully satisfactory. (CIE 1990, 1995a, 2001; CEN, 1998). The most important are that the definitions are not always internally consistent, that the definitions for the average and the non-uniformity and glare often do not agree, that the definitions for the illuminance and for the luminance are not in agreement, and that the definitions used in measurements often conflict with those used in calculations.

The three most important grounds for these discrepancies are a lack of unity in defining the position of the observer, differences in the systems used to define grid points, and the cross-wise position fo the observer in different conditions. The conventions as regards the grid points are discussed in more detail in sec. 14.5.3d. The following considerations about a set of definitions for the lighting parameters that together establish a closed system, may help to reduce the uncertainty and the confusion in theory and practice of street lighting. The considerations are based an unpublished report, prepared for discussion in CIE and CEN (Schreuder, 1995a).

When the illuminance is mentioned, primarily the horizontal illuminance on the road surface is meant. As desired, the proposal can be applied as well to the vertical, the semi-cylindrical or the hemispherical illuminance.

All usual definitions, those of the present proposal included, are valid only for horizontal road sections that show no horizontal nor vertical curvatures, no super-elevation, camber or bumps, that are uniform over a sufficient length regarding the geometry and the equipment of the installation (masts, luminaires, lamps etc.) and also of the road surface. These are considerable restrictions: it is therefore recommended to try to establish future systems of definitions that allow a wider area of application.

The first point to discuss is the angle of observation. The luminance is always assessed, both in measurements as in calculations, for an observation angle α of one degree to the horizontal. Further, the luminance is always assessed, both in measurements as in calculations, for a position of the observer 1,5 m above the plane of the road surface. This, of course, presupposes a flat, horizontal and straight road, as is indicated earlier. These two outsets together imply that the observation distance always equals 85,935 m. This observation distance is rounded off to 86 m. This set-up is called the 'moving observer'. The reason for this designation is that consecutive points in the lengthwise direction of the road, can only be assessed by moving the observer forward.

The definition of the 'moving observer' is used for the calculation of the point-values of the road surface luminance, because these calculations are based on the reflection properties of the road surface, that in their turn are assessed for a constant angle α. Because the assessments of the average road surface luminance and the non-uniformity are derived from such point-values, they are defined for the moving observer as well. The 'moving observer' is also used for many systems to calculate the disability glare, but not for all of them, and not for discomfort glare; furthermore, another height of the observer is often used, e.g. 1,2 m or 1,25 m.

Most luminance measurements – both integral measurements and spot measurements – are made, however, from an observation point that is constant in location. This means that the distance between the location of the measuring equipment and the points on the road where the luminance is measured, is not constant. However, the height of the observer – of the measuring apparatus – over the road is constant. This implies that the measuring angle α is not constant. An exception is the system where a moving apparatus and a 'line scan' detector are used, which keeps α constant. This system is mentioned in sec. 14.5.2b, when discussing properties of CCDs. Details are given in Schreuder (1996; 1998, p. 71) and Schreuder & Van de Velde (1995).

A strict application of the above rule to use the 'moving observer' would mean that all current integral measurement systems and spot measurement systems could not be used any more, and that only the moving apparatus in combination with a line scan detector could be applied. Field comparisons have suggested, however, that under practical conditions, the discrepancies are only minor (Rossi, ed., 1996). Further research, however, is needed, where the actual measuring accuracy must be compared to the inherent variability within lighting installations, and also to the tolerances that are permitted in the lighting design specifications and in the final check of the installation. We will come back to this point in sec. 14.5.3d, when discussing the measuring and calculation grid for road lighting.

14.1.7 The luminance of virtual objects

(a) The continuity principle

The continuity principle is one of the fundamental concepts of physics. For fluids, it is succinctly described as follows: "For continuous motion, the increase in mass of fluid in any time interval δt within a closed surface in the fluid is equal to the difference of the mass flow in and the mass flow out through the surface" (Illingworth, ed., 1991, p. 85). For incompressible fluids, this results from the Bernoulli law of hydrodynamics (Gerlach, ed., 1964, p. 232).

Here, it is stated for fluids, but is can be applied equally well to any other form of moving particles or waves. As regards the electric charges in electromagnetism, it can be written as:

$$\text{div } i + \frac{\delta\rho}{\delta t} = 0 \qquad [14.1.17]$$

in which:
i is the current density;
ρ is the charge density;
t is the time.
(Gerlach, ed., 1964, p. 94).

It can be shown that this relation follows from the well-known Maxwell equations. The basic concept if the Maxwell equations is explained in Illingworth, ed., 1991, p. 291-292 and in Gerlach, ed., 1964, p. 97-99.

The continuity principle means for the Maxwell equations, that the current density i is invariant in time i.e. the equations do not change when t is replaced by -t, which mans of course a reverse of the flow direction. More generally it can be stated that the equations do not change when t is replaced by t', where t is the time for a stationary object and t' the time for a moving object (Feynman et al., 1977, p. 15-2).

(b) Invariance of luminance

As is explained in an earlier part of this section, the luminance is usually expressed in terms of the luminous intensity per square unit area, viz. cd/m^2. This makes it difficult to image what the luminance of a virtual object like the sky, really means to say. In order to clarify this, we need to consider some of the principles of photometry. Of course, the principles of photometry are the same as those of radiometry, as far as the spectral luminous efficiency curve is taken into account. For this discussion, use is made of Sterken & Manfroid (1992, sec. 1.2.1, p. 7-9). The basic notion is that, as indicated earlier, photometry is essentially just nothing but 'counting photons'. Taking the spectral luminous efficiency curve into account, provides the weighing factors for photons of different 'colour' – or wavelength, or energy.

The luminance describes the geometrical distribution of luminous flux with respect to position and direction. It equals the flux per unit of projected area, and per unit of solid angle (Born & Wolf, 1964, as referred to by Sterken & Manfroid, 1992, p. 8). It must be stressed as essential, that the area is always the apparent area of the emitting surface as seen by the observer – or by the measuring device.

The geometry is depicted in Figure 14.1.13.

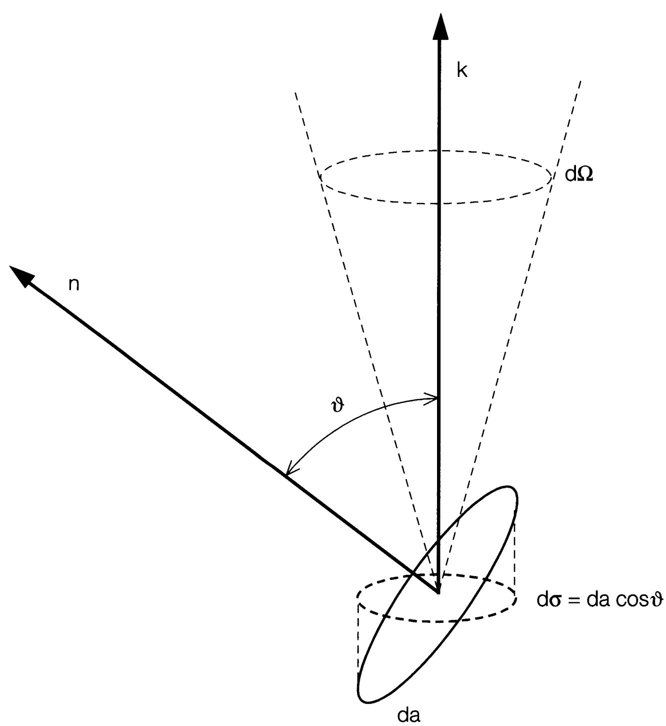

Figure 14.1.13: *The luminance in the direction **k** is the ratio between the luminous intensity in that direction, and the projected area. After Sterken & Manfroid, 1992, Fig. 1.4. **n** is the normal on the plane of da.*

Consider the surface element da, as indicated in Figure 14.1.13. The luminance in a given direction **k** is the luminous intensity in that direction, divided by the area da. It must be noted that the direction is a vectorial concept, hence the letter **k** being printed in **bold type**. In stead of da we need the area projected on a plane perpendicular to **k**. This is called $d\sigma = da \cdot \cos\Theta$ as indicated in Figure 14.1.13. The luminance L can be written as:

$$L = \lim_{da \to 0} \frac{dI}{da \cdot \cos\theta} \qquad [14.1.18a]$$

or as:

$$L = \lim_{da \to 0, d\Omega \to 0} \frac{d_2F}{d\Omega \cdot da \cdot \cos\theta} \qquad [14.1.18b]$$

The luminance has the interesting property of being invariant along the light beam. This is adstructed in Figure 14.1.14.

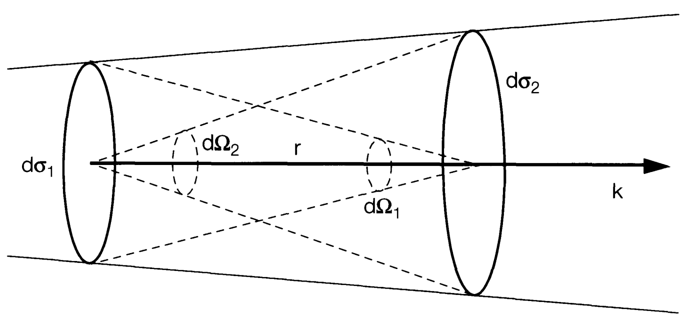

Figure 14.1.14: Invariance of luminance along a pencil of light defined by **k**, *$d\sigma_1$ and $d\sigma_2$. After Sterken & Manfroid, 1992, Fig. 1.5.*

In Figure 14.1.14, a light beam (a light pencil) is defined by the direction of propagation **k**, and two surface elements $d\sigma_1$ and $d\sigma_2$, of surfaces S_1 and S_2 respectively, both perpendicular to **k**. Being a light pencil, where no radiation is entered nor lost through the outer mantle surface, the fluxes through both end are equal. The flux through surface S_1 is:

$$dF_1 = L_1 \cdot d\sigma_1 \cdot d\Omega_1 \qquad [14.1.19a]$$

The flux through surface S_2 is:

$$dF_2 = L_2 \cdot d\sigma_2 \cdot d\Omega_2 \qquad [14.1.19b]$$

From Figure 14.1.14, it is clear that

$$d\sigma_1 \cdot d\Omega_1 = d\sigma_2 \cdot d\Omega_2 \qquad [14.1.20]$$

From [14.1.19a], [14.1.19b] and [14.1.20], it follows that $L_1 = L_2$. Although it is not mentioned by Sterken & Manfroid (1992, p. 9), according to the continuity principle (14.1.7a), only the scalar quantity of the flux matters, the direction is not relevant. From L_1 and L_2 being equal, it follows that: "Along a light pencil, the decrease in divergence $d\Omega$ is exactly compensated by the increase of the cross-section area $d\sigma$" (Sterken & Manfroid, 1992, p. 9).

(c) *The throughput*

From this, the throughput – or étendue – can be defined. This is adstructed in Figure 14.1.15.

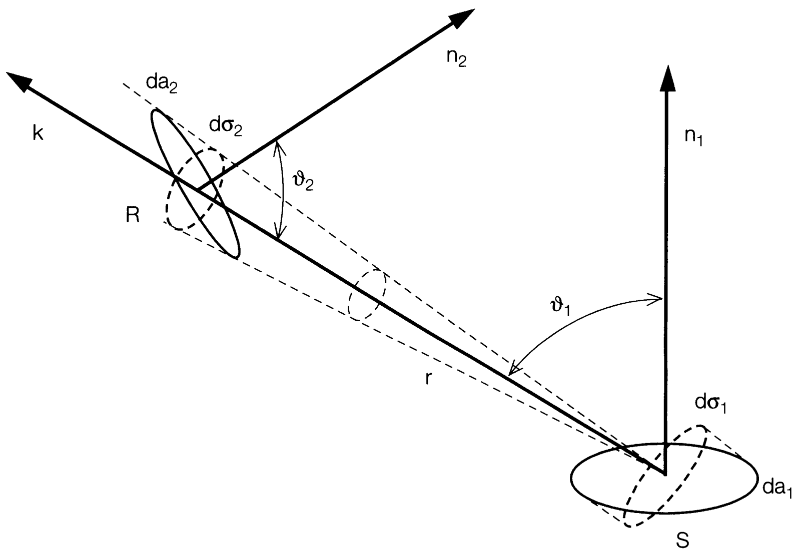

Figure 14.1.15: *The throughput of a light beam is conserved. After Sterken & Manfroid, 1992, Fig. 1.6.*

Figure 14.1.15 describes the luminous flux carried from a surface with an area da_1 at S to a receiving surface of area da_2 at R. Again taking only the scalar value of F, it follows from Figure 14.1.15, that:

$$\begin{aligned} dF &= L \cdot d\sigma_1 \cdot d\Omega_2 \\ &= L \cdot da_1 \cos\theta_1 \cdot da_2 \cdot \frac{\cos\theta_2}{r^2} \\ &= L \cdot d\sigma_2 \cdot d\Omega_1 \end{aligned}$$

The quantity

$$d\sigma_1 \cdot d\Omega_2 = d\sigma_2 \cdot d\Omega_1 = da_1 \cdot \cos\theta_1 \cdot da_2 \cdot \frac{\cos\theta_2}{r^2} \qquad [14.1.21]$$

is called the throughput. It is purely a geometric notion. What it actually means is, that along a pencil of light, the divergence is in fact constant, and for two opening angles, the flux per unit area goes down as much as the angles increase, hence the conservation of throughput (Schwarz, 2003). It should be noted that, for reasons of clarity, the solid angle $d\Omega_2$ is not included in Figure 14.1.15. See for this Figure 14.1.14. This discussion is adapted from Sterken & Manfroid (1992, p. 7-9). The same considerations are described in Hentschel (1994, sec. 2.2, p. 21-24).

(d) *The sky luminance*

Now we come back to the problem, how to define the luminance of a virtual object. The term virtual object is used here for objects that have no physical counterpart; for the reduction of light pollution, the most important virtual object is, of course, the night sky. The definition of its luminance in necessary because, as is explained in sec. 5.1.1, light pollution makes it more difficult to see – or to photograph – certain types of astronomical phenomena, more in particular weak, extended light sources like distant galaxies, nebulae etc., because the contrast is reduced. The loss in visibility is a phenomenon that is similar to that of disability glare, that is explained in sec. 9.2.2. The contrast the object against its background decreases when light pollution is present. The decrease of the contrast makes it more difficult to observe the objects.

The major contributing factor of light pollution is an increase in the luminance of the sky, usually indicated as the urban, or rather artificial sky glow. The effect of the artificial sky glow must be added to the effect of the cosmic background radiation, that is explained in sec. 3.1. This addition is only possible if both the sky glow and the background radiation are expressed in terms of luminance. Therefore, it is necessary to be able to define the luminance of the sky.

For the definition of the sky luminance, we go back to two remarks that were made earlier in this section:
(1) Photometry is essentially only a matter of counting photons;
(2) The luminance is invariant along the light beam; the throughput of a light beam is conserved (Sterken & Manfroid, 1992, p. 9);

When we go back to the definition of the luminous intensity, that is explained in sec, 14.1.4, we may rewrite the relevant formula as:

$$I = \frac{d\Phi}{d\Omega} \qquad [14.1.22]$$

with:
I: the luminous intensity;
Φ: the luminous flux;
Ω; the solid angle.

This representation is quoted from Baer (1990, p. 17). It is depicted in Figure 14.1.16.

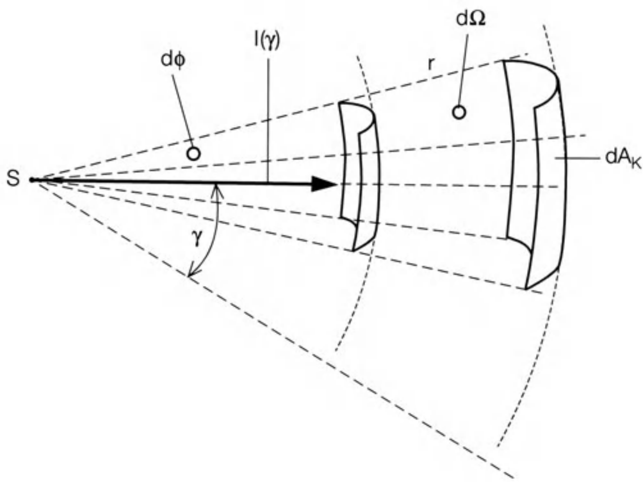

Figure 14.1.16: *The definition of the luminous intensity. After Baer, 1990, Figure 1.9. S: source.*

Figure 14.1.16 refers to the situation where the direction of the radiation is from the apex of the cone – the light source – outward. The 'point' at the apex of the cone has actually a dimension of r_s, r_s being the radius of the light source. As is explained in sec. 14.1.4, the definition of the luminous intensity is valid only when the limit for dr_s is zero. Taking into account that, as is explained in sec. 14.1.7b, when considering the throughput, the direction of the radiation is irrelevant, we may use the same figure, but with a reversed direction of radiation. When in Figure 14.1.16, dΩ represents a pencil of light, all photons from the area dA_k will reach the apex of the cone, where we place now, in stead of the light source, a photodetector. A is suggested in Figure 14.1.16, the surface A_k, of which dA_k is an infinitesimal small part, is at a distance of r from the apex of the cone. Because the throughput of a light beam is conserved, the same flux goes through any surface in the cone. This includes, of course, the surface at a distance of 1 metre from the apex of the cone. The luminance of the sky – that may stretch arbitrary far outside the surface A_k – can be described in terms of the total energy of all photons that are contained within the cone, or by the total energy of all photons that pass through any surface within the cone, as long as that surface is closer the apex than the sky.

The consequence is, that the two ways to define and describe the sky luminance that are used in practice, are really equivalent, and equally 'true'. Lighting engineers are accustomed to quantify luminances in terms of 'cd/m^2', whereas astronomers do so in terms of 'magnitudes per square seconds of arc'. From the considerations given above, it is clear that lighting engineers can equally well express the sky luminance – all luminances, for that matter – in terms of 'cd/sr'. This looks similar to the 'magnitudes per square seconds of arc' of the astronomers, considering that 'square seconds of arc' are tiny parts of a steradian, and that 'magnitude' is a non-ISO measure of the luminous intensity. In sec. 14.2, when discussing photometry in astronomy, details are given about the magnitude and the way it is used in ancient and modern astronomy.

As has been indicated earlier already several times, measuring the sky luminance is, in theory at least, no problem. We simply point a well-calibrated photon-counting device upwards, and start counting photons. In sec. 14.6, the practical aspects of measuring sky glow are discussed in some detail.

14.1.8 The luminance factor

(a) The mathematical form of the luminance factor

In sec. 14.1.6, it is explained that, for any object, the illuminance being unchanged, the reflection is higher, also the brightness increases. The brightness will increase proportionally to the reflection. These two factors lead to the simple relation:

$$L = R \cdot E \qquad [14.1.22]$$

in which R is the luminance factor. A more strict mathematical treatise of the case where the luminance factor depends on the direction, is discussed in Baer (1990, sec. 1.2.1.1, p. 23). Although it is not mentioned in Baer (1990, p. 23), one may assume that this treatise refers to isotropic materials, that have a circular symmetry as regards their reflection properties.

If the material is isotropic, it is sufficient to introduce only one angle to define the direction. In this treatise, γ is used, the angle to the normal. The luminance factor is given as:

$$q(\gamma) = \frac{L(\gamma)}{E} \Omega_0 \qquad [14.1.23]$$

in which:
γ: the angle to the normal;
$q(\gamma)$: the luminance factor as dependent on the direction;
$L(\gamma)$: the luminance as dependent on the direction;
Ω_0: the unit solid angle of 1 steradian (See for the definition of Ω: Baer, 1990, p. 15).

If the regular ISO-units are used, and if one prefers a reflection factor without any dimensions, relation [14.1.22] must be rewritten:

$$L = \frac{\rho}{\pi} \cdot E \qquad [14.1.24]$$

Here, ρ is a dimensionless number, the ratio between the incident luminous flux and the reflected luminous flux (Schreuder, 1998, p. 49). The factor π must be introduced in the relation if the common ISO-units are used, e.i. lux for the illuminance, and cd/m^2 for the luminance. See e.g. Stevens (1969, p. 35-37).

Many practical materials, like e.g. road surfaces, do not show such circular symmetry as regards their reflection properties. They require the vectorial approach. As is indicated earlier, the luminance of a non-emitting surface is determined by two quantities: the amount of incident light and the reflection characteristic of the surface. Both quantities have a vectorial character, showing both magnitude and direction (without being, mathematically speaking, 'true' vectors, as vector summation usually is not valid). The direction of each vector can be described with two angles; this means four directional parameters in total, plus two scalars for the length of the vectors. The product of two vectors, is of course, a tensor. See also Schreuder (1967, sec. 3.3.1; 1998, sec. 10.4). The theory of vectors and of vector analysis is discussed in great detail in Feynman et al,. (1977, sec. I-11 and sec. II-12). The theory of tensor and tensor calculus is discussed in great detail in Feynman et al,. (1977, sec. II-33).

As is explained earlier, If the material is isotropic, it is sufficient to introduce only one angle to define the direction. In this treatise, γ is used, the angle to the normal.

(b) *The light reflection of road surfaces*

As is mentioned earlier in this section, the luminance of a non-emitting surface is determined by two quantities: the amount of incident light and the reflection characteristic of the surface. Both quantities have a vectorial character, showing both magnitude and direction, without being, mathematically speaking, 'true' vectors. The direction of each vector can be described with two angles; this means four directional parameters in total, plus two scalars for the length of the vectors.

In many cases the directional dependency can be neglected, and the calculation of the luminance is reduced to a multiplication of two scalars: the illuminance and the reflectance. In road surfaces, however, this is never allowed, particularly because lighting for motorized traffic requires to know the luminance at a considerable distance in front of the vehicle (Schreuder, 1967, 1998). This means that the angle of observation (the angle between the line of sight and the surface of the road) is very small indeed; the angle is standardized to be one degree, but there are doubts whether this standard may always be used. This glancing angle implies that also glancing angles of light incidence may be relevant. And finally, many surfaces are not isotropic – their reflection changes when the surface is rotated around a vertical axis. Fortunately, most asphalt surfaces are almost isotropic, and asphalt is the most common surface for traffic routes. So, when the angle of observation is kept constant, and the surface is considered as being isotropic, two angles are sufficient to describe the angular aspect.

The scalar aspect is simple: in order to find the luminance in the required direction, it is sufficient to multiply the scalar values of the luminous intensity from the luminaire and of the reflection characteristic, both in the relevant directions. And this is precisely what is done in the design of road lighting installations. A table that contains the angular information about the luminous intensity distribution of luminaires is called the 'I-table'. Usually, I-tables are included in the product information of luminaires, either in tabular or in graphical form. A table that contains the angular information about the reflection characteristics of road surfaces is called the 'R-table'. R-tables can be found in CIE documents or in standard books on road lighting (CIE, 1984, 1990, 2001; Baer, 1990, Hentschel, 1994, Schreuder, 1998, Van Bommel & De Boer, 1980).

As has been explained above, using I-tables and R-tables, the geometry of the installation, and the position of the observer, the luminance for each point on the road can be assessed. By repeating the process for all luminaries, that contribute to the lighting of that point, and again for all points, the quality of the lighting installation can be determined.

All common dry road surfaces exhibit, when observed under a glancing angle, a mixture of specular and diffuse reflection. In sec. 14.1.3b, it is explained what specular and diffuse reflection mean. When wet, the specular component usually is the dominant; when viewed under a steeper angle – for instance as a pedestrian would do – the diffuse component dominates.

In order to characterize and classify road surfaces, systems are used that take these two components in account. The older one (introduced by Westermann, 1963, 1964) uses the Q_0 to quantify the diffuse component, and κ to quantify the specular component. This classification system of road surfaces is called the '$Q_0 - \kappa_p$' system, later replaced by the '$Q_0 - L_p$' system.

These two parameters are defined as follows:

$$Q_0 = \frac{\int q \cdot d\Omega}{\int d\Omega} \qquad [14.1.25a]$$

$$\kappa_p = {}^{10}\log\left(\frac{Q_0}{q_p}\right) \qquad [14.1.25b]$$

in which:
Q_0: the lightness of the road;
q: the reflection, derived from $q = L/E_h$;
Ω: the solid angle;
κ_p: the specular factor, standardized for vertical incidence;
q_p: q for vertical; light incidence.
Details are given in Schreuder (1967; 1998, sec. 10.4.2).
The factor q is explained in SCW (1974, p. 35).

Because the two are not independent, or, in mathematical terms not orthogonal, and because they were very hard to measure, they are not used often any more. We will not discuss them here. Details can be found in Schreuder (1967, 1967a, 1998).

They have been replaced by another system, proposed in the Netherlands by Burghout (1977). It is subsequently adopted by CIE as an alternative of the $Q_0 - \kappa$-system (CIE, 1984). The relevant notation uses P as the luminance factor, multiplied by $\cos^3 \gamma$:

$$P = q \cdot \cos^3 \gamma \qquad [14.1.26]$$

The three quantities of this method are: P(0;0), P(2;0), and P(1;90). The first digit is the tangent of the angle of incidence in the plane of observation, and the second digit is the angle (in degrees) in the plane perpendicular to the plane of observation. The three reflection 'factors' can easily be measured in the laboratory, using samples cut out of the road. As mentioned already, a new classification system of road surfaces is based on these three parameters. The system is called the 'C1-C2 system'. It replaces the earlier '$Q_0 - \kappa_p$' system.

It must be taken into account that measuring area must be large in comparison to the elements (the 'graininess') of the road surface. For traditional asphalt an area of 400 cm^2 did prove to be sufficient (SCW, 1974; 1984). For some modern surfaces, like e.g. porous asphalt, or drainage asphalt as it is also known, the area must be considerably larger (Schreuder, 1991, 1998). Porous asphalt is an extremely effective measure to reduce the 'splash-and-spray' from wet road surfaces, and therefore to reduce skidding accidents and improve visibility. In spite of the fact that part of these benefits are 'used up' by faster driving, the accident reduction is remarkable. Details can be found in PIARC (1990), Schreuder (1988, 1998), SCW (1977) and Tromp (1993, 1994).

14.1.9 Retroreflecting devices

(a) *The luminance factor of retroreflecting devices*

When considering the luminance factor, there is a further peculiarity, that must be taken into account. This refers to the luminance of retroreflecting devices. In sec. 14.1.3b, it is explained that the traditional definition of the reflection factor follows from the relation given earlier:

$$L = \frac{\rho}{\pi} \cdot E$$

This relation can be used only if ρ is a scalar. If we would apply this formula to a retroreflecting device, it is likely that ρ would be well over 100% – a physical impossibility. The answer is, of course, as is explained in an earlier part of this section, that ρ is actually a tensor. A tensor is the product of two vectors. Also it is explained, that the illuminance as well as the luminance both have magnitude and direction, and therefore have the character of a vector, without being a 'real' vector.

Retroreflection is an optical phenomenon, characterized by the fact that light is reflected back by a reflector, precisely in the direction where it came from, irrespective of the position of the reflector in relation to the light beam. A reflector, that shows these characteristics is called a retroreflector. A plane mirror is not a retroreflector, because it only reflects the light back precisely in the direction where it came from, when the mirror is placed exactly perpendicular to the direction of the incident light.

Retroreflectors are difficult to measure. According to their optical principle, the measuring apparatus should precisely coincide with the light source. This can be done only by using semi-transparent mirrors; such mirrors are notorious as sources of measuring errors. Therefore, it has been agreed to measure them 'almost' in the same direction. CIE has defined measuring methods, including measuring geometries, that are adopted by the United Nations (CIE, 1982; UN, 1958).

It is assumed that retroreflective devices have at least two axes of circular symmetry. Therefore, the geometry can be characterized by two angles only. These angles are called the angle of incidence and the observation angle. The observation angle is also called the angle of divergence (UN, 1993, 1996).

The angle of incidence is the angle between the direction of the incident light, and the direction of the normal to the surface at the point of incidence. The observation angle is the angle between the direction of the incident light, and the direction of the measured, reflected light.

There are two measures for the reflective characteristics or retroreflectors. The first is the coefficient of luminous intensity R. It is usually expressed in (cd/lux), or, as the numbers tend to be small, in (mcd/lux). This measure is used for separate retroreflective devices, such as those that are mounted on vehicles, hazard warning triangles, cycle pedals or road side delineators. The second is the coefficient of retroreflection R'. It is expressed in ($cd \cdot m^{-2} \cdot lux^{-1}$). This measure is used for retroreflective materials that are produced in sheet form.

Retroreflectors are widely used in road traffic as markers or signs, because the headlights of the oncoming cars are sufficient to make them visible. Apart for these retroreflecting devices, that will be discussed further on in this section, retroreflection also can be an unwanted side-effect that takes place when strong light strikes a signal. When sunlight strikes road traffic signals, the effect is called the phantom effect, or just the sun phantom. The resulting retroreflection is called the phantom light. Although sun phantom is unwanted, and may obstruct the visibility of signals, the optical principles are the same as those of regular retroreflecting devices.

In road traffic, there different types of optical devices are used, that are called 'retroreflecting devices'. They are usually designated as:

(1) Corner-cubes.
(2) Lens reflector.
(3) Glass-beaded sheets.

As we have explained earlier in this section, the sun phantom in traffic signals must be added as a fourth type of retroreflection. The optical principle of these four types are depicted in Figure 14.1.17,

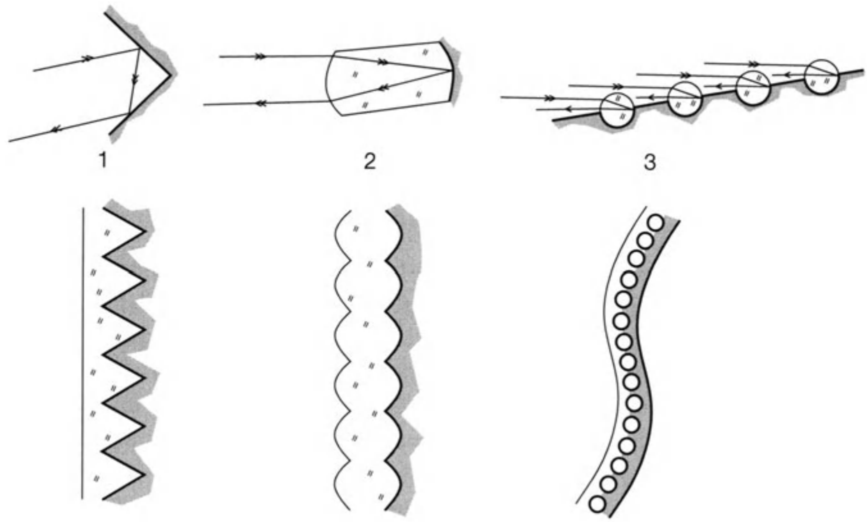

Figure 14.1.17: *The optical principle of retroreflecting devices.*
Based on Schreuder, 1988, Figure 1.

Notes to Figure 14.1.17:
(1): Corner-cubes (2): Lens reflector (3): Glass-beaded sheets

In Table 14.1.3, some values are given that are based on measurements.

Type	R' ($cd \cdot m^{-2} \cdot lux^{-1}$)	Angle of incidence	Observation angle	Source
Corner-cubes				
– white	700	5°	20'	A
– yellow	420	5°	20'	A
– orange	280	5°	20'	A
– red	175	5°	20'	A
– green	105	5°	20'	A
– blue	35	5°	20'	A
Microprisms				
– white	550	5°	20'	A
– white	1100	4°	0,2°	B
Sheet class I				
– white	120	4°	0,2°	B
Sheet class II				
– white	310	4°	0,2°	B

Table 14.1.3: *Coefficient of retroreflection R' in ($cd \cdot m^{-2} \cdot lux^{-1}$) of several retroreflective sheeting materials. After Schreuder, 1988, Table 1. Based on data of CIE, 1987a (A), and Erickson & Woltman, 1988 (B). The angle of incidence and the observation angle are explained in earlier in this section.*

(b) The optical principles

The optical principles will be briefly explained. Corner-cubes are called so, because they are just that: the corner of a cube of glass or plastic. The light is always reflected three times, and it is reflected back exactly in the direction where it came from. Therefore, a corner-cube is a 'true' retroreflector. It should be noted, that the surfaces of the cube need to be covered by a mirror: the angle is, at least in one of the three reflections, smaller than the angle of total reflection, so that, without the mirror, the light would be lost. It should also be noted, that Figure 14.1.17 gives a simplified picture: it is depicted as if it were a two-dimensional device. As will be explained in a further part of this section, corner cube reflectors are used in different sizes. The most common type consists of elements, a few milliliters large. They are usually made of glass or rigid plastic, and they are widely in use for marking roads and vehicles. Also, sheet materials are used with very small elements, not much larger than about 0,1 mm. These are used for high-performance road signs.

The optical principle of a lens reflector, or, as they are often called, a cat's eye, is different. Here, the spherical front surface of the device acts as a positive lens with its focal point on the – spherical – rear surface of the device. A parallel beam of incident light is focussed on that rear surface. When the rear surface is mirrored, the light is reflected back. If the curvatures of the surfaces, their interdistance and the index of refraction of the lens material – usually again glass or plastic – are chosen correctly, the reflected beam is parallel to the incident beam. The light is reflected back exactly in the direction where it came from. A lens reflectors is, just as a corner-cube device, a 'true' retroreflector. As will be explained in a further part of this section, lens reflectors are used in different sizes. A rather common type consists of elements, about one centimetre large. They are usually made of glass, sometimes of rigid plastic. They are used for road marking in raised pavement markers. Much more common are sheet materials with very small elements, not much larger than about 0,1 mm. Almost always, the elements are made of glass. They are designated as the CIE Type II materials, widely in use for road signs as well as in many other areas of signing.

Glass beaded sheets have a different optical principle. Basically, they are a white, diffuse sheet. So, in essence, they are diffuse reflectors. However, a lens, placed in front of the sheet, will focus the incident light on a small part of the sheet, making it relatively bright. This part will act as a – secondary, diffuse – light source. The same lens, that did focus the incident light, will act as a collimator, rendering the reflected light into an almost parallel beam. The direction of the reflected beam is close to the direction of the incident beam. In this way, the device as a whole acts as a retroreflector, without being so in essence. We will, however, still call them retroreflectors. This type of retroreflector comes almost always in the form of sheets. The two main field of application are, first, in horizontal road markings, or stripes. The white material is either road paint or thermoplast. The stripes are attached directly to the road surface. The second field of application is as sheet material, that can be attached to almost any surface and in almost any shape. These sheets are designated as the CIE Type I materials, widely in use for road signs as well as in many other areas of signing. One remark: we have explained the optical principle, using a white background material. This is, of course, not essential at all. Sheet materials come in almost all colours. It should be noted, that glass beaded materials show the colour of the background, contrary to the corner cubes and the lens type reflectors, that show the same colour as the incident light. If they need to be coloured for some signing purpose, a colour filter must be added.

The optical principle of the sun phantom of signals is again somewhat different. Road traffic control signals, or traffic lights, usually consists of an incandescent lamp with a small filament, that is placed in the focal point of a paraboloid mirror. The result is, as is explained in sec. 14.1.5f, a parallel beam of light. Usually, the actual beam needs to have a somewhat different shape. For this, and for adding the correct, relevant colour, a specially shaped, coloured lens is placed in front of the mirror. The resulting beam shape is, however, still very close to parallel. If direct sunlight hits the front plane of the signal, the beam is focussed on the filament of the lamp. This filament reflects some of the light, that follows the normal pathway in the signal. The result is that, for an approaching driver, the signal seems to be in operation, while it is not. Hence the term 'phantom light'. Phantom light may easily lead to confusion. Needles to say, that this always leads to hazardous situations. Standards for road traffic control signals give a maximum value for the phantom light. The design of the equipment includes means to reduce the phantom effect, e.g by placing screens in the parabolic reflector, or hoods in front of the signal, or one of many other methods.

Many modern traffic lights are equipped with LEDs. It is usually assumed that, in the near future, almost all new installations will use LEDs (Schreuder, 2000). There are two kinds: the first uses an array of LEDs of the size of the light (i.e. 20 or 30 cm diameter), the second uses a small array of high-intensity LEDs that resemble in brightness and in size a traditional incandescent lamp. The lights that are equipped with an array of the size of the light, do not need a reflector. Such lanterns cannot show any sun phantom. The absence of sun phantom is one of the major advantages of using LEDs in traffic lights. Lanterns that use a small array of high-intensity LEDs seem, however, to be slightly cheaper. If these are used, it would mean that lower costs have priority over road safety.

(c) Corner cube reflectors, requirements and actual measured values

In Table 14.1.4, the coefficient of retroreflection R' of several retroreflective materials have been given. These values can be compared with the values that are required for different fields of application.

As an example, several regulations of the Netherlands are quoted, regarding road safety equipment.

For hazard warning triangles, the requirements correspond, converted into ISO-units, to about R' = 90 (in $cd \cdot m^{-2} \cdot lux^{-1}$). (Lazet et al., 1967; SWOV, 1969). In Germany, the minimum requirement is R' = 125 (in $cd \cdot m^{-2} \cdot lux^{-1}$). (SWOV, 1969; Schreuder, 1988, p. 1129).

In order to enhance road users to be visible at night, retroreflectors are required. For bicycles, the legal minimum requirements are:
- for rear lamps (10 cm^2): R' = 15 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$;
- for rear reflectors (225 cm^2): R' = 44 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$;
- for pedal reflectors (10 cm^2): R' = 15 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$.

Especially for bicycles, side reflectors are required. Usually they are an integral part of the tyre (Blokpoel et al., 1982). The tires have to comply with the UN-Requirements (UN, 1993). The coefficient of luminous intensity R must be at least $16 \cdot D$, where D is the inside diameter of the reflecting part of the tyre (in cm).

For motor vehicles, the international requirements are to be fulfilled. Retroreflective devices have to comply to the UN-Requirements (UN, 1996). The coefficient of luminous intensity R of Class IV-materials must be at least 1800 for white, 1125 for amber and 450 for red. For normal sized red rear reflectors, this corresponds to about R' = 122 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$. (SWOV, 1973; Schreuder, 1988, p. 1129).

Corner cubes are also applied in reflectorized raised pavement marker or road reflectors, that are discussed in a further part of this section, although, as is explained in that part, most road reflectors contain lens reflectors. As an example, we will quote the reflection values of several products of the Stimsonite Company, one of the major producers of this type of equipment. There are many types and colours, but we will quote only three different types, and only the white colour. The types differ not only in the construction and the material of the housing, but also in the type of reflectors. The product information sheets give for an observation angle of 0,2° and for an angle of incidence of 0°, the following values of the coefficient of luminous intensity:
- for type 911: 279 mcd/lux;
- for type 953: 558 mcd/lux;
- for type 952 AL: 220 mcd/lux.

(d) Sheet materials, requirements and actual measured values

As indicated earlier in this section, a retroreflector is characterized by the fact, that the light is reflected back into the direction where it came from. For measuring purposes, usually a small angle between the two directions is allowed. The angle, usually a small fraction of one degree only, is called, as mentioned earlier, the observation angle (α). In order to avoid gloss from the front surface of the material during the measurement, which might confuse the outcome, the device is tilted over a small angle, usually about 5 degrees. This angle is called the angle of incidence (β). The geometry is established by CIE (1982).

As is indicated earlier in this section, there are three types of retroreflective sheet materials. Two of them have a CIE designation (CIE, 1987):
- Class I is called 'Sheetings with enclosed glass spheres'. More common is the designation of the 3M-Company, one of the major producers of sheet materials. They call it: 'Engineer grade sheeting'.

- Class II is called 'Sheetings with encapsulated spheres'. The 3M-designation is 'High intensity sheeting'
- The third is more recent, and does not have yet a CIE classification. It is called 'Prismatic sheeting'. The 3M-designation is 'Diamond grade sheeting'.

Because retroreflective sheet materials are used in many fields of application, there are many standards that give requirements regarding the reflective characteristics. As an example, a few are quoted here.

For the retroreflective materials that are used on road signs, the draft European Standard (EN 12899-1:2001 (E), 2001), gives the following requirements, as given in Table 14.1.4. It may be noted that, as is required in Europe, the vales are identical to the values given in the Dutch Standard of 1999 (NEN, 1999).

Geometry				**Colour**		
α	β	**white**	**yellow**	**red**	**green**	**orange**
Class I						
12'	5°	70	50	14,5	9	25
20'	5°	50	35	10	7	20
Class II						
12'	5°	250	170	45	45	100
20'	5°	180	120	25	21	65

Table 14.1.4: *Coefficient of retroreflection in $cd{\cdot}m^{-2}{\cdot}lux^{-1}$. Class I and Class II after CIE. Based on EN, 2002, table 8 and table 9.*

Traffic signs contain coded information (Schreuder, 1971). Consequently, the visibility of traffic signs with symbols is rather complicated (Van Norren, 1974, 1981). See also Jenkins & Cole (1984); Schreuder (1988, p. 1130).
The visibility, or rather, the conspicuity, depends mainly on:
- the observer (age, conditions of observation, weather, etc);
- the sign luminance;
- the contrast between the symbol and its background;
- the colour;
- the dimension and the shape of the symbols.

On the basis of research and practice, it is found that usually, adequate visibility is reached when the luminance is about 50-10 cd/m^2. For dark surroundings, with a luminance of lower than 0,4 cd/m^2, the optimum of the readability is found to be at about 75 cd/m^2 (Sivak & Olson, 1983).

When the required luminance is known, the required reflection properties can be assessed, using the formulae for this, that are given in sec. 14.1.8. For signs placed at the curb of the road – that is, for non-overhead signs – a rule-of-thumb has been given by Youngblood & Woltman (1978). For one car at a distance of 600 ft (183 m), the following relation can be used:

$$L = 0{,}04R' - 0{,}25 \qquad [14.1.27]$$

in which:
L: the sign luminance in cd/m^2;
R': the coefficient of retroreflection in cd·m^{-2}·lux^{-1}.

Although it is not mentioned, one may assume that this relation is valid for a car with US-type low-beam headlamps.

In order to enhance cyclists to be visible from the side, in the Netherlands side reflectors are required. Usually, they are incorporated in the tires. The legal minimum requirements are about 102 cd·m^{-2}·lux^{-1} (Blokpoel et al. 1982).

On the basis of research it is recommended that retroreflecting licence plates for motor vehicles should comply with R' = 35 cd·m^{-2}·lux^{-1} or higher (Schreuder, 1988, p. 1129. SWOV, 1969a, p. 56).

Finally, some values are given that are based on measurements. See Table 14.1.5.

Type	R' (cd·m^{-2}·lux^{-1})	Angle of incidence	Observation angle	Source
Corner-cubes				
– white	700	5°	20’	A
– yellow	420	5°	20’	A
– orange	280	5°	20’	A
– red	175	5°	20’	A
– green	105	5°	20’	A
– blue	35	5°	20’	A
Microprisms				
– white	550	5°	20’	A
– white	1100	4°	0,2°	B
Sheet class I				
– white	120	4°	0,2°	B
Sheet class II				
– white	310	4°	0,2°	B

Table 14.1.5: *Coefficient of retroreflection R’ in (cd·m^{-2}·lux^{-1}) of several rertroreflective sheeting materials. After Schreuder, 1988, Table 1. Based on data of CIE, 1987a (A), and Erickson & Woltman, 1988 (B). See also Table 14.1.3.*

As is explained in an earlier part of this section, CIE has introduced two classes of retroreflective sheeting materials, based on the retroreflection characteristics (CIE, 1987). They are called Class I and Class II materials. Since quite a few years, a third type of retroreflective sheeting material is on the market, that as yet has not been given a class designation by CIE. The material consists of tiny corner-cube reflectors; it is sometimes called 'microprism' material. The reflection is much higher than that of Class I and Class II materials. Their use is explained here, on the basis of 3M product information (Anon., 1998a). For easy reference, the 3M designation has been used here. The product information gives only one value of the reflection factor for each material:

(1) for Engineer Grade (CIE Class I): 40 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$;
(2) for High Intensity Grade (CIE Class II): 120 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$;
(3) for Diamond Grade: 430 $cd{\cdot}m^{-2}{\cdot}lux^{-1}$.

These values are approximations. They are based on Anon. (1998a, 1998b).

Based on studies that are not especially mentioned, it has been found that the requirements regarding the retroreflective characteristics of traffic sign materials depend on the ambient luminance. The requirements depend, of course, also on the driving task difficulty and on the ambient traffic conditions. From these studies, two regions of reflection are deduced, one for minimal driving comfort ('minimal conditions') and one for high driving comfort ('ideal conditions'). One may assume that these characteristics broadly agree with minimal driving task difficulty, and high driving task difficulty, respectively.

Some findings are summarized in Figure 14.1.18.

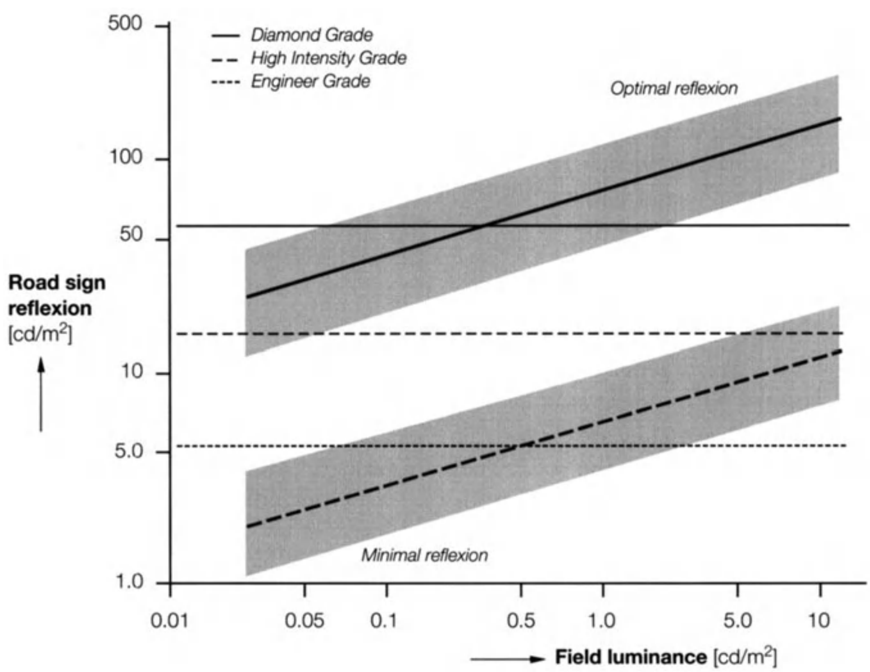

Figure 14.1.18: *Required reflection values of road sign materials. After Anon., 1998a, based on data from IZF (1992).*

In this figure, the regions of 'ideal conditions' and of 'minimal conditions' are indicated for different values of the surrounding luminance. Also, the factor of retroreflection for the three materials that were mentioned earlier, are inserted. It is clear, that Class I is, in most cases, not adequate, whereas Class II is sufficient for all cases. Diamond Grade is justified only in difficult traffic conditions, or in cases with special requirements as regards driving comfort. This is not the place to discuss policy decision to use Diamond Grade on traffic signs. Because almost all the light is reflected back into the drivers' eyes, unwarranted use of Diamond Grade may result in glare for the driver. For the same reason, the choice of sign material has little consequence as regards light pollution.

(e) Road markings

Participating in road traffic is a complicated affair. The traffic participant must perform a variety of different activities. These activities are different for each different mode of traffic participation; furthermore, they usually differ for different persons, for different traffic situations and for different environmental conditions (day or night, weather, urbanization etc.).

In sec. 10.4.3, several aspects are discussed of the driving task. A basic consideration in the driving task is that the task elements are the outcome of a decision making process. The decision usually has to do with the choice between two, occasionally more, alternatives. The choice is made on the basis of the comparison between the expected outcome of the different alternatives. The driving task requires a considerable amount of information, for the greater part visual information. A major part of the visual information is provided by road markings.

In sec. 10.4.3e, it is explained that, at the level of manoeuvres, there are two major aspects of the driving task.

(1) Keeping the driving speed at the desired level, or, alternatively, keeping the distance to the preceding vehicle at the desired level (speed control);
(2) Keeping the distance to the road side at the desired level (crosswise position control).

The first is usually described in terms of car following (Schreuder, 1992). For the second, road markings are essential.

Road markings is a generic term. The main types are:

- lengthwise stripes on the road, usually in the road axis (centre stripes) or at the road sides (edge markings). They are termed 'horizontal road markings', or simply 'road markings';
- separate elements on the road. They are termed 'raised pavement markers' or 'road studs'. They are described in a further part of this section, when discussing lens reflectors;
- separate elements in the shoulder of the road. They are termed vertical markers, post markers, or, more in general, delineators. They are described in an earlier part of this section, when discussing corner cube reflectors.

A frequent problem is, that road markings are rendered invisible by moisture. This may happen both at day and at night. The problem is greatest, of course, at night on unlit roads. Most road markings are almost flush with the road surface. Even a thin layer of water will cover them completely. Light from the vehicle headlamps is not reflected by the road marking any more, but by the water sheet. Naturally, this will render the road markings invisible. These problems are discussed in great detail in: CROW (1987); Domhan & Serres (1987); Schreuder (1992); Schmidt-Clausen, (1990); Tooke & Hurst (1975).

The obvious solution to solve the problem of 'wet night visibility' is to make the road marking so, that they stick out from the water sheet, apart, of course, from the solution of using self-luminous road markings. Self-luminous road markings are discussed in sec. 7.2.1c. Three possibilities to do so are:
(1) Use raised pavement markers. As mentioned earlier, they are described in a further part of this section, when discussing lens reflectors;
(2) Make the road markings high. This can be done by applying 'corrugated road markings' (Kop, 1990; Schreuder, 1980);
(3) Use large beads (Anon., 1988).

In the Netherlands, in the 1980s a large series of studies and tests have been made to find practical solutions for the problem of the wet night visibility. They included literature studies (Schreuder, 1980, 1985; Schreuder & Schoon, 1990), and road tests (Blaauw & Padmos, 1981, 1982; Van Gorkum, 1982). The results are summarized in Schreuder (1986). Part of the studies related to raised pavement markers. These are mentioned described in a further part of this section, when discussing lens reflectors.

Some of the results are summarized here. It relates to three types of experimental road markings, two profiled types and one thermoplast, as well as ordinary beaded road paint. All were new, and measured in dry conditions. See Table 14.1.6.

Type	**Reflection** ($cd \cdot m^{-2} \cdot lux^{-1}$)
profiled marking type 2	2
profiled marking type 1	1,6
thermoplast	1,2
beaded road paint	0,7

Table 14.1.6: *Coefficients of retro-reflection for experimental markings. Based on data from Blaauw & Padmos, 1981, figure 1.*

(f) Lens reflectors

As is explained in an earlier part of this section, road traffic can be seriously hampered when at night, during rain, road markings are not easily visible – the wet night visibility problem. The problem results from the fact that flat road markings will be covered by the same sheet of water as the road surface. As is mentioned earlier, one solution is to make the road marking stick out from the water sheet. For this, raised pavement markers, or road studs, are used. Usually, they consist of a metal, plastic or rubber housing, that contains a number of lens reflectors. The optical system of lens reflectors is explained in sec. 14.1.9b. To some, the lens reflectors, when illuminated by car headlamps, look like the eyes of a cat. Hence the name cat's eyes. Also, the term 'road reflectors' is used.

Many aspects of the construction and operation of road reflectors, as well as other aspects of road markings and delineation are discussed in a comprehensive report of OECD (1975). Although that report is already quite old, almost all principles are still valid.

In the research, that was mentioned already in the discussion of road markings, also a number of road reflectors were studied. The summary of some of the results indicate that visibility is adequate, if the coefficient of luminous intensity for a speed of 80 km/h is at least 0,004 cd/lux, and for 100 km/h at least 0,006 cd/lux (After Schreuder, 1986, p. 58-59, based on Blaauw & Padmos, 1982 and Van Gorkum, 1982).

(g) Sun phantom of traffic signals

As is mentioned in an earlier part of this section, retroreflection also can be an unwanted side-effect that takes place when direct sunlight strikes a road traffic signal. As is explained in an earlier part of this section, when discussing the optical principles of retroreflection, direct sunlight that hits the front plane of the signal, is focussed on the filament of the lamp. This filament reflects some of the light, that follows the normal pathway in the signal. The result is that, for an approaching driver, the signal seems to be in operation, while it is not. Hence the term 'phantom light'. Phantom light may easily lead to confusion. Needles to say, that this always leads to hazardous situations. Standards for road traffic control signals give a maximum value for the phantom light.

As an example, in Table 14.1.7. some data are given from the European standard.

	Class of the signal				
Signal colour	**1**	**2**	**3**	**4**	**5**
red, yellow	1	5	4	8	16
green	1	5	8	16	16

Table 14.1.7: *Maximum values of phantom light. After EN, 2000.*

The phantom signal is expressed in the relation between I_{ph} and I_s, where I_{ph} is the actual measured value of the phantom signal light, incident under an angle of 10° with the reference axis, and where I_s is the actual measured value of the luminous intensity of the signal. The five classes, designated in Table 14.1.7, are the signal heads that are recommended for use in different traffic conditions. See EN (2000) for details.

14.2 Photometry in astronomy

14.2.1 Subjective and objective photometry

In astronomy, two distinct ways of photometry are in use:

(1) Subjective photometry. This is the traditional way to express the conspicuity of heavenly objects – stars, planets, nebulae etc – in a scale that is essentially subjective. This scale is the magnitude scale that is discussed in detail in sec. 14.2.2a. The scale does not have an actual beginning nor an end; as will be explained later in this section, it is an interval scale. The scales are still widely used, although they are often adhered to objective measurements. One might say that the magnitude scale is still used as a basis of the observational astronomy, particularly by amateur astronomers.

(2) Objective photometry. This is a special case of radiometry, the measurement of the energy contained in electromagnetic radiation. As radiometry is essentially nothing else but 'counting photons', the scales that are used are metric scales. The different scales are discussed in sec. 9.2.3, and will be briefly explained further on in this section. Objective photometry is the cornerstone of modern astrophysical research.

Because subjective and objective photometry serve different purposes, not only in the past but also at present, it is interesting to consider what happened over the years with the precision of photometric measurements. In part, this aspect is depicted in Figure 14.2.1.

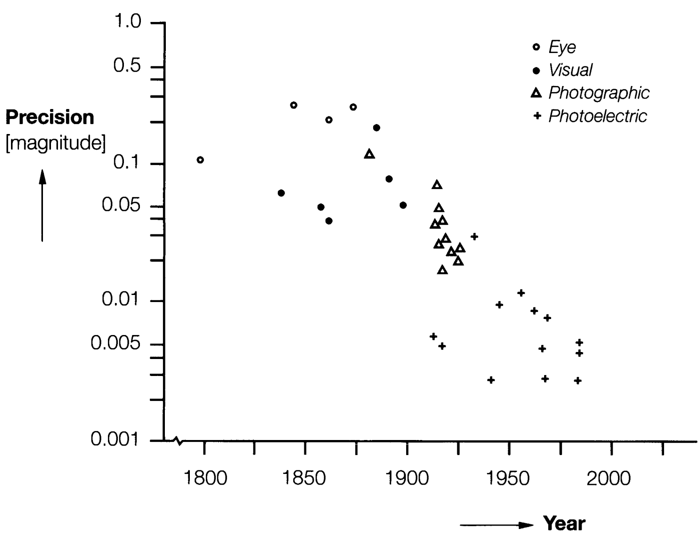

Figure 14.2.1: *Evolution of the precision of photometric measurements. After Sterken & Manfroid, 1992, Figure 1.15, based on data from Young, 1984.*

Notes to Figure 14.2.1:
'Eye' means visual estimated aided by telescopes only.
'Visual' refers to all methods where the eye, as a detector, is assisted by other means like e.g. attenuation wedges, comparison lamps, etc.

Although it is not clearly indicated, one may assume that Figure 14.2.1 represents the 'cutting edge of science'; one may assume that today, in 2004, the precision of the different modes is at least equal to those of the graph.

14.2.2 Subjective photometry

(a) *The magnitude scale*

In astronomy, the visual classification of cosmic objects is based on the 'magnitude' of luminous objects like e.g. stars as they present themselves to the eye. As is explained later on, the magnitude scale is essentially a logarithmical one, where a magnitude difference of 5 relates to a flux ratio of 100. A magnitude of 0 is arbitrarily chosen; it corresponds to very bright, be it not the brightest stars. Astronomical photometry is based on the radiation flux of cosmic objects. The total flux measured by a certain detection system depends on the spectral distribution of the flux emitted by the object, and on the spectral sensitivity distribution of the detector, including filters, if any. Astronomical photometry is discussed in detail in Crawford, 1997; Budding, 1993; Sterken & Manfroid, 1992. See also Weigert & Wendker, 1989, and CIE, 1997.

As is explained in sec. 9.1.7f, when discussing the perception of the colour of stars, the Greek philosopher Hipparchus classified, in about 120 B.C., the stars that can be seen by the unaided eye in six classes, called magnitudes. The brightest were the stars of the first class, the faintest stars were of the sixth class. Later on, this system was adopted by Ptolemy, taken from the Almagest, and later supported by many other sources (Schaefer, 1993, 2003). The brightness of the stars were estimated during twilight, when, after sunset, first the brightest stars became visible and later the fainter stars. Therefore, the magnitudes represent equal steps in visual perception. As is explained in sec 9.1.1., when discussing the Weber-fraction and Fechner's Law, equal steps in experience usually correspond with equal steps in the logarithm of the stimulus. It has been found that this effect is not restricted to the visual sense, but that it is equally valid for hearing, estimating the weights and size of objects, etc. Thus, it is often stated that 'the senses work logarithmically'. Not a very precise expression, but basically true. As regards stellar magnitudes, it seems that it was noted this for the first time by Pogson (Sterken & Manfroid, 1992, p. 24). Pogson also selected the value of 2,512 as the photometric ratio between consecutive magnitudes (Pogson, 1856). When defined in this way, the magnitude scale has no 'zero point', because the logarithm of zero is minus infinity. It is essentially an interval scale, as is explained in sec. 9.2.3.

Setting up an interval scale of this type is not a simple matter. As is explained in more detail in sec. 9.2.3, there are several difficulties:

(1) There is a large difference between observers. For experienced observers ('star gazer' the limiting magnitude is sometimes given as $V = 6{,}5$ magnitude, but that some individual people may even reach $V = 8{,}2$ or $8{,}4$ magnitude (Schaefer, 2003). As is explained in sec. 9.1.3, psycho-physical observations that concern the assessment of visibility thresholds are probabilistic in nature, the best thing to do is to quote the 50%

limiting magnitudes. As is explained in 9.1.7, the majority of people have 50% limiting magnitudes of V about 5 magnitude. The Almagest actually gives a magnitude limit of somewhere between V = 4,0 to 4,7 magnitude. It is likely that no stars fainter than V = 5,5 magnitude are included (Schaefer, 2001).

(2) Because stars are tiny, bright specks in a dark night sky surrounding, one never can be certain whether the photopic or the scotopic spectral sensitivity curves apply. These curves are described in detail in secs. 8.2.2 and 8.2.3d.

There are, of course, many more difficulties and 'pitfalls', when doing visual photometry and interpreting the results. A few are listed here, in summary of Sterken & Manfroid (1992, Sec. 1.10; p. 29-30).

(1) The error in magnitude estimate caused by the colour of the stars;
(2) The influence of the brightness of the background. This may occur when comparing estimates made on moonlit nights and dark nights. Also, the Milky Way may have its influence. This effect can easily be understood in terms of the contrasts that are discussed later on in this section;
(3) The position error. The sensitivity of different retinal areas is different;
(4) The decimal preference. It is a well-known fact that people have a preference for different decimal numbers when making estimates;
(5) The extinction of the atmosphere in not always correctly taken into account.

(b) Definition of magnitude

Because, as is indicated in an earlier part of this section, the magnitude scale is an interval scale, it is not possible to define the magnitude, only the difference in magnitude. The most straight-forward way to define the difference in magnitude between two celestial light sources is:

$$(m_1 - m_2) = 2{,}5 \log \frac{I_1}{I_2} \qquad [14.2.1]$$

in which:
m_1: the magnitude of source 1;
m_2: the magnitude of source 2;
I_1: the intensity of source 1;
I_2: the intensity of source 2.

This relation is given by Budding (1993, eq. 2.1; p. 16). It is attributed to Pogson, 1856. The same relation is written in a somewhat different but mathematically identical form by Herrmann (1993, p. 31):

$$\log \frac{I_1}{I_2} = -0{,}4(m_1 - m_2) \qquad [14.2.1a]$$

(c) Diffraction

In sec. 9.1.4 it is explained, when discussing visual acuity, that the resolving power of any optical device is limited by the diffraction that results from the wave-character of light. The resolving power depends on the wavelength of the light and on the diameter of the aperture by which the light enters into the device:

$$\sigma = 0{,}61\frac{\lambda}{r} \qquad [14.2.2]$$

in which:
σ: the smallest angle to be dissolved in radians – the 'minimum separable';
λ: the wavelength of the light in m;
r: the aperture in m.
(Kuchling, 1995, equation 0-26.12; p. 388)

For a different measure of the resolving power, the Raleigh-criterion applies: "Two point sources are resolved by a telescope of aperture D, provided their angular separation in radians is not less than:

$$1{,}22 \cdot \frac{\lambda}{D} \qquad [14.2.2a]$$

with:
λ: the wavelength of the light in m;
D: the aperture in m" (Illingworth, 1991, p. 410).

As an example, we will assess the resolving power of a few observation methods, using the Raleigh-criterion. We will consider observations with the unaided human eye, with field glasses and with a top-class optical telescope, as well as with a long base interferometer radio astronomical system. The results are summarized in Table 14.2.1.

Observation mode	**Aperture** (m)	**Wavelength** (m)	**Resolving power** (arc seconds)
eye	$5 \cdot 10^{-3}$	$555 \cdot 10^{-9}$	27,9
field glass	$5 \cdot 10^{-2}$	$555 \cdot 10^{-9}$	2,8
telescope	15	$555 \cdot 10^{-9}$	$9{,}3 \cdot 10^{-3}$
LBI	$15 \cdot 10^{6}$	10^{-2}	$1{,}67 \cdot 10^{-6}$

Table 14.2.1: *The resolving power of observation methods.*

Note: LBI means 'long base interferometer radio astronomical system'.

The dimensions of stars are so small in relation to their distance, that they may be regarded as point sources. As an example, we will consider the Polar Star. Its mass is 8 times that of the Sun (Herrmann, 1993, p. 219). Assuming that its specific mass is equal to that of the Sun, the diameter of the Polar Star would be twice that of the Sun. The radius of the Sun is about 696 000 km (Herrmann, 1993, p. 105). The diameter of the Polar Star is about

$4 \cdot 696\,000 = 2\,800\,000$ km. Its distance to the Sun is 360 light years (Herrmann, 1993, p. 219). A light year equals 95 000 000 000 000 km (Thomas, 1944, p. 410). The distance from the Polar Star to the Sun – and to the Earth – is 342 000 000 000 000 km. At this distance, a disk with a diameter of 2 800 000 km will be seen under an angle, in radians, of:

$$\frac{2800000}{342000000000000} = 8{,}19 \cdot 10^{-9}$$

A complete circle of 360 degrees contains $2 \cdot \pi$ radians. A radian equals 57,31 degrees or 206 304 arc seconds. The Polar Star will be seen from the Earth under an angle of about $1{,}6 \cdot 10^{-3}$ arc seconds. For the unaided eyes and for modest telescopes, this may be regarded as being a point source. It is, however, questionable, whether this is always the case for top class telescopes.

At any rate, for many other celestial objects, this is not true. With the naked eye, it is easy to see that the Sun, the Moon, the Milky Way, and several cluster of stars, like e.g. the Pleiads, are not point sources. With a modest telescope, the apparent dimensions of hundreds of objects can be easily observed. Many of these are listed by Mizon (2002, sec. 2.3, p. 94-138).

(d) The effect of sky glow on observation of contrast objects; the 'sky glow formula'

To understand the effect of the diffuse sky glow, one must realize that all observations, both visual, photographic and electronic, of light emitting objects is essentially an observation of contrast (sec. 5.1.1). This applies not only to the celestial bodies that we have indicated earlier, as having a considerable apparent dimension, but also for the stars that, as is explained earlier in this section, may measure angles of 10^{-3} arc seconds, or maybe even much smaller. The reason is, that in every observation, whatever the method, the aperture of the apparatus which with the observations are made, is limited in size. As is mentioned in sec. 8.1, the diameter of the pupil of the human eye is somewhere between 2 and 7 mm. Astronomical telescope range from 5 cm to 15 m. In an earlier part of this section (Table 14.2.1), it is pointed out that the resolving power in these cases is somewhere between 30 and 0,001 arc seconds – quite large, but not infinite. Therefore, observations cannot make a distinction between a point and a surface of between some 30 and 0,001 arc seconds. One may say that, for the observing system, the light might be 'smeared out' just as well over an area measuring between 30 and 0,001 arc seconds in diameter for the different observation modes. This is exactly the same as saying that all celestial objects have a dimension larger than zero, and that, therefore, they have to be considered as 'luminance objects'.

The following considerations are based on Schreuder (1987, 1991, 1994, 1997). They are, to a large extent, included in CIE (1997). As is explained in sec. 5.1.1, the visibility of luminance objects is determined by the contrast between the object and its direct background. When the luminance of the object is called L_o and the luminance of its background, against which the object must be observed, is called L_b, the contrast C is conventionally defined as:

$$C = \frac{L_o - L_b}{L_b} \qquad [14.2.3]$$

The visibility losses due to sky glow are very similar to those caused by disability glare, that is discussed in detail in sec. 9.2.2. The considerations given here, are similar to those given in that section. In both cases, the visibility is reduced by a luminance veil. In the case of disability glare, the veil is a result of light that is scattered within the eye. Therefore, the veil is called an 'equivalent' veil. In the case of urban sky glow, it is a physical light veil. In both cases, however, the veil extends over the field of observation. This veil has a luminance as well, that will be called L_v. The veiling luminance has to be added to all luminances in the field of observation. All contrasts will be reduced, as can be shown as follows:

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{L_o - L_b}{L_b + L_v} \qquad [14.2.4]$$

As the nominator stays the same and the denominator always is greater, thus:

$$C' < C \qquad [14.2.5]$$

The same formula is used to describe the disability glare phenomena, that are described in detail in sec. 9.2.2. When the object to be observed is a star, one might suppose that its observed luminance equals the intrinsic luminance of its surface, and therefore is much, much higher than L_v. However, while a distant star is a close geometric approximation to a 'point source', its image in the instrument with which the observations are made is not a point at all. As is explained in an earlier part of this section, the image can never be smaller than a certain limiting size, even with excellent 'diffraction limited' optics.

The limiting magnitude follows from the definition of the difference in magnitude, that is mentioned in an earlier part of this section, but written here in a slightly different form:

$$m = 2.5 \log(I_1 / I_2) \qquad [14.2.6]$$

where I_1 and I_2 are the luminous intensities of the two stars that are compared. The use of the luminous intensity to characterise a star is subject to the restrictions given in sec. 14.1.4.

When assessing the influence of the sky glow, the smallest luminance for the most favourable conditions is L_{o1} and under sky glow conditions L_{o2}. The background luminance is L_b and L_v respectively. With $L_v = a \cdot L_b$, and according to [14.2.3] and [14.2.4], for observation at the threshold of the contrast sensitivity, C equals C' :

$$C = C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{L_o - L_b}{L_b + L_v} \quad [14.2.7]$$

When L_b is small compared to L_{o1} and L_{o2}, L_b may be disregarded in the nominators. The formula [14.2.7] becomes:

$$(a + 1) = \frac{1}{L_{o1} / L_{o2}} \quad [14.2.8]$$

When inserting L_{o1} and L_{o2} for l_1 and l_2 in formula [4], one gets:

$$m = -2.5 \log(a + 1) \quad [14.2.9]$$

with m the increase in the threshold, or the decrease in the limiting magnitude as a result of the veiling luminance. This formula is called the 'sky glow formula'.

14.2.3 Objective photometry

(a) Radiometry; counting photons

Measuring radiation, e.g. electromagnetic radiation, is called radiometry. In the last instance, radiometry is nothing but 'counting photons' (Cinzano, 1997, sec. 3.1.1; p. 107). Therefore, the basic unit of radiometry should be the number of photons. As we discuss 'measurements' here, this number must be specified as the number of photons that hit the receiver. The receiver is usually called the detector. In sec. 14.5.1, different types of detector are discussed in some more detail.

In sec. 8.2.1, when discussing visual functions, photons are briefly mentioned as the elements of electromagnetic radiation. In that section it is explained that a photon has an energy of $h \cdot \nu$, where h is the Planck-constant and ν the frequency of the radiation (Illingworth, 1991, p. 350). See also sec. 14.1.2b. The energy of n photons equals $n \cdot h \cdot \nu$. What interests lighting engineers and astronomers alike is usually not the number of photons, but rather the number of photons that are emitted – or that pass – per second. So, the logical basic unit of radiometry is the energy flux.

As is mentioned earlier, measuring radiation presupposes some sort of detector, which must have a limited receiving area. If the receiving area is too large, the device will be difficult to handle. If, at the other hand, the receiving area is too small, the number of photons that hit it, will be too small for reliable measurements. When saying this, one should remember that any stream of photons has inherent stochastic characteristics. There are always fluctuations in the stream because the emission of photons is essentially a random effect. These random effects are briefly explained in the next part of this section.

(b) The S/N ratio

Data transmission is a form of communication engineering. The aim of communication engineering is, to send a signal from the sender to the receiver in such a way that the receiver can use the message. In almost all cases, the communication is hindered by noise from the background. Noise can, of course, literally, be sound from the background, but it can be also other disturbance. In communication engineering, the word 'noise' is used only, if it is composed of the same stuff as the message. If the message is sound, only other sounds are considered as 'noise' in communication engineering. If the message consists of is electromagnetic energy, loud sounds are not considered as 'noise'. The reason is, that, if no special measures are taken, high-intensity noise may destroy the message, because message and noise are essentially the same 'stuff'. If a radio operator is bothered by people talking aloud, it is not a job for a communication engineer to improve the situation, but for an ergonomist.

Because message – or signal – and noise consist of the same stuff, the relation between the two can be expressed by a dimensionless number, the signal-to-noise ratio or 'S/N ratio'.

(c) Photon shot noise

The following discussion on noise effects is based on Sterken & Manfroid (1992, Sec. 1.1., p. 3-4). Photons are emitted and receives at a random rate. As regards the emission, it should be noted that most celestial bodies are so large, that the random aspect may be disregarded. This is not always the case at the receptor-side. Here, photons arrive 'like rainfall'. The statistical aspects are complicated, because photons have a tendency to group themselves in packets or wave-trains (Van Heel, 1950; Illingworth, ed., 1991, p. 521). When this effect is neglected, photon arrival rates can be described as a Poisson distribution (Moroney, 1990, chapter 8; Dixon & Massey, 1957).

The probability that exactly i photons will arrive during a time interval t can be described as:

$$P(i) = \frac{e^{-n} \cdot n_i}{i!} \qquad [14.2.10]$$

in which n is the mean photon arrival rate in the time interval t (After Sterken & Manfroid, 1992, equation 1.4., p. 3).

The variance σ^2 of the Poisson distribution is equal to the mean value n. A derivation may be found in Bronstein et al. (1997, p. 700-701). This means that the root-mean-square rms deviation from the mean value is:

$$\sigma = n^{1/2} \qquad [14.2.11]$$

These deviations are a measure of the precision with which the average number of photons n within a time interval t can be determined. Photon noise – or shot noise – is the ultimate source of noise that cannot be overcome, because it is an essential aspect of the 'graininess' of the Universe. These fluctuations can also be classified as electromagnetic noise. In fact, these fluctuations did give rise to the whole idea of 'noise' in the field of communication engineering in the first place, as well as to the associated concept of signal-to-noise ratio (Bok, 1948; Van Soest, 1956; Wiener, 1950, 1954). Only when very large numbers of photons are involved, one may disregard these stochastic aspects. In other words, they may be disregarded if the signal-to-noise ratio becomes acceptably small. 'Acceptable' is, of course, not an absolute measure. The noise effects can only be judged to be acceptable, if the use of the signal is precisely specified.

(d) Radiometry; the integration time

As is mentioned earlier, the shot noise cannot be eliminated altogether, but its negative effects can be diminished. Evidently, the influence becomes smaller when the noise is getting smaller in relation to the signal, represented by the intensity of the stream of photons one wants to measure, or when the signal-to-noise ratio, that is mentioned earlier, is large enough.

As is mentioned earlier, n is the mean photon arrival rate in the time interval t. Having more photons to count, means a larger n that can be achieved by choosing a larger detection area, or using more time, that is, increase t. In practice this means that the integration time must be increased, because, usually, the measuring device is selected at the outset, and cannot be changed easily. The integration time is associated with the concept of 'exposure' that is discussed in sec. 14.1.3a.

What this means for measurements in astronomy can be explained as follows. Usually, one is interested in the energy flow that is received from a source. In the terms we used earlier, this means the number of photons n. The number of photons that will be counted in a time interval t with a measuring device with a receiving area of A equals $n \cdot t \cdot A$. As a consequence of the stochastic nature of photon arrival, and because n is a sample of limited size, this number may not be considered as the 'real' value. One may approach the 'real' number as closely as one wants. The precision can be expressed in the signal-to-noise ratio (S/N), or, rather, the noise-to-signal ratio (N/S). Both noise and signal can be expressed in photon numbers. The noise in n' and the signal is, of course, n. The value of n' may be estimated while assuming that the noise is 'shot noise', that can be, as is explained earlier in this section, by a Poisson distribution. So, the noise-to-signal ratio equals (n'/n). The desired precision is $a \cdot$ (N/S). For equality, this leads to:

$$n \cdot t \cdot A = a \cdot \frac{n'}{n} \qquad [14.2.12]$$

From this, it follows directly that:

$$t = \frac{a \cdot n'}{n^2 \cdot A} \qquad [14.2.12a]$$

The time interval t may be interpreted as the integration time for the measurements. If the desired precision and the noise are high, a large time is needed; the same applies if the number of photons is small or if the area is tiny. In most practical cases, the integration time is between several seconds and 10^{-3} seconds (Budding, 1993, p. 115).

(e) Size and costs of telescopes

The following discourse is based in part on Schwarz (2003) and Tritton (1997). One may state that, also in view of what is explained in sec. 11.1.1 about the diffraction, all sources are more difficult to observe in sky-glow conditions – point sources, such as stars, as well as extended sources. The significant difference in observing celestial bodies is, whether a source is fainter or brighter than the sky background. In case of that astronomical observations are constrained by sky glow, a 'figure of merit' can be introduced. It can be shown that the required integration time, is proportional to the background luminance, the square of the seeing, and inversely proportional to the efficiency of the detector and the telescope area (Tritton, 1997, as quoted by Schwarz, 2003). This is only an approximation for star-like objects. "The calculations assume that the starlight is spread into an area occupied by the half-power area of the seeing disk. This approximation only provides a crude model for the dramatic effects of 'seeing'" (Unger et al., 1988, p. 82-83).

The integration time is discussed in the preceding part of this section. So, doubling the background luminance doubles the required integration time. Put differently, one needs a telescope with double the area to get the same signal-to-noise, or S/N, in the same time. "Observations cannot be continued into indefinitely faint limits. For short exposure times the S/N-ratio is proportional to the exposure time – the 'noise limited case'. For long exposure times the S/N-ratio is proportional to the square root of the exposure time – the 'sky-limited case'" (Unger et al., 1988, p. 83). For point sources, the transition point between the two cases seems to be at about 23-24 mag in the V-band (Unger et al., 1988, p. 83, figure 4.1b).

The signal-to-noise ratio (S/N-ratio) seems to play an essential role in the observation of faint, point-like celestial objects (Tritton, 1997; Unger et al., 1988, sec. 4.3.2, p. 81-85; sec. 6.4, p. 140-145). In this, it must be realized that most high-class observations are made nowadays with CCDs. CCDs are discussed in detail in sec. 14.5.2. The main sources of noise in a CDD image are:
(1) The noise of the signal itself;
(2) The noise of the sky background;
(3) The detector readout noise.
Sources (1) and (2) are statistical noise sources, that follow, like as all shot-noise phenomena, Poisson-distribution. Noise must be squared before adding, so the signal-to-noise ratio (S/N) is:

$$\frac{S}{N} = S_{obj}\left(N_{2\ obj} + N_{2\ sky} + N_{2\ read}\right)^2 \qquad [14.2.13]$$

with S_{obj}: the total signal from the object being observed, and N_{obj}, N_{sky} and N_{read}) the three kinds of noise (after Tritton, 1997, equation 1).

Because the noise is poissonian, it follows that ($N_{2\ obj} = S_{obj}$ for an image spread over n pixels of the CCD, and $N_{2\ sky} = n\ S_{sky}$ where S_{sky} is the signal per pixel from the total sky background, both natural and artificial. Thus S/N can be written as:

$$\frac{S}{N} = S_{obj}\left(S_{obj} + n\left\{S_{sky} + r^2\right\}\right)^{-0,5} \qquad [14.2.14]$$

where r is the root-mean-square of the pixel noise (after Tritton, 1997, equation 2).

Based on these considerations, the relation between the exposure time needed for making an image, and the magnitude of the object, can be given for different values of the sky background. For a S/N value of 4, this is depicted in Figure 14.2.2.

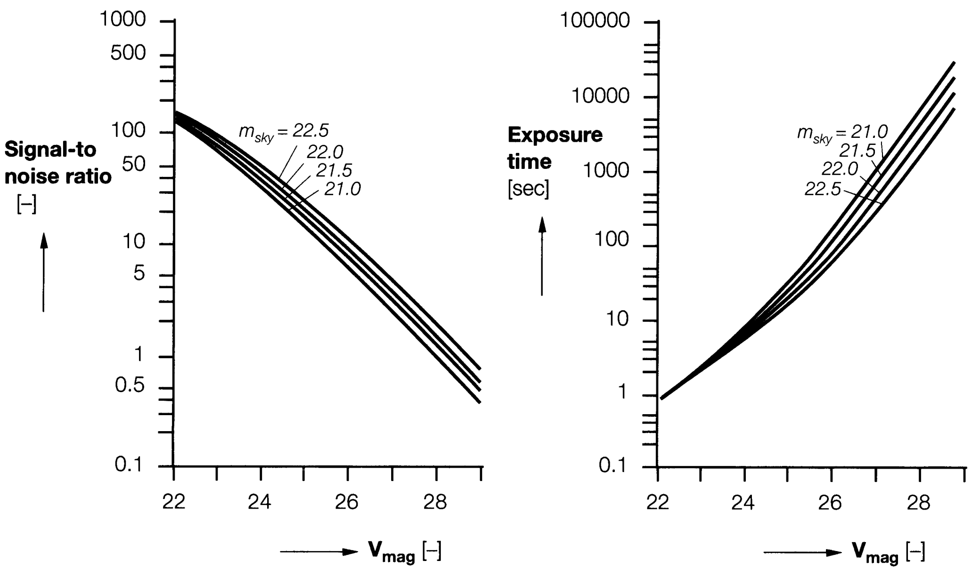

Figure 14.2.2: *The exposure time needed for four values of he sky background. From top to bottom: m_{sky} = 21,0; 21,5; 22,0 and 22,5. As is custom in astronomy, m_{sky} is expressed in mag per square arcsec. After Tritton, 1997, figure 2b.*

These considerations lead to the following conclusions (Schwarz, 2003). The mirror diameter r should be increased by the square root. Since, as is explained in sec. 1.2.5d, the price of a telescope is approximately proportional to $r^{2,8}$, doubling the sky luminance increases the cost of a telescope by a factor of 2,6 or so (Schwarz, 2003). Murdin (1997) used a slightly different rule-of-thumb: the costs of a telescope increase with the third power of the lens or mirror diameter – that is, with the volume of the dome. Anyway, artificial sky glow reduces the effectivity of telescopes.

There is another way to represent the influence of stray light on astronomical observations. As is mentioned in secs. 1.2.6 and 3.3.2, the loss of effective aperture is given in relation to the level of sky glow. "A small portion of the sky surrounding the target is always included in the measurement, and it must be removed from the data. This is done by measuring an adjacent region of blank sky. By subtracting the blank sky data from the data in the first measurement, astronomers are left with a relatively 'clean' measurement of the target object" (Crawford, 1992, p. 40, table 2.1). As a consequence, according to Crawford (1992), artificial sky glow reduces the effectivity of telescopes. What is indicated here is in fact a simple mention of the S/N-considerations that were given earlier. In Table 3.2.2, the loss of effective aperture is given in relation to the level of (artificial, urban) sky glow. If the sky luminance as a result of artificial light is 10% of the natural background luminance, the relative effective aperture of the telescope would decrease by 12%. A sky glow of 10% corresponds to the value that is proposed by IAU as the maximum permissible sky glow. Sky glow values that are 0,2 or 0,5 times the natural background are quite common in less favourable locations of observatories. According to Table 3.2.2, this would result in a decrease of the relative effective aperture of the telescope of 22% and 42% respectively. Using the exponent of 2,8 (Schwarz, 2003), the relative costs would be 1,52; 1,75 and 2,69 respectively of the 'ideal' location, with a sky glow equal to zero. Table 3.2.2 is reproduced here again as Table 14.2.2.

Relative sky glow (%)	Relative effective aperture (%)	Example (m)
100	100	4,0
110	88	3,81
120	78	3,65
150	58	3,27
200	39	2,83
300	23	2,31
500	11	1,79

Table 14.2.2: *Relative effective aperture in relation to relative level of sky glow. See Table 3.2.2. After Crawford, 1992, table 2.1.*

(f) Radiometry; spectral distributions

As is explained earlier in this section, radiometry is the measurement of electromagnetic radiation. We expressed that in counting photons. When counting photons, there are two fundamental aspects to be taken into account:

(1) The spectral characteristics of the photons;
(2) The spectral characteristics of the detector.

Not all photons are alike. They carry a certain amount of energy expressed as $E = h \cdot \nu$, where h is the Planck-constant and ν the frequency of the radiation. The energy per photon increases with increasing frequency, or with decreasing wavelength. The total energy that is emitted by a source depends, therefore, on the abundance of photons of different frequency, or, in other words, on the spectral characteristics of the emission of the source. As regards the detectors, most detectors are not equally sensitive to photons of different frequency; they have a certain response characteristic. It should be added, that usually not the energy is measured, but rather the energy in a time interval, or the power as it is usually called in physics. Power is expressed in Watts.

It follows that, if we want to know the power, that is received by a specific measuring device from a specific source, we need to know the spectral characteristics of the source and of the detector. Both can be expressed in terms of a function of the frequency – or of the wavelength, as is more usual to do. The total power is found by integration of the two functions in the following way:

$$W = \int_0^\infty S\lambda \cdot D\lambda \cdot d\lambda \qquad [14.2.15]$$

with:

S (λ): the spectral characteristics of the source in the interval between (λ) and (λ + dλ);
D (λ): the spectral characteristics of the detector in the interval between (λ) and (λ + dλ).

As is explained in sec. 14.1.2a, the ISO-Standard has defined all photometric units and quantities on the basis of V_λ-curve. This curve represents the spectral response curve for photopic vision in humans. All photometry that is used in engineering is based on the ISO-Standard, so in engineering, D (λ) from [14.2.15] is fixed. As a matter of fact, the integral from zero to infinity of D (λ) · dλ is, as is explained in sec. 14.1.2a, the photometric radiation equivalent, measuring 683 lm/W, as described by Schreuder (1998, sec. 5.2.1, p. 46) and Hentschel (1994, p. 38).

In engineering, the spectral characteristics of light sources can differ very much. On the one hand, many light sources, like e.g. the widely-used low-pressure sodium lamps, have a spectrum that is very close to a monochromatic spectrum. This means that all light energy is emitted in one spectral line only, or, in the case of the low-pressure sodium lamps, on two very close and very narrow spectral bands. On the other hand, blackbody radiators are very common as well, characterized by a very smooth spectrum. In between lay most lamps that are used in the practice of illuminating engineering. Almost all spectral types may be found in the incandescent lamps, the fluorescent lamps, the gas discharge lamps, and the LEDs, that are discussed in great detail in sec. 11.3.

Contrary to this, astronomers use a wide variety of detectors. They range, on the one hand, from bolometers that collect all incident electromagnetic radiation, to, on the other hand, spectroscopes that are sensitive to one very narrow spectral line only. In sec. 14.5.1, the different detectors that are used in astronomy, are described. So, the term S (λ) · D (λ) from [14.2.15] must in al cases be considered very carefully. As regards the sources, however, almost all celestial bodies show a spectrum that is at least similar to the blackbody radiation. As an example, the spectrum of the Sun can be compared to that of a 5770 K blackbody (After Budding, 1993, Figure 3.3, p. 36). The two curves almost coincide. In many cases, it is sufficient to consider only the blackbody radiation, that can be measured with a bolometer, and apply a correction for the actual spectral composition (the colour) of the source.

It should be stressed, that there are many reasons for astronomers to want to know the precise spectrum of light source itself; we will mention only two.

(1) The precise spectrum, and more in particular the many Fraunhofer spectral lines as well as their relative conspicuity, give important information about the chemical composition of the source;

(2) The way that specific spectral lines in the spectrum of the source are shifted in relation to the same lines measured at the Earth, gives important information about the speed of the source in relation to the Earth. When the shift is toward the red end of the spectrum, the source is moving away. This is the well-known Doppler effect. The red shift is a measure of the radial speed. Because there is a relation between the speed and the distance – the Hubble-relation, the red shift also gives information about the distance of the source. In its turn, because the speed of light is limited, sources at a large distance from the Earth can provide information about earlier states of the Universe. In the view of cosmologists, the importance of this information warrants the highest possible precision of the spectral measurements. Accurate, modern measurements suggest that the expansion of the Universe is accelerating, and not decelerating as previously assumed. This has profound consequences on the ideas about the fundamental forces in the Universe: one might be forced to assume the existence of an anti-gravity force, counteracting the traditional gravity force (Smith, 2003).

(g) Multi-colour photometry

In spite of the fact that, as is mentioned in an earlier part of this section, the spectrum of most celestial bodies is similar to the blackbody radiation, for specific studies, the spectral distribution of the source must be known. The spectral distribution can be measured directly by a spectro-photometer. For astronomical purposes, self-registering, automatic spectro-photometers are available. Their use is limited to sources that show a clear spectrum. Often it is sufficiently accurate to take pictures of the source with different coloured filters, with precise, well-established, spectral transmissions. The photometric data for these different pictures are compared. Most common is the UBV-photometry, where wideband filters are used that transmit ultraviolet, blue and visible spectral regions (Herrmann, 1993, p. 33). This is called 'multi-colour photometry' (Sterken & Manfroid, 1992, p. 52). Other terms in common use are heterochromatic photometry or wide-band photometry (Sterken & Manfroid, 1992, p. 124). A more recent variation of the UBV-system is the uvby-system, where ultraviolet, violet, blue and yellow spectral regions are used (Sterken & Manfroid, 1992, p. 60). The transmission curves of filters that are used in this system are depicted in Figure 14.2.3.

Heterochromatic photometry is, of course, an approximation. In principle, monochromatic photometry or narrow-band photometry would yield much more accurate data (Sterken & Manfroid, 1992, p. 124). If the related mathematical equations could be solved, one could obtain the monochromatic magnitude at one wavelength λ. "However, this is impossible unless a dense sampling of the spectrum is realised, which is not the case for any of the existing photometric systems. Consequently, in practice there is no alternative to using empirical relations, involving colour indices over wide spectral ranges" (Sterken & Manfroid, 1992, Sec. 8.3. p. 125).

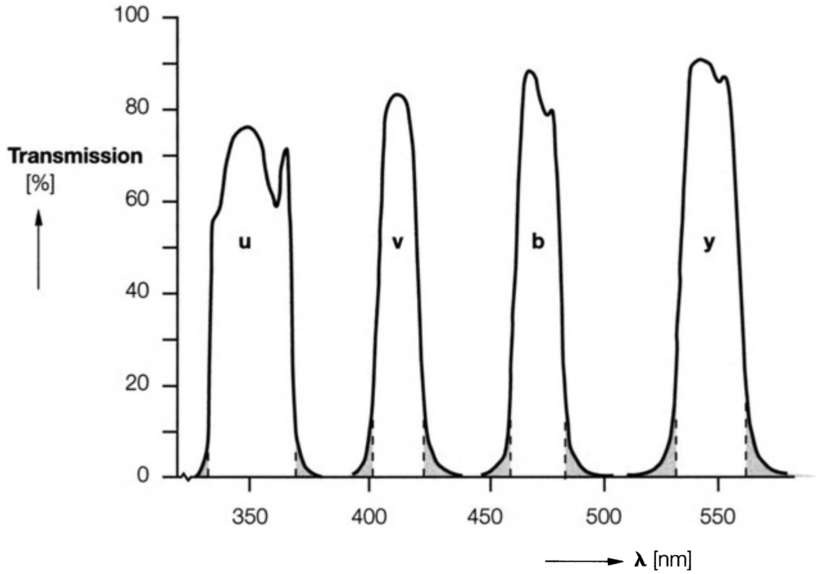

Figure 14.2.3: *Transmission curves of filters of the uvby-system. After Sterken & Manfroid, 1992, Figure 3.6. Shaded areas are cut off.*

Often, heterochromatic photometric systems are called 'standard photometric systems' (Crawford, 1997). Such systems are, as mentioned earlier, characterized by a specific set of filters, labelled by central wavelength and bandwidth, and a specific detector, like e.g. the eye, photomultipliers, or CCDs, and a set of standard stars that set the zero point and scale of the magnitudes and colour indices. Such standard systems are necessary, so that different observers can compare their results. "Typical accuracy in modern photometry is better than 0,01 mag" (Crawford, 1997).

(h) Photometric systems used in astronomy.

The following discourse is based in part on Schwarz (2003) and in part on Sterken & Manfroid (1992, Chapter 16). Contrary to engineering photometrists, who, as is explained earlier, use only one detector, the photopic human eye, astronomers are really radiometrists and consider a much wider wavelength range. Magnitudes are based on the human eye response which can be, to a fair degree, be considered as being logarithmic. As is explained in sec. 14.2.2a, $\delta(m) = m_1 - m_2 = -2.5 \log(B_1/B_2)$ relates magnitude differences to brightness ratios (After Schwarz, 2003, who uses the terminology that is usual in astronomy).

As is explained earlier, scientific astrophysics use objective photometry, because visual photometry has severe drawbacks. Absolute photometric measurements of celestial bodies is also very difficult. As is explained earlier, astronomical photometry would need to give a complete spectrum of any celestial body, because neither the source nor the detector are fixed beforehand. We mentioned earlier, that most celestial bodies have a spectrum that is 'similar' to a blackbody, but for precise photometry that is not accurate enough. "Formally, a photometer system would be precisely described if the function s_λ that is used in equation [1.16] is known" (Sterken & Manfroid (1992, p. 229).

The difficulty of absolute photometry may be inferred from the fact that Sterken and Manfroid devote only a small section – the very last one in their book – to this subject (Sterken & Manfroid, 1992, sec., 16.5, p. 245-247). An uncertainty level of about 10% is to be expected. "However, several calibrations of the energy distribution of α Lyrae, published since 1960, have shown a range amounting to 0,1 magnitude (Sterken & Manfroid, 1992, p. 247, referring to Hayes, 1970, and Hayes et al., 1975). It is a pretty large discrepancy for a case that seems to be quoted as an example of accurate measurements.

It is stated that: "The system would then be defined in terms of a specific receiver attached to a unique telescope" (Sterken & Manfroid, 1992, p. 229). In general, this is not true, of course. If the function s_λ is known, it would be independent of instrumental peculiarities. In practice that seems not to be possible, because small changes in s_λ are always to be expected. On practical grounds, and not on theoretical considerations, it is concluded: "Therefore, any photometric system is being defined in terms of a system of magnitudes of selected 'standard' stars" (Sterken & Manfroid, 1992, p. 229). Magnitudes are expressed for standard astronomical filters, and are calibrated against standard stars, using detailed atmospheric models for stars. Standard stars are objects selected to have a low probability to be variable, are observed many times and have at some point or points been calibrated absolutely. Calibrating an astronomical source absolutely is done by comparing to a secondary standard. Such secondary standards are laboratory blackbody sources that, in turn, have been calibrated against one of the few absolutely known blackbody sources in the national reference laboratories, like those in the UK or on the USA. In this way, the star spectrum is calibrated on an absolute scale. These are primary standards, from which secondary standards are derived, of which there are many in the sky (Schwarz, 2003).

A number of problems will be immediately clear. There are a fair number of steps involved in the calibration process, each step introducing its own set of systematic and stochastic errors. The final standard should be, of course, the ISO-Standard. As is explained in sec. 14.1.2, ISO abandoned the system of physically present standard lamps in laboratories, and replaced it by the candela as the basic concept for photometry. The candela is defined in such a way, that it can be reproduced with absolute precision at any place and at any time, being based on fundamental laws and relations of physics only. As is mentioned in sec. 14.1.2a, the candela is defined as: "The luminous intensity of a light source in a specified direction, that emits a monochromatic radiation with a frequency of $540 \cdot 10^{12}$ Hz, with a radiation intensity of (1/683) W/sr" (Hentschel, 1994, p. 36-37, based on CGPM, 1979).

There is another problem. ISO has defined the candela – and with it, the complete set of photometric concepts and units – on monochromatic radiation, and not any more on a well-defined blackbody. It may be added that the collection of incandescent lamps in the vaults of the US National Bureau of Standards, that were used, in the old days, as 'the' standard of the candela, are no blackbodies at all, but pieces of heated tungsten. Hot tungsten hardly resembles a blackbody radiator.

Also, we mentioned earlier, that most celestial bodies have a spectrum that is 'similar' to a blackbody, but that this is not accurate enough for precise photometry. Without discussing this complicated subject in depth, we will quote one remark only: "For narrow bands in the order of one wavelength unit or less, the amount of star light would be so small, that it would be impossible to secure enough measurements to build a standard photometric system. Strictly monochromatic magnitudes would be strongly affected by even weak absorption or emission lines in the specified wavelength range" (Sterken & Manfroid, 1992, p. 234). One may assume that 'one wavelength unit' means in effect 'one nm'.

Not only the 'standard stars' need to be selected carefully; it is also necessary to take the detailed atmospheric models for stars into account. These are used to model the spectrum of the star using a model for its atmosphere, using many hundred-thousands of spectral lines, as well as appropriate scattering and absorption mechanisms. These spectra can then be convolved with know profiles of the filters and instrument to predict what the photometry would look like. It is stated that one of the best models is the 'Uppsala code', and another much used code is the 'Kurucs model'. Because of their specialized nature, we will not discuss here what these codes are, nor what they mean. A good example of excellent standard star systems is the Walraven photometric system. It is known to perform typically to a few millimagnitudes (= 0.002-0.004 in relative errors), which is better than all other systems (Schwarz, 1993). We just mention these models, but we will not discuss this complicated matter.

The ideal of absolute photometry is thus abandoned, and with that the possibility to define and measure photometric characteristics of celestial bodies independent on their nature – stars, nebulae etc. – as well as independent of the peculiarities of the measuring equipment, including the human observer. As the practice of many decades of astrophysical research show, this does not seem to offer major problems. There are conversions from flux measures to magnitudes in all photometric systems that are used in practice.

There are many photometric systems in use in astronomy. The most common are discussed in detail in Sterken & Manfroid (1992, sec. 16.4, p. 234-245). The best-known systems that are used in practice, all suffer problems at the 1% level. This is often considered as being inherent in astronomical measurements. "Basically everything varies all the time and on all time scales and amplitudes you care to think of" (Schwarz, 2003). This statement makes one wonder about the tenacity, the skill, the patience – and the funds – of astronomers that allow them to come up with all the wonderful knowledge about the Universe, in spite of these setbacks.

As mentioned earlier, there is a great number of 'standard photometric systems'. Apart from the visual and photographic systems, that seem to be somewhat outdated for large, professional observatories, 8 different photo-electric systems are listed by Sterken & Manfroid (1992, sec. 16.4). There seem to be many more. "Photo-electric photometry yielded tens of different systems" (Sterken & Manfroid, 1992, p. 234, quoting Lamla, 1965, 1982).

In sec. 14.2.3g, the UBV-system is briefly mentioned, as well as the uvby-system. (Sterken & Manfroid, 1992, p. 60). The transmission curves of the filters that are used in this system are depicted as well. One of the best systems seems to be the Walraven system. As mentioned earlier, it is accurate to a few millimagnitudes, corresponding to 0,002 to 0,004 in relative errors, which is better than all other systems (Schwarz, 2003). It contains five spectral bands: VBLUW. The central wavelength and the bandwith of the filters are given in Table 14.2.3

Band	λ_0 (nm)	$\delta\lambda$ (nm)
V	547	72
B	432	45
L	384	23
U	363	24
W	325	14

Table 14.2.3: *Characteristics of the Walraven VBLUW system. After Sterken & Manfroid, 1992, Table 16.4.*

The Walraven system is described briefly in Sterken & Manfroid (1992, p. 241). Reference is made to Walraven & Walraven, 1960, as well as, for the filters, to Lub & Pel (1977).

The description given by Sterken and Manfroid points to the weak aspects of these highly specialised systems. "There exists only one 'Walraven photometer'. It was first attached to the Dutch 90 cm light collector in South Africa, and later at the same telescope, relocated at ESO La Silla, Chile" (Sterken & Manfroid, 1992, p. 241). Clearly, this system does not comply with the requirements for a 'standard system' as put up by Crawford: "Standard systems are necessary, so that different observers can compare their results" (Crawford, 1997).

Finally, for all earth-bound observations, the Earth atmosphere must be taken into account.

14.3 Relation between photometry in engineering and in astronomy

14.3.1 Radiometry and photometry

It is mentioned earlier that there are differences in the way photometry is applied in the fields of illuminating engineering, and astronomy. Some people even speak of 'two photometries'. This is a somewhat misleading figure of speech, because the two systems are essentially the same. In practice, the nomenclature is different. We will quote a part of a paragraph from Sterken and Manfroid, to explain what we mean. "Photometry is beset with numerous problems of nomenclature. The notations used by photometrists and physicists are in agreement. However, when it comes to engineering (in applications such as radiative transfer in industrial furnaces and solar energy) and astrophysics (radiative transfer in stellar or planetary atmospheres and in nebulae), the usage is often different. The main disagreement relates to what engineers and astrophysicists call the intensity, which is equivalent to the concept of radiance of radiometrists" (Sterken & Manfroid, 1992, p. 10). It might be mentioned here, just as is done in Chapter 9 of this book, that not only the differences in nomenclature, but also in the underlying mathematics, prompted Moon and Spencer to introduce a completely new set of photometric units and quantities, that is consequently based on the concepts of radiometry (Moon, 1961; Moon & Spencer, 1981).

The confusion becomes even greater when engineers and astrophysicists talk about 'light'. However, irrespective of the way it is applied, photometry is a special case of the more general radiometry. This is explained in sec 14.2.3f, while using the equation [14.2.15], that may be regarded as the basic equation of radiometry. Because of its importance, we will give the equation here again. It determines the power, that is received by a specific measuring device from a specific source:

$$W = \int_0^\infty S\lambda \cdot D\lambda \cdot d\lambda \qquad [14.2.15]$$

with:

S (λ): the spectral characteristics of the source in the interval between (λ) and (λ + dλ);

D (λ): the spectral characteristics of the detector in the interval between (λ) and (λ + dλ).

There is more to it. A major distinction between the fields of application of illuminating engineering and astrophysics is that the first consistently use only one detector type, the photopic human eye, that is completely characterized by the V_λ-curve. The sources of radiations, at the other and, show enormous variations, so that, apart from calibration purposes, precise spectral distributions are normally not required. Usually, it is sufficient to indicate the class of light source, like e.g. low-pressure sodium lamps, or fluorescent tubes with a specific colour designation. It should be mentioned that, as is explained in sec. 8.2.2, the spectral differences of lamp types can have a critical influence on the perceived brightness, when another spectral sensitivity curve is used, instead of the photopic V_λ-curve.

Astronomers use a wide variety of detectors. They are not only interested in the visual region of the electromagnetic spectrum. Many measurements are made in the ultraviolet or the infrared. In fact, the desire to do observations in all other region of the electromagnetic spectrum, like the short-wave ultraviolet, or the Röntgen radiations, was the main motive to launch space observatories. At the other hand, most sources have a spectrum that is 'similar' to the blackbody radiation. Small deviations from the blackbody spectrum are often very important, much more so than in illuminating engineering. Therefore, spectroscopy is a major branch of observational astrophysics. The implication is, that astrophysics use two parallel sets of radiometric – or photometric – quantities and units, a wide-band one for the continuous spectrum, and a monochromatic one for the narrow-band, or line, spectrum.

A comparison of the different quantities that are used in photometry and astrophysics is given in Table 14.3.2, compared to the quantities that are used in radiometry. It should be added that the photometric nomenclature as is used in engineering as well as the photometric nomenclature as is used in radiometry agree with the ISO-Standards, and so do the corresponding units.

Photometry	**Radiometry**	**Astrophysics**
luminous flux	radiant flux	luminosity
	spectral radiant flux	monochromatic luminosity
luminous intensity	radiant intensity	
	spectral radiant intensity	
illuminance	irradiance	flux
	spectral irradiance	monochromatic flux
luminance	radiance	intensity
	spectral radiance	specific intensity

Table 14.3.2: *Nomenclature in photometry, radiometry and astrophysics. Based on Sterken & Manfroid, 1992, Table 1.1.*

14.3.2 Photometric units used in astronomy

The units that are commonly used in astronomy are given in the following survey, that is in part based on Garstang (2001, 2002).

(1) The energy carried by 1 lumen, entering and stimulating the eye is 0,001 477 W in photopic vision and 0,000 583 W in scotopic vision;

(2) One lumen corresponds to $4{,}13 \cdot 10^{15}$ photons per second (for '555 nm-photons'). The indication '555 nm-photons' means, of course, photons that correspond to a wavelength of 555 nm;

(3) Surface brightness is expressed in luminance and measured in $\mathrm{cd} \cdot \mathrm{m}^{-2}$. Strangely enough, there is no name for this. Some persons tried to introduce the 'nit', but the

idea was abandoned when it was realised what that word means in common English. One may, however, find the term still in some older, publications that stem from non-English authors (e.g. De Boer, ed., 1967, Appendix II). For high values, the Stilb is sometimes used, measured in $cd \cdot cm^{-2}$. Although it is a non-ISO unit, we mention the Lambert (L), because it is still often used by some astronomers, particularly in North America. A Lambert is equivalent to $1/\pi$ Stilb. It should be noted that the solid angle is included in the unit; hence the factor π. For low values, the nL (or 10^{-9} L) is used. It follows that 1 nL = $3{,}18 \cdot 10^{-6}$ cd/m^2 (Crawford, 1997). Also, one nL corresponds to $1{,}31 \cdot 10^6$ photons per cm^2 per second per steradian (for 555 nm-photons);

(4) Wavelength bands are used for photometric measurements in astronomy. As is mentioned in sec. 14.2.3g, the most common system uses two bands, B (blue) and V (visual), apart from other bands in the UV- and IR-regions. The V-band is used as an approximation of the spectral sensitivity curve of the photopic human visual system. The mean wavelength is about 550 nm and its equivalent bandwidth is about 89 nm. The mean is very close to the maximum of the V_λ-curve, but the bandwidth is much narrower than the visual curve. Thus, the approximation of the V-band for the spectral sensitivity curve of the photopic human visual system is not very good. The B-band is used as an approximation of the spectral sensitivity curve of the blue-sensitive photographic plates that were widely used in the past, before CCDs became available. For the V-band, it is found that:
   - 1 lumen = $3{,}22 \cdot 10^{15}$ photons per second (for 550 nm-photons);
   - 1 nL = $3{,}18 \cdot 10^{-6}$ cd/m^2 = $1{,}09 \cdot 10^6$ photons per square cm per second per steradian (550 nm-photons);

(5) Astronomers measure the 'brightness' of stars in magnitudes. The magnitude-scale is essentially an interval scale, that, being a logarithmic scale, has no zero point, because the logarithm of zero can only be described as minus infinity (sec. 9.2.3c). It is explained in sec. 14.2.2a, that this interval scale is transformed into a metric scale by taking a sample of stars – dubbed 'standard stars – to which the arbitrary number of 'zero magnitude' is allotted. To the magnitude, the band in which the measurements are made, must be specified. A zero magnitude star is often designated as a '1 V = 0' star, or a 'mV = 0' star.

14.3.3 Magnitude loss as a result of outdoor lighting

The following discourse is based in part on Soardo et al., 2001 and on Soardo 2001. It may be noted that Soardo et al., 2001, is a newer version of Felin et al., 2000. Because no further data are available on these reports, one may assume that both are still drafts.

The total luminous flux emitted by the luminaires of a complete outdoor lighting installation is Φ_L. From this, the fraction Φ_U is send upwards. One may define the 'Ratio of upward emission' Rn of the whole installation as:

$$R_n = \frac{\Phi_U}{\Phi_L} \qquad [14.3.2]$$

In sec. 14.2.2d, the 'sky glow formula' is introduced:

$$m = -2.5 \log(a+1) \qquad [14.2.9]$$

with m the increase in the threshold, or the decrease in the limiting magnitude as a result of the veiling luminance. The factor a follows from $L_v = a \cdot L_b$, where L_v is the veiling luminance as a result of the sky glow, and L_b is the background luminance.

Using the sky glow formula as a starting point, one may state:

$$\delta m_s = -2{,}5 \log\left(1+\frac{\Phi_U}{\Phi_L}\right) \qquad [14.3.3]$$

where δm_s is the contribution to the drop of threshold magnitude, due solely to the upward (spill) light from the luminaires. This relation is quoted from Soardo et al., 2001, equation (10).

One may assume that the surface of the Earth reflects the light from outdoor lighting installations as a perfect diffuser, in spite of the fact that this assumption is not valid universally. Using R_n that is introduced earlier in this section, and with the diffuse reflection factor of the surface equal to ρ, the equation [14.3.3] can be written as:

$$\delta m_s = -2{,}5 \log\left(1+\frac{R_n}{\rho(1-R_n)}\right) \qquad [14.3.4]$$

The derivation is given in Soardo et al., 2002. equation (13).
The results are depicted in Figure 14.3.1. for different values of ρ.

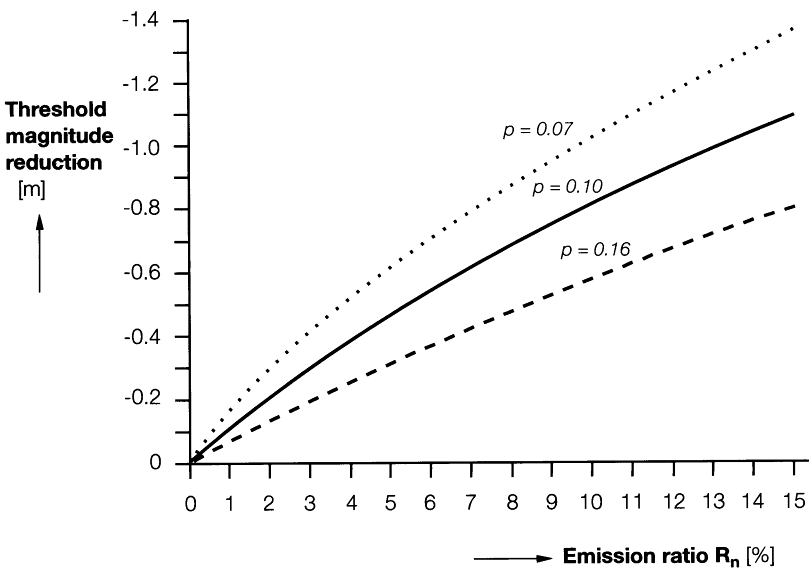

Figure 14.3.1: *Reduction of threshold magnitude (δm) versus upward emission ratio (R_n). After Soardo et al., 2001, Figure 1.*

14.3.4 Conversion of astrophysical and engineering units

Based on the correspondence between the astronomical and the lighting engineering photometry, the luminance values for different degrees of sky glow that are equivalent to specific values of the natural background radiation can be assessed. See Table 7.3.2.

The units that have been described in earlier parts of this section, allow the conversion from astrophysical units into engineering units, and vice-versa. This is explained in the following survey, that also is based, in part, on Garstang (2001, 2002) and on Crawford (1997).

- One may express the brightness of stars in the illuminance they give at the surface of the Earth, or rather 'outside the atmosphere', because, usually, one does not take the atmosphere into account. A star with a visual magnitude of 0 (1 V = 0 star) gives, outside the atmosphere, an illuminance of $2{,}54 \cdot 10^{-6}$ lux. for i lux, one would need 394 000 'mV = 0' stars;
- The luminance of an area of one square degree with one V = 0 star in it, would be 2,63; $\cdot\ 10^{-6}$ Lambert, or 2630 nL, or $8{,}36^{-3}$ cd/m^2;
- The sky luminance can also be expressed in a somewhat strange unit: the number of stars of mV= 10 per square degree, written as 'S10' (Cinzano, 1997, sec 3.1.5, p. 112-113). When the stars are measured in the V-band, this is written as 'S10V'. As an example, the sky brightness of 300 S10V equals $2{,}1 \cdot 10^{-4}$ cd/m^2;
- For the B region, the following equivalence is given: One star of magnitude 1 in the B-region is equivalent to $1{,}88 \cdot 10^9$ photons per sec. per square cm per steradian (Garstang, 2001, 2002).

14.3.5 A general formula for the conversion

It is proposed to use as a general formulation of the conversion:

$$L = 1{,}085 \cdot 10^5 \cdot 10^{-0{,}92102\,V} \qquad [14.3.5]$$

where V is the visual magnitude per square arcsec.

This formula is based on equation (27) of Garstang (1989). In that formula, b is used instead of L for the luminance. It is converted into ISO measures by Garstang (2000) while using 1 cd/m^2 = $\pi \cdot 10^5$ nL, as given earlier in this section.

In one puts V = 26,33 the answer is b = $3{,}187 \cdot 10^{-6}$ cd/m^2, within 1% of the value that is introduced in CIE (1997), where the following conversion was proposed: "A luminance of $3{,}2 \cdot 10^{-6}$ cd/m^2 corresponds to 26,33 magnitude per arcsec^2" (CIE, 1997, after Crawford, 1997, Table III). No wonder, because Crawford refers to the work of Garstang.

14.3.6 Conversion tables

(a) Photometric equivalents

In sec. 14.1.2b, it is explained that the ISO-Standards for photometry are based on the candela (cd). Other units standardized by ISO are the metre (m) and the steradian (sr). All photometric units and quantities are based on these fundamental concepts. In the past, many other photometric units and quantities have been used; furthermore, many other definitions were used for the same unit. So is the candela defined as a specific type of gas burner, as a set of incandescent lamps, or as an attribute to a blackbody radiator at a specified temperature. More recently, in a number of English speaking countries, a rather different set of photometric units and quantities were used. These were based on the fundamental concepts that were designated as Imperial or as English. In the USA, this photometric system is still used on a large scale, whereas most other English speaking countries like e.g. Canada, Australia, the UK, did, at least for scientific activities, change over to the ISO (or SI, or metric) system. Because, as is made clear in many parts of this book, the 'English' system of photometry still abounds, a set of conversions is given in this section. Because the main differences are in the measures for illuminance and for luminance, these will be shown here. When relevant, differences in nomenclature will be added. In another part of this section, a similar set of conversions is given for the photometric units and quantities that are in use in radiometry, in engineering, and in astrophysics. For the sake of completeness, a few of these conversions are repeated here.

One candela per square foot – or foot-candle –	equals 10,75 cd/m^2
One candela per square inch	equals 1550 cd/m^2
One candela per square cm	equals 10 000 cd/m^2
One apostilb	equals 0,318 cd/m^2
One Lambert	equals 3183 cd/m^2
One foot-Lambert	equals 3,43 cd/m^2

Table 14.3.3: *Conversion of non-ISO units of illuminance and of luminance to the ISO-unit of luminance. Based on De Boer, ed., 1967, Appendix II, p. 688. It should be added that the foot-candle is abbreviated to f-c, and the foot-Lambert to fL (Stevens, 1969, p. 34; 36).*

One:	Equals:
nit	1 cd/m^2
Stilb	1 cd/cm^2
millilambert (mL)	10^{-3} Lambert
nano-lambert (nL)	10^{-9} Lambert
footlambert (fL)	1 equivalent footcandle
lux	1 lumen/m^2
footcandle	1 lumen per square foot

Table 14.3.4: *Nomenclature of units of luminance and illuminance. Based on De Boer, ed., 1967, Appendix II, p. 688.*

(b) Sky luminance

In section 14.3.5, a general formula has been introduced for the conversion of ISO- and non-ISO-luminance values. See [14.3.5]. Although this relation can be assessed using a hand calculator, a tabulated form may be convenient for other purposes. See Table 14.3.5. The limiting magnitude for observation with the unaided eye is added. This relation is used in the Recommendations that recently have been issued in the Netherlands (Schmidt, 2002; NSVV, 2003, 2003a,b).

L (10^{-6} cd/m^2)	**bV** (magnitude per square arcsec)	**Limiting magnitude** (V-band)
190	21,9	5,4
320	21,3	5,1
800	20,3	4,7
1600	19,6	4,3
3200	18,8	4,0
8000	17,8	3,7
16 000	17,1	3,5
32 000	16,3	3,3

Table 14.3.5: *Sky luminance in 10^{-6} cd/m^2 and in magnitude per square arcsec, versus the limiting magnitude for observation with the unaided eye. After Garstang, 2001, Table 2.*

In Sec. 7.3.2, a table is given that contains the luminance values for different degrees of sky glow, expressed in the units that are common in astronomy and in lighting engineering respectively (magnitude per square arcsec, and cd/m^2). The table 7.3.2 is given here again as Table 14.3.6.

Magn arcsec$_2$	**Magn diff**	**Log (%)**	**r** (10^{-4} cd/m^2)	**Luminance**
21,6	0	0	0	3,52
21,5	0,1	0,04	10	3,88
21,4	0,2	0,08	20	4,23
21,1	0,5	0,2	60	5,64
20,7	0,9	0,36	120	7,79
20,6	1	0,4	150	8,81
20,1	1,5	0,6	300	14,1
19,6	2	0,8	530	22,2
18,6	3	1,2	1480	55,7
17,6	4	1,6	3880	140
16,6	5	2	9900	352

Table 14.3.7: *Luminance values compared to natural background for different degrees of sky glow. See also Table 7.3.2.*

(c) Number of visible stars

Also, it is often important to have an estimate of the number of stars that is visible by the unaided eye to a 'normal' observer, under circumstances of light pollution. This may give an indication of the severity of pollution. It is sometimes suggested to use the number of 'just visible stars' as a measure of the actual light pollution. This suggestion can be followed only when the observations are made by experienced observers. See Table 14.3.8a.

Limiting magnitude	Number of visible stars	
+7	about 7000	
+6	about 2500	
+5	about 800	
+4	under 400	(Milky Way not visible)
+3	under 50	
+2	under 25	

Table 14.3.8a: *Number of visible stars versus limiting star magnitude (Schmidt, 2002, Table 1; Mizon, 2002, p. 34).*

Limiting magnitude	Number of visible stars Year 2002 N. hemisphere?	 1872 N. hemisphere	 1944 whole world
+7	about 7000		
+6	about 2500	3974	4720
+5	about 800	854	1460
+4	under 400	313	445
+3	under 50	152	105
+2	under 25	48	39
+1		13	12

Table 14.3.8b: *Number of stars of different magnitude classes.*

Notes to table 14.3.8b:
2002: after Mizon, 2002, p. 34;
1872: after Kaiser, 1888, p. 25;
1944: after Thomas, 1944, p. 401.

Similar information can be derived from the number of stars of different magnitude that is present in the sky. As the precision to assess the magnitude varied over the years, this number also varies. As an example of data about stars of different magnitude, three sets of numbers are given from different periods and from different authors. See Table 14.3.8b. Although one may safely assume that neither the stars, nor the visual systems of people did change much in 150 years, the differences in the published numbers are striking. There does not seem to be any system in the deviations, so the obvious reason that different criteria for 'visible' were used, does not seem to apply here. We have included these data as a warning, not to rely too much on data about limiting magnitudes. A similar precaution may be extracted from the data of Schaefer (2003), that are discussed in sec. 14.6.2b.

(d) Well-known sources

In Table 14.3.9, an impression is given of the magnitudes that may be found for common sources. The source brightness is also expressed in the illuminance they provoke on the surface of the Earth. The atmospheric extinction is not taken into account.

Source	**Magnitude** (mV)	**Illuminance** (lux)
Sun	-26,7	$1{,}2 \cdot 10^{5}$
Full Moon	-12,7	$2{,}9 \cdot 10^{-1}$
Venus	-4,6	$1{,}6 \cdot 10^{-4}$
60 W lamp at 1 km	-3,6	$6{,}4 \cdot 10^{-5}$
Sirius	-1,5	$9 \cdot 10^{-6}$
Polaris	2,0	$4 \cdot 10^{-7}$
typical naked eye limit	6	$9 \cdot 10^{-9}$
typical binocular limit	9	$6 \cdot 10^{-10}$
brightest quasar	13,0	$2 \cdot 10^{-11}$
approx HST limit	28	$1 \cdot 10^{-17}$

Table 14.3.9: *Source brightness. After Crawford, 1997, Table 2. See also Hartmann, 2002.*

Note: HST stands for Hubble Space Telescope.

In Table 14.3.10, as an example, similar data are given for the luminance of a number of common objects.

(e) Magnitudes and ratios

As is explained in sec. 14.2.2a, the magnitude scale is not a linear one. The conversion of magnitude differences into luminous intensity ratios or illuminance rations can be done easily by means of a modern programmable hand calculator while using the fact that 5 magnitudes correspond to a factor of 100. Sometimes, however, tabulated values are more convenient. See Table 14.3.11.

Source luminance	cd/m^2	magnitude per square arcsec
surface of the Sun	$1{,}6 \cdot 10^9$	
surface full Moon	2500	
typical daytime sky	3000	
overcast daytime sky	300	
zenith at sunset	100	
typical sky in a big city	3	11,3
zenith at 'Civil Twilight'	0,3	
typical sky at full Moon	0,03	16,8
sky with 10 day Moon	$5 \cdot 10^{-3}$	18,5
zenith at 'Nautical Twilight'	$1 \cdot 10^{-3}$	20,2
horizon for a dark sky	$8 \cdot 10^{4}$	20,3
zenith average dark sky site	$6 \cdot 10^{-4}$	20,7
zenith good dark sky site	$4 \cdot 10^{-4}$	21,1
darkest sky ever observed	$2 \cdot 10^{-4}$	22,0

Table 14.3.10: *Luminance of common, well-known objects. Based on data from Crawford, 1997, Table 3.*

Notes to Table 14.3.10:
Civil Twilight: Sun less than 6 degrees under the horizon;
Nautical Twilight: Sun between 6 and 12 degrees under the horizon;
Astronomical Twilight: Sun between 12 and 18 degrees under the horizon (added for completeness' sake).

Magnitude difference	Ratio	Ratio rounded off
0		
0,1	1,096478	1,10
0,2	1,202264	1,20
0,3	1,318257	1,32
0,4	1,44544	1,45
0,5	1,584893	1,58
0,6	1,737801	1,74
0,7	1,905461	1,91
0,8	2,089296	2,1
0,9	2,290868	2,3
1	2,511886	2,5
1,1	2,754229	2,8
1,2	3,019952	3,0
1,3	3,311311	3,3
1,4	3,630781	3,6
1,5	3,981072	4,0
1,6	4,365158	4,4
1,7	4,786301	4,8
1,8	5,248075	5,2

Magnitude difference	Ratio	Ratio rounded off
1,9	5,754399	5,8
2	6,309573	6,3
2,1	6,91831	6,9
2,2	7,585776	7,6
2,3	8,317638	8,3
2,4	9,120108	9,1
2,5	10	10
2,6	10,96478	11
2,7	12,02264	12
2,8	13,18257	13
2,9	14,4544	14
3	15,84893	16
3,1	17,37801	17
3,2	19,05461	19
3,3	20,89296	21
3,4	22,90868	23
3,5	25,11886	25
3,6	27,54229	28
3,7	30,19952	30
3,8	33,11311	33
3,9	36,30781	36
4	39,81072	40
4,1	43,65158	44
4,2	47,86301	48
4,3	52,48075	52
4,4	57,54399	58
4,5	63,09573	63
4,6	69,1831	69
4,7	75,85776	76
4,8	83,17638	83
4,9	91,20108	91
5	100	100

Table 14.3.11: *The conversion of magnitude differences into luminous intensity ratios or illuminance ratios.*

14.4 Light pollution and light immission

The relation between spill light and light pollution is discussed in sec. 1.2.1. The function of all outdoor lighting is to enhance the visibility or of the aesthetics in their surroundings. The effectiveness of the lighting is the degree to which the function is fulfilled. Usually, one can define the area where the lighting is needed, rather precisely. It is explained in sec. 11.2.1, that 'good' lighting design ensures that the light comes where it is needed, and does not fall elsewhere. Light that ends up outside the area where the light is needed, or useful, is spilled. Spill light represents a loss as regards costs and electric energy (Schreuder, 1995, 2001). Light that is generated and disappears without having any use, is a waste (sec. 1.2.2).

But there is more. It has been pointed out many times in this book that spill light has considerable, and sometimes disastrous, negative effect on the environment. Spill light from outdoor lighting installations is usually a major cause of disturbance and discomfort for many persons, also for those that have nothing to do with the activities for which the lighting is installed. The light invades into the private sphere of people; it intrudes into the living space of people who do not have any interest in the lighting in the first place. This is 'intrusive light' or 'light trespass'.

Intrusive light has victims. In sec. 7.1.3, a 'victim matrix' is introduced. As is explained in that section, the two groups of victims that are the most vulnerable, are the residents and the astronomers. Residents suffer most when the light invades their private life, when it falls directly into the living space. As mentioned earlier, this is usually called 'intrusive light'. In many cases it relates to light falling into bedrooms, but also to light intruding into living rooms or private gardens. In sec. 7.2.1, limiting values are quoted for intrusive light, in order to reduce its impact, as well as suggestions how these limiting values can be reached.

Astronomers are restricted in their possibilities to make accurate observations. Astronomers include both the professionals and the amateurs, but also the much larger group of people who enjoy the darkness. The main concern of astronomers is the diffuse type of light pollution that arises from light emitted upwards and scattered in the atmosphere. This diffusely scattered light is called sky glow.

The main concern of this book is to discuss the negative effects of urban sky glow and the way these negative effects originate, and to suggest means to reduce these negative effects. In general, these effects are often called 'light pollution', although it will be clear that intrusive light is also a form of light pollution.

Intrusive light refers to light that shines directly into the living space of people, e.g. into their bedroom, living room or garden. Thus, its main cause is the light that comes directly from the light sources. The photometric characterization is, therefore, assessed in terms of illuminance or luminance (NSVV, 2002; CIE, 2003).

Sky glow refers to the light that is send upward by the lighting installation, and that is scattered back towards the surface of the Earth. The photometric characterization is assessed in terms of the luminance of the sky (CIE, 1997). Obviously, these two characterizations require quite different measuring methods. Also, there are differences in the measuring equipment. These different measuring methods and the relevant measuring equipment are discussed in further parts of this section. Measuring light pollution is in part based on Schreuder (1994a). See also sec. 14.5. This material is used for the preparation of CIE (1997). The measuring of light intrusion is discussed in sec. 14.6.

14.5 The measurement of light

14.5.1 Detectors

(a) *The eye*

In sec. 8.1, the function of the human visual system as a detector for astronomical photometric measurements is discussed in detail. The fundamental problem is, that all results of photometric measurements are expressed in ISO-Standards on the base of the photopic spectral sensitivity curve of the human visual system, whereas it is far from obvious that astronomical observations will be made by the photopic system. The only way to avoid this problem is to measure differences in light from sources that are very close in luminance, so that, even if the visual functions are not precisely known, at least one can be certain that the visual system reacts in the same way in the two luminance fields that are to be compared. This is the essence of all visual photometry. For many centuries, this was the only way to make photometric measurements.

The principle of all visual photometric systems is the same. The visual field is divided in two parts. One part is illuminated by the source that must be measured. The other part is illuminated by a standard light source, the lighting characteristics of which are exactly known. In most cases, the two parts will give a different visual impression. By changing the standard part by a calibrated way to reduce its illuminance – e.g. a gray wedge – so far that the two parts are of equal impression, the two light sources will be equal as well. It should be mentioned that in most cases, the two parts are side-by-side, but they also can be presented alternating in time. The flicker photometers, that are discussed in a further part of this section, are of this type.

Usually, the procedure is to arrange the two light sources in such a way that they will produce a certain luminance in the corresponding part of the field of view. What is originally to be measured can be different, e.g. illuminance, luminous intensity etc. The comparison will then be a comparison in brightness. When the brightnesses are almost equal, one may safely assume that the comparison is a comparison in luminance. In the past, a large number of very ingenious constructions have been introduced to arrive at two parts of the field of view that differed in luminance only. Some devices that were used for visual photometry, are described in Hentschel (1994, sec. 4.2); Barrows (1938, chapters 4 and 5) and in Hütte (1919).

Three major problems made visual photometry obsolete, as soon as trustworthy and accurate devices became available, with which instrumental photometry could be performed:

(1) Visual photometry requires a highly skilled photometrist to arrive at repeatable measurements;

(2) In almost all cases, the two light sources did differ in colour. The colour effect was very hard to compensate for;
(3) Standard light sources, that were stable in output and colour, and that were sufficiently bright for comparison purposes, did not exist at the time.

So, after several centuries of visual photometry, in the second half of the 20th century it was abolished and superseded by instrumental photometry. In almost all cases, this does imply the use of photo-electric devices. These devices will be discussed in the further parts of this section.

There is, of course, one area, where the visual photometry is indispensable, that is the assessment of the spectral sensitivity curve of the human visual system. All visual functions are related to the spectral sensitivity curve of the human visual system. In so far as daytime vision, or cone vision is used, the curve is the V_λ-curve, or the photopic curve. When nighttime vision, or cone vision is used, the curve is the V'_λ-curve, or the scotopic curve (sec. 8.2.2). As is mentioned in sec. 8.3.5, for mesopic vision, sometimes a family of mesopic curves is introduced. As is explained in detail in sec. 14.1.2, all ISO-photometry is based on the photopic V_λ-curve. So it is essential for all photometric measurements, as well as for all photometric definitions, to know exactly how the visual system reacts to light of different wavelength – of different colour. Obviously, this can be assessed only by means of visual photometry.

In most cases, a flicker photometer is used. As is mentioned earlier, such photometers have one field of view that is illuminated alternately by the two light sources. The principle of heterochromatic flicker photometry is, that the lowest frequency where the flicker is noticeable (the 'critical fusion frequency' or CFF) is lower for colour differences than for brightness differences (Hentschel, 1994, p. 69). This means that, when the two sources differ only slightly in colour, the colour difference is noticeable at a low frequency but not at a high frequency. In the intermediate range, the flicker is noticeable only for the brightness.

By using flicker photometry, the spectral sensitivity curve can be established by a step-by-step method. Sources that show large colour differences cannot be compared in this way. The problems are obvious:
(1) The measurements can be made only by a small number of highly trained photometrists. There is no guarantee that this small number can be regarded as a 'random sample' out of the whole population. Worse still, there is no means to establish this. It is just a matter of faith, that the group of people that was used to establish the CIE Standard Observer, that is supposed to represent humankind;
(2) There is no way to ascertain that the measurements are made in photopic vision. One may assume so, if the source brightnesses are very high, but, as is mentioned in earlier, this was not technically feasible in the 1920s, particularly at the blue end of the spectrum. There are serious reasons to believe that the blue spectral values are systematically too low (Schreuder, 1997, p. 43-44);

(3) The CFF depends seriously on the experimental conditions. Most striking is the difference in the V_λ-curve when it is measured with a field of 2 degrees diameter, or of 10 degrees diameter. As is explained in sec. 8.2.2, in the blue part of the spectrum, the difference in the spectral sensitivity can be as large as 30% at specific wavelengths. See Figure 8.2.6.

As a conclusion, it may be stated that the fundaments of photometry, because it is based on the V_λ-curve, is somewhat shaky – to say the least. Maybe this is part of the reason that many astronomers prefer for many studies, radiometric measurements over photometric measurements.

(b) Photographic emulsions; colour photography.

The first attempts for objective photometric measurements in astronomy were made by using photographic emulsions as a photon collector. The process of photography is well-known. A substrate, glass plates in the past, and some plastic film material more recently, is covered by a thin layer of light-sensitive material, usually silver halide. The emulsion is put on the substrate in the form of small grains. When a photon strikes a grain, one of the silver atoms is ionized. The grain is said to be activated.

After the plate or film is exposed, it is put in a bath containing a developer. The developing process consists in the transformation of the silver halide molecules into silver atoms. The essence of the process is, that not only the ionized atoms will be reduced to silver, but also all other silver halide molecules in that particular grain. The ionized silver acts as a 'germ cell' in the grain. In fact, the process can be described as an amplifier. The developing process acts only on the grains that contain silver ions – thus, the grains that were hit by photons. In the fixing process that follows, all remaining silver halide molecules are removed, so that only the grains of silver remain. The grains with silver atoms look black under these circumstances. So, the parts of the plate or film that was hit by photons are opaque and look black, whereas the rest is transparent. Obviously, this results in a black-and-white image in the negative. Aptly, a developed film is called a photographic negative.

There is another special feature in the photographic method on light measurement. Contrary to most photocells that measure power (Watts, that is), a photographic emulsion measures energy (Reeb, 1962, p. 166-167). This means that the effect does increase with increasing exposure time. The photometric concept of exposure is discussed in sec. 14.1.3a. The effect can be expressed in the number of ionized silver atoms, but also in the density of the film after development (Reeb, 1962, p. 167). The photographic purposes, the exposure is defined as:

$$H = E \cdot t \qquad [14.5.1]$$

in which:
H: the density after development;
E: the illuminance on the film;
t: the exposure time.

In photography, the density refers to the degree of opacity of a negative (Lafferty & Rowe, eds., 1994, p. 173).

The relation [14.5.1] is valid only over a limited range of exposure times. This is illustrated in principle in Figure 14.5.1, where in a schematic representation, the logarithm of the density is plotted against the logarithm of the exposure time. The relation [14.5.1] is valid only in the linear part of the log-log representation as given in Figure 14.5.1. A representation like this is called the characteristic curve of a photographic emulsion (Sterken & Manfroid, 1992, p. 214).

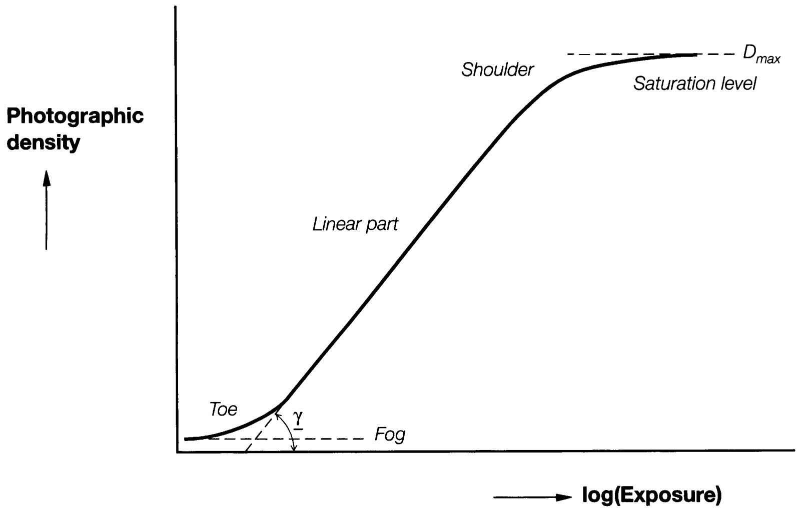

Figure 14.5.1: *The characteristic curve of a photographic emulsion. After Sterken & Manfroid, 1992, Figure 14.1.*

In spite of this, photography is not very efficient as a photon collector, because only about 10% of the incident photons is absorbed by the grains of the emulsion. Furthermore, a large number of photons must be absorbed by a grain for it to be activated. The 'grain-to-photon' ratio is only a few percent at the most (Sterken & Manfroid, 1992, p. 211).

A few remarks about using a photographic emulsion as a photometric tool, must be made:
(1) The storing capacity of a photographic plate is very large when compared to a CCD or other digital storing devices. The plates that are commonly used for sky surveys like the so-called Schmidt-plates are equivalent to about one Giga-pixel. "Giga-pixel CCDs are still far away" (Sterken & Manfroid, 1992, p. 212);
(2) All colour information is lost;
(3) The overall sensitivity of the plate or film depends on the size of the grains. The larger the grains, the greater the chance that they will be hit by photons. However, large

grains result in a coarse image. So, coarse-grained emulsions are sensitive but do not allow to make sharp images;

(4) Spectral response depends on the type of silver halide. In the early days, photographic emulsions were essentially blue-sensitive. Consequently, the early measurements, when compared to visual magnitude estimates, overestimated the magnitude of hot objects, that emit relatively much light at short wavelengths, and underestimated the magnitude of cool objects, that emit relatively much light at long wavelengths (Budding, 1993, p. 17-18). The 'blue' filter in the multi-colour photometry that is discussed in sec. 14.2.3, essentially represents the blue sensitive photographic emulsions. Later, orthochromatic and panchromatic emulsions were introduced, that were more sensitive at longer wavelengths. The modern panchromatic emulsions approach reasonably well the photopic spectral sensitivity curve, without, of course, the colour information, and at the price of a lesser overall sensitivity. For stellar photography they are still widely used, particularly by amateur astronomers. For specialized photometric measurements, however, they are replaced by photo-electric devices, and more in particular by the CCDs, that are discussed in sec. 14.5.2.

In general photography, black-and-white emulsions are almost exclusively used by artists. Amateur and professional photographers, tourists, and the general public use colour photography. The first and by far the most essential requirement of colour photography is the exact reproduction of colours. It has been shown that most people have a very good memory for colours in their natural setting, particularly for the colours of objects they know well. Also, relative brightness and brightness contrasts are important, whereas most people do not seem to be bothered by considerable deviations in the brightness as such of objects. The modern colour photographic systems are designed to fulfill these requirements, so they are very well suited for the type of surveys, e.g. regarding urban sky glow, that are discussed in sec. 14.6.2d.

It must be noted that in recent years, many professional photographers as well as many people from the general public, use CCD cameras with digital photography. In 2002, in the Netherlands, more CCD cameras than 'chemical' cameras were sold. One may expect that the choice of method it is of minor importance for the results of the surveys, that are mentioned in sec. 14.6.2d. In may have, however, considerable consequences for the organization of such surveys, and consequently on their costs. One may consider to send in the pictures by e-mail rather than by post.

(c) Photocells

As is mentioned earlier, photocells have the same properties as the human visual system, in so far that they measure power (in Watts) and not energy, like photographic emulsions (Reeb, 1962, p. 166-167). This means that, when photocells are used, a separate storage for the information is needed.

Photocells convert the incoming light flux into electric current, using some sort of photo-electric principle. Therefore, they are often called photo-electric cells. There are three different processes that can be involved in the photo-electric effect. All three rest on the absorption of photons by a crystal (Hentschel, 1994, p. 73).

(1) The free electrons in the crystal become more energetic, so they may leave the crystal. This is often called the external photo-effect;
(2) The free electrons in the crystal become more energetic, so that the electric conductivity of the crystal is increased. This is often called the internal photo-effect;
(3) The free electrons in the crystal become more energetic, so that they may cross over a 'forbidden' zone. This is often called the barrier-layer photo-effect.

Free electrons and forbidden zones are discussed in detail the next part of this section. In engineering photometry, several types of photo-electric cells are in use. The most important ones will be described in further parts of this section.

Several general aspects of detectors are discussed in Sterken & Manfroid (1992, sec. 1.4, p. 12-18). In order to explain the requirements for detectors, more in particular for electric detectors like photocells, they introduced the 'ideal detector'. They also discuss photo-electric photometers in general, without giving details on specific equipment (Sterken & Manfroid, 1992, chapter 3, p. 51-64).

(d) Barrier-layer photo-effect.

Barrier-layer photocells are, as in indicated in an earlier part of this section, based on the fact that, when free electrons in the crystal are hit by incoming photons, they become more energetic, so that they may cross over a 'forbidden' zone. A barrier-layer photocell is, in fact, a semiconductor. Their use preceded the formulation of the physical theory of semiconductors for many decades. The photo-effect is possible when a P- and an N-semiconductor are in contact. In a P-semiconductor, there is an excess of free electrons, whereas in an N-semiconductor, there is a lack of free electrons, which in turn may be described as an excess in 'holes'. At the contact, the differences in their respective Fermi-level result in a reduction of carriers of electricity, which leads to a rectifier function. This is a function that passes electric current in one direction, but not in the other. When a light quantum – a photon – is absorbed, a pair of charged particles is formed. This pair will be separated, causing a negative charge in the N-semiconductor. The result is a photovoltage over the barrier layer. When the N- and P-semiconductors are connected over an external resistance, a photocurrent will flow. This description is based on a summary treatment given by Hentschel (1994, p. 78-82). Details about the physical aspects of the barrier-layer photo-effect are given in Simon & Suhrmann (1958); Spenke (1956) and Feynman et al., (1977).

The photocurrent is proportional to the illuminance on the cell. It is interesting to note, that there is no need of an external source of electric energy. In the past, most barrier cells were made of selenium (Schreuder, 1967, Keitz, 1967). The selenium is 'doped' with cadmium. The cells are sometimes designated as Se+Cd-cells (Hentschel, 1994, p. 80). Most modern cells are made of silicium. The photocurrent of Si-cells is much higher than that of Se-cells. This is depicted in Figure 14.5.2, where the photocurrent is given for short-cut condition, as well as the photovoltage for an open cell. The photocurrent depends heavily on the external resistance of the circuit.

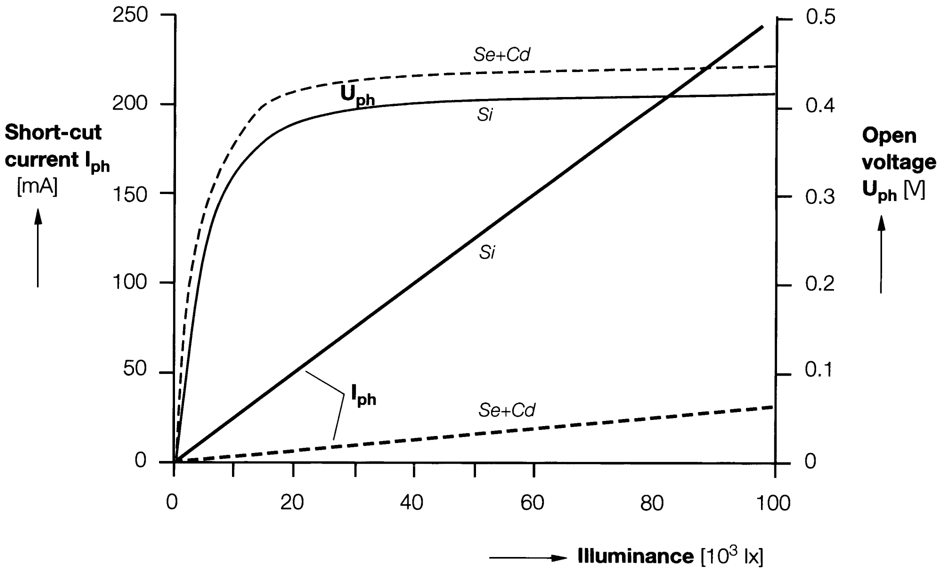

Figure 14.5.2: *The photocurrent and the photovoltage versus the illuminance on the cell. After Hentschel, 1994, Figure 4.16. See also Ris, 1992.*

The spectral sensitivity of Se+Cd-cells is quite different from the Si-cells. This is depicted in Figure 14.5.3.

Photocells show a variety of sources of deviation. In many cases, the compensation can be done more easy for the combination of the detector and its measuring device than for the two separately. This means, of course, that the two always need to be used together. The requirements regarding the degree of correction depends on the class of measuring equipment. The most important corrections to be taken into account for photometric measurements are listen in Ris (1992, p. 330-336).

- colour correction, that is the degree in which the apparatus follows the V_{λ}-curve for photopic vision;
- influence of UV and IR radiation. This means to ensure that for the application in photometric equipment, the apparatus is not sensitive to UV and IR radiation;
- influence of ambient temperature. This means either a thermal correction or the application of a correction factor based on the measurement of the temperature;
- correction for lack of linearity.

For the measurement of illuminance, the correct measurement of obliquely incident light is essential. Often, this is called a 'good cosine correction'. Several ways to ensure that are

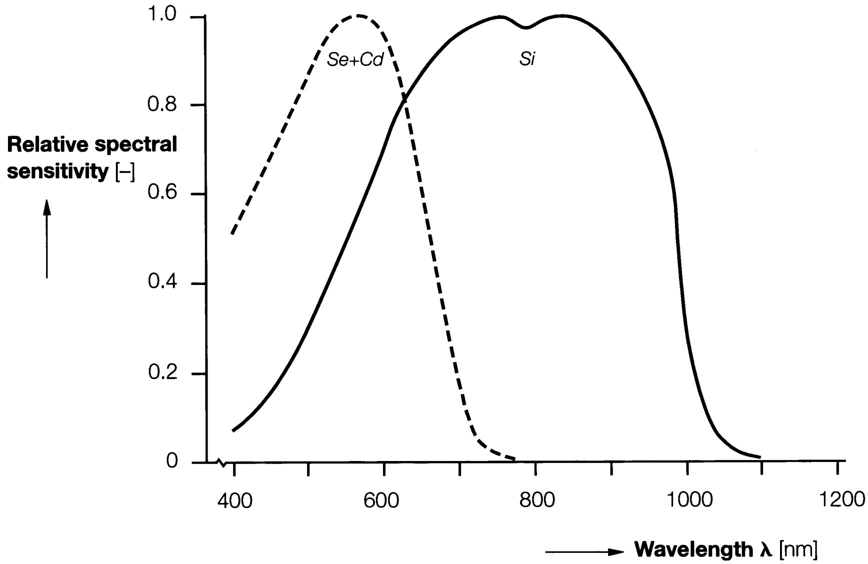

Figure 14.5.3: *The relative spectral sensitivity of Se+Cd-cells and Si-cells. After Hentschel, 1994, Figure 4.18.*

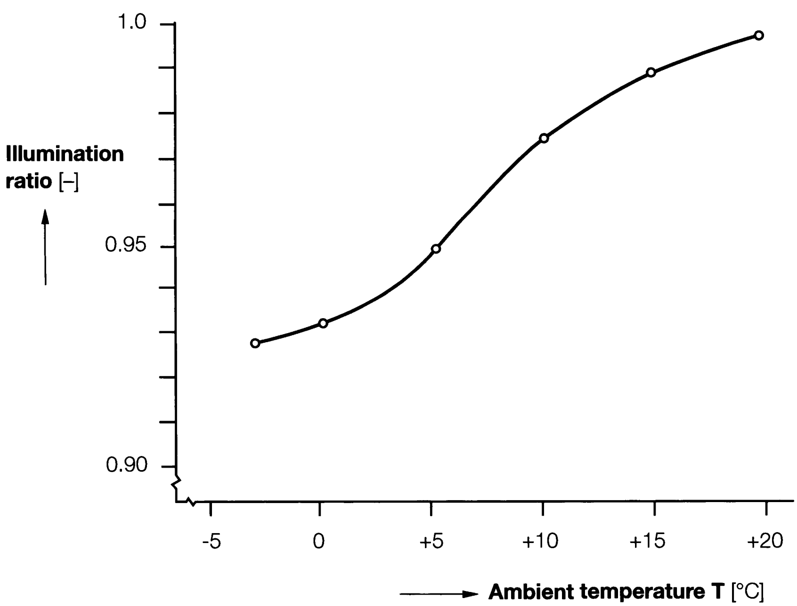

Figure 14.5.4: *The relative error for a luxmeter versus the temperature.*

listed in Hentschel (1994, p. 96-97); Ris (1992; p. 332-333) and Schreuder (1967, sec. 8.1.3, p. 435-441). In sec. 14.5.3a, some points are mentioned that refer to the overall accuracy of equipment for different photometric measurements. See also Ris (1992, sec. 10.1.2), where the different classes are described. As an example, the temperature dependency of an illuminance meter is given. See Figure 14.5.4. For a luxmeter of class B, the relative error must be not more than 1%.

(e) Photocells for internal photo-effects

Some crystals change their electric resistance, when they are hit by light, and absorb photons. This effect is, as is explained earlier in this section, an internal photo-effect. The effect is described in a summary form in Hentschel (1994, p. 76-78). For details about the theory, see again Feynman et al. (1977).

In 1873, the effect of photoresistance in pure selenium was reported (Smith, 1873, quoted by Hentschel, 1994 p. 78). Later, other material were found to posses the same characteristics, notably lead sulfide PbS. As is explained in sec. 11.1.1h, when discussing how LEDs work, it is mentioned that crystalline materials have a number of energy bands, in which their free electrons may find their place. If the lower band – the valence band – is exactly full with electrons and the upper band – the conductor band – is empty of free electrons, there are no electrons available to conduct any current. If there is a sizable gap between the valence band and the conductor band, there will be no current when a voltage is applied; the material is an insulator. If there are free electrons in the conductor band, these free electrons are available to conduct any current. The material will be an electric conductor. If, however, there is only a narrow energy gap between the filled valence band and the empty conductor band, some electrons may 'jump' the gap and may conduct current. Such materials are aptly called 'semiconductors'.

Semiconductors have a number of interesting features. In sec. 11.1.1h, the application for light generation in LEDs is described. The use of semiconductors in electronic elements, like rectifier and amplifiers – the diode and the transistor – are, of course, very well known.

The change in resistance under the influence of light, that is described above, is simple to use. Photoresistors are not accurate enough for measuring purposes, because their change in resistance depends on many other factors, apart from the illuminance. Photoresistors are, however, very well suited for switching purposes.

Photodiodes are similar to the barrier cells, that are discussed in an earlier part of this section. As indicated earlier, they are, in fact, rectifiers. The current can flow in one direction, but it is blocked in the other direction. The P-N junction is responsible for that. This blocking can, in part, be lifted if the P-N junction is hit by light; the energy of the photons may knock some electrons out of the P-semiconductor, through the junction, into the N-semiconductor. When a voltage is applied, the photocurrent is proportional to the illuminance. Contrary to barrier cells, photodiodes require an external source of electric energy. At present, photodiodes are the most common photocells, either as single units or as assemblies in CCDs. CCDs will be discussed in a separate part of this section.

Phototransistors are, like all transistors, amplifiers. Many are made of gallium arsenide GaAs. Because of their non-linear character, they are very well suitable for switching purposes, but less for measurements. Their main application is as detectors in CD and DVD players.

(f) *Photocells for the external photo-effect.*

When a surface is hit by photons, their energy may knock electrons out of the material. As is explained earlier in this section, this is often called the external photo-effect. The photo-electric effect is described in some detail in Sterken & Manfroid (1992, sec. 4.1, p. 65-67). See also Hentschel (1994). The theory goes back, as is well-known, on Einstein. As a matter of fact, it was the formulation of the correct theoretical explanation of this effect, that gained him his Nobel prize for physics. When a light quantum with energy $h \cdot \nu$ strikes the surface, an electron with a smaller energy $h \cdot \nu_0$ can be emitted. For reasons of conservation of energy, $h \cdot \nu_0$ never can be larger than $h \cdot \nu$. In general:

$$h \cdot \nu = e_0 \cdot U_m + h \cdot \nu_o \qquad [14.5.2]$$

with:
h: the Planck-constant;
e_0: the electrical charge of an (of any) electron;
U_m: the voltage related to the exit electron. (After Hentschel, 1994, p. 73, equation 4.9).

Because the kinetic energy of the electron is $(m \cdot v) /2 = c_0 \cdot U_m$; and because $\nu \cdot c_0 = \lambda$, with c_0 the universal speed of light, we may write:

$$U_a = (h \cdot \nu_0)c_0 \qquad [14.5.3]$$

with Ua: the exit potential of the electron. (After Hentschel, 1994, p. 74, eq. 4.10).

This effect is used in photocell tubes, where the light is directed towards a cathode, from which the electrons are knocked out. An anode is added. As a result of the voltage difference between the cathode and the anode, a photocurrent will flow, when light strikes the cathode. It was the main contribution of Einstein that only the number of knocked-out electrons, but not their frequency – or wavelength – depends on the illuminance. Thus, the photocurrent depends on the illuminance of the cathode. Also, the photocurrent depends on the voltage difference U_b between the cathode and the anode. In a vacuum photocell tube, the photocurrent reaches a maximum, a saturation value, but in a gas-filled photocell tube, ionization and recombination allow to a steady, non-linear increase of the photocurrent for an increasing voltage difference. This is illustrated in Figure 14.5.5. These characteristics make photocell tubes more suitable for switching purposes than for measuring purposes (Schreuder, 1997, p.59)

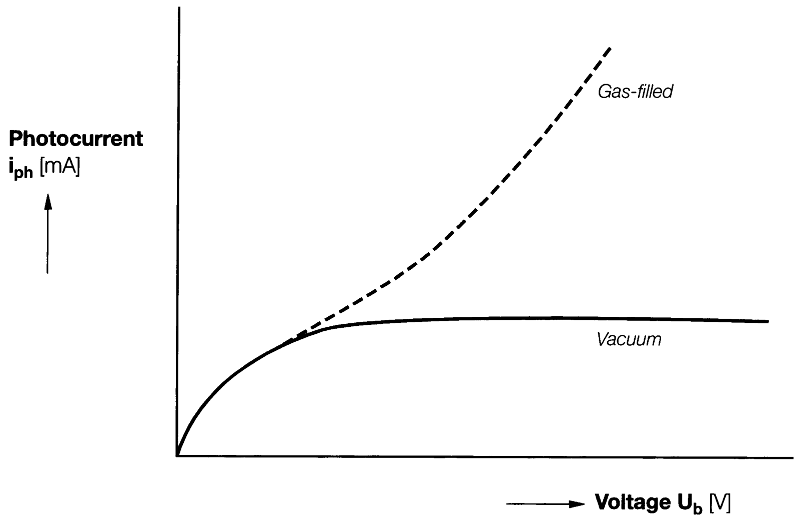

Figure 14.5.5: *The relation between the photocurrent i_{ph} and the voltage U_b for gas-filled photocell tubes and for vacuum photocell tubes After Hentschel, 1994, Figure 4.8.*

(g) *Photomultipliers*

In an earlier part of this section, the external photo-effect is described briefly, as well as its application in photocell tubes. An important class of detectors is based, at least in part, on the same effect: the photomultipliers. Photomultipliers are described in summary in Hentschel (1994, p. 76), and in detail in Sterken & Manfroid (1992, chapter 4, p. 65-79). Some types of photomultipliers are described in Sterken & Manfroid (1992, sec. 4.3, p. 67-68).

The first part of a photomultiplier resembles a vacuum photocell tube, such as is discussed in an earlier part of this section. When photons of sufficient energy hit a cathode, electrons are knocked out. In a vacuum photocell tube, these electrons are accelerated by a voltage difference, and arrive at the anode, where they may give rise to a photocurrent in an external circuit. In a photomultiplier, the electrons that are knocked out of the cathode, are called 'primary electrons', for reasons that will be made clear hereafter. The primary electrons are accelerated by a voltage difference as well, but they do not arrive at the anode, but at an intermediate surface, called the dynode. Here, secondary emission takes place, which means that, again, electrons are knocked out of the surface, but this time by the primary electrons, and not by the incident photons. These electrons are, for obvious reasons, called 'secondary electrons'. By sending the secondary electrons to another dynode, this effect may be repeated. Of course, a photomultiplier multiplies light only if the number of secondary electrons is larger than the number of primary electrons. The secondary emission process can be described by the secondary emission coefficient δ. This is the ratio between the secondary electrons and the incident electrons (Sterken &

Manfroid, 1992, p. 71). On theoretical grounds, one may expect hat the maximum value per dynode is between 200 and 1000. It can be approximated by:

$$\delta = A \cdot E^{\alpha} \qquad [14.5.4]$$

with:
A: constant;
E: interstage voltage;
α: a coefficient, determined by dynode material and geometry. Usually α is about 0,7 (After Sterken & Manfroid, 1992, eq. 4.3, p. 72).

It seems, however, that this theoretical maximum is not easy to reach. For practice, a factor of 4 per dynode is given by Sterken & Manfroid (1992, p. 66). This does not seem very impressive, but if 10 dynodes are used, the total amplification – or gain – of the device is approximatively 4^{10}, which corresponds to about 10^6. Similar data are given by Budding (1993). It seems that per stage a factor of 3 is used. For a 12-stage photomultiplier, the number of anode electrons per released cathode electron, the gain, is 3^{12}. This equals to about the same number, viz.: 10^6 (Budding, 1993, p. 123).

In the end, the electrons arrive at the anode, where they may give rise to a photocurrent in an external circuit, just as in the case of a photocell tube.

Photomultipliers are particularly suited to measure very small amounts of light at very high frequencies. The inertia of the device is limited only by the time the electrons need to cross from the cathode to the anode. This time is in the order of 10^{-9} seconds or even less (Hentschel, 1994, p. 76).

The spectral sensitivity of a photomultiplier follows that of the photocathode. Some examples are given in Figure 14.5.6. In this figure, the relative spectral sensitivity curves are given for three common materials, such as are standardized in Germany (DIN, 1969).

Many more materials that are used in cathodes are listed by Sterken & Manfroid (1992, table 4.1). The dark emission of the listed materials range from 900 to $0{,}0003 \cdot 10^{-15}$ Ampere per cm^2.

In order to give the desired results, the equipment has to fulfill a number of requirements, some of which are listed here (Hentschel, 1994, p. 76).
(1) The thermal emission of the cathode must be reduced as far as possible, because that is multiplied as well. Solutions are to cool the cathode, or to use alternate ‘chopped’ light;
(2) The voltage over the dynodes must be very stable, at least to a factor of 10^{-4};
(3) The device must have a very sturdy construction. Even slight deviations in the position of the dynodes in the tube may change the amplification considerably;
(4) The overall voltage between cathode and anode is usually between 1000 and 3000 V.

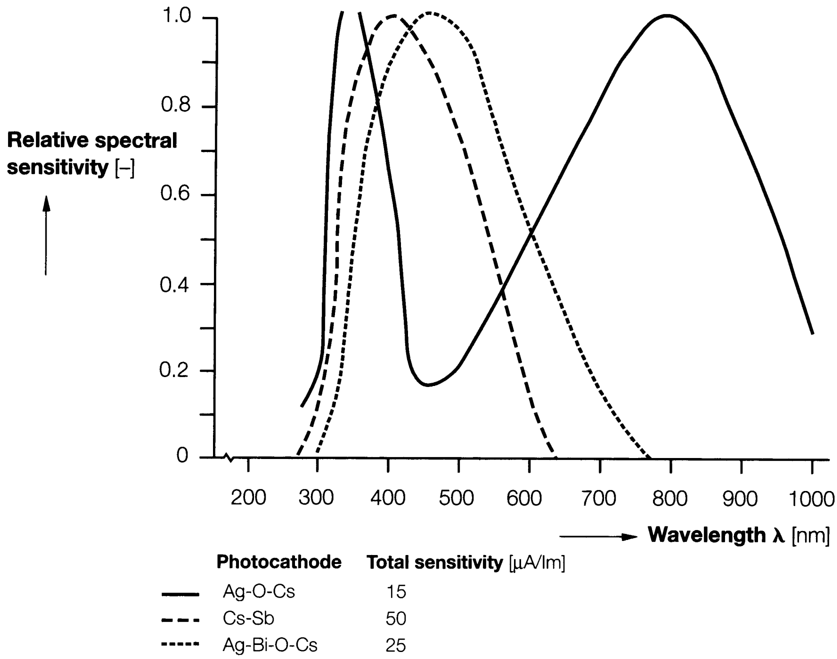

Figure 14.5.6: *The relative spectral sensitivity curves for cathode materials. After Hentschel, 1994, Figure 4.9.*

These requirements make photomultipliers less suitable for day-to-day engineering photometric work, particularly outdoor work. Early attempts were not very successful. Photomultipliers have been in use for the measurement of the road surface luminance (Schreuder, 1967a, secs. 8.2.5 and 8.2.6). A special device, the Morass-meter, is described in Morass & Rendl (1967), see Van Bommel & De Boer (1980, p. 214). Its application for the measurement of the reflection characteristics of road surfaces is described in Schreuder (1967a, sec. 8.5.1). In passing, we will mention here the application of vidicon tubes, in fact a TV recording device (Dalderop, 1986).

Nowadays, there are more simple alternatives. The need is less pressing, because at present electric amplifiers with amplification ratios of 10^{10} or more, are readily available. With such amplifiers, standard Si-cells can be used just as well. For precision work, for calibrations and other laboratory work, and for photometry of exceedingly weak light sources, such as are common in astrophysical research, photomultipliers are indispensable. As mentioned in sec. 5.3.2, the satellites of the Defense Meteorological Satellite Program (DMSP) use a photomultiplier as a light detector as part of an oscillating scan radiometer (Elvidge et al., 1999). As is explained in sec. 5.3, the 'First World Atlas of the artificial sky brightness' is based on measurements made with the DMSP system (Cinzano et al., 2000).

(h) Accuracy requirements

There are many photometric systems in use in astronomy. The most common are discussed in detail in Sterken & Manfroid (1992, sec. 16.4, p. 234-245). The best-known systems that are used in practice, all suffer problems at the 1% level. This is often considered as being inherent in astronomical measurements. "Basically everything varies all the time and on all time scales and amplitudes you care to think of" (Schwarz, 2003). As we mentioned earlier, this statement makes one wonder about the tenacity, the skill, the patience – and the funds – of astronomers that allow them to come up with all the wonderful knowledge about the Universe, in spite of these setbacks.

Notwithstanding this admiration, real life dictates that all measurements are fraught with inaccuracies. The most basic source of inaccuracy in measurements is found in the 'graininess' of the Universe; it manifests itself in the well-known Heisenberg uncertainty relation, also called the uncertainty principle (Illingworth, ed., 1991, p. 503-504). In mathematical terms is can expressed as:

$$\Delta p \cdot \Delta x \geq \frac{h}{4\pi} \qquad [14.5.5]$$

in which:
p: the momentum of a particle;
x: the location of the particle;
h: the Planck-constant (Illingworth, ed., 1991, p. 354)

A similar description can be given for several other pairs of variables. The basic considerations of the uncertainty principle are given in Feynman et al. (1977; p. 2.6 and sec. 37-8). See also Van Melsen (1946; 1983).

The uncertainty principle represents the 'bottom line' of all measurements. The philosophical implications are briefly discussed in Feynman et al. (1977, sec 38.6). "Speaking more precisely, given an arbitrary accuracy, no matter how precise, one can find a time long enough that we cannot make predictions valid for that long time. The time goes, in fact, only logarithmically with the error, and it turns out that in only a very, very tiny time we lose all our information" (Feynman et al., 1977, p. 38-10).

Because the Planck constant h is so small, in most practical photometric assessments in astronomy and in all cases in engineering, the Heisenberg considerations can be disregarded.

There is another fundamental aspect that restricts the accuracy in which we may 'know' the world. Certain non-linear dynamic systems may never come to an equilibrium state, and behave in an unpredictable fashion, in spite of the fact that the elements follow the normal dynamic laws of e.g. Newton. These systems are often called 'chaotic systems'. "Chaos places limits on science: it implies that even when we know the equations that govern a system's behaviour, we may not in practice be able to make effective predictions" (Stewart, 1994).

Another approach is to state what is the minimum required accuracy of measuring equipment. Many national and international bodies have set up standards, regulations and recommendations to do so. See e.g. CEN (1998), CIE (1987b) and DIN (1998). They exist for almost all possible types of measurements. Usually, classes are defined, and for each individual measuring apparatus it is possible to indicate to what class it belongs. In Germany, the current classification in given in DIN 5032 part 7 (See Hentschel, 1994, p. 85). For scientific work this is important, because it may give a hint about the value of claims that are made in the scientific literature. For many practical applications it is much more important, because in many cases, e.g. by granting permission to set up outdoor lighting installations, the limiting values e.g. about light pollution, are set down to which the installations must agree. Such limits have little value if there is no indication about the class of accuracy to which the measurements must be made. This is particularly important if there is disagreement between the parties involved, and if court action is considered. Court actions may, of course, lead to convictions and damage claims. A further implication is, that the quality of the testing is important. Testing of instruments must be performed by test houses that are 'certified' to do so. There are special ISO-Standards that describe in detail the underlying processes and considerations.

Measuring lighting installations has a number of different but mutually related aims. The major aims of measuring lighting installations are:
(1) To provide the base for legal product liability inquiries;
(2) To provide the base for the quality assessment for the product delivery guarantees;
(3) To provide the base for standards, rules or recommendations;
(4) To provide the base for lighting design methods;
(5) To provide data for scientific research;
(6) To provide data for maintenance schemes for lighting installations;
(7) To provide the base for survey-type of studies (e.g. lighting and accident studies).

The requirements for the measurements are not identical for each aim. In Table 14.5.1, a 'matrix' is given that gives, in a tentative way, the different requirements for the different aims.

Type of measurement	Status	Accuracy	Speed	Cost	Interference
product liability	+++	++	–	– –	– – –
product delivery	+++	+++	– –	– –	– – –
standards	++	++	–	–	– – –
lighting design	o	++	+	o	–
scientific research	– –	+++	+	+	o
maintenance schemes	– – –	+	++	+++	+++
survey studies	– – –	– –	+++	+++	+++

Table 14.5.1: *Types of measurement: recommended status, accuracy, speed, costs and interference with normal traffic operations for measurements that serve different purposes in Table 14.5.1, the headings of the columns have the following meaning:*

- Status means the legal or formal status of the measurement; usually a high status is established by having the measurements done by an independent, well-established institute that is officially certified to do this type of measurements. + means high status;
- Accuracy speaks for itself. + means high accuracy;
- Speed means the time it takes to do the measurements. In many cases the time is not an important factor, but often it is. + means rapid measurement;
- Cost means the costs to do the actual measurements. + means cheap measurements;
- Interference relates to the way the persons using the installation, e.g. the road users in a tunnel are bothered by the measurements. + means little interference.

Measurements never can be absolutely correct. That is, of course, usually not necessary, In Table 14.5.1, some qualitative suggestions have been given as to how accurate the measurements – and thus the equipment to be used – must be for some specific fields of application.

There is a ground rule, however. Almost without any exception, accurate measurements are more costly than casual measurements: costly in money for the equipment, costly in measuring time and costly in expertise of the operators. So it is worth-while to insure that the measurements are not more accurate than necessary. In the following, some suggestions given for the degree that is required for outdoor lighting installations. As can easily be seen, road lighting served as an example for this:
(1) Errors in input data for calculations: less than 5%;
(2) Differences between measurements and calculations: less than 2%;
(3) Errors in measurements (instrument errors)
- horizontal illuminance: less than 3%;
- vertical illuminance: less than 5%;

(4) Luminance factors: less than dan 5%;
(5) Luminances
- road surface luminance: less than 10%;
- point luminances: less than 15%;
- veiling luminances: less than 25%;

(6) Photometric measurements:
- illuminances: cosine correction: better than 99%; colour correction: better than 95%;
- temperature correction: better than 99%;
- luminances: colour correction: better than 95%; temperature correction: better than 99%.

These values are quoted from Schreuder (1998; sec. 10.7). They are based on draft documents that were made for discussion in several working groups of CIE and CEN (Schreuder, 1995b).

Finally, we will give two examples of the classification of photometric measuring equipment, one for illuminance measurements and another for luminance measurements. In general terms, the accuracy of field luminance measurements with spotmeters is usually not better than 20% (Van Bommel & De Boer, 1980, p. 215, referring to Walthert, 1977).

They are quoted from Ris (1992). Many data agree with the classification given by in Baer (1990), referring to Krochmann (1984). See Table 14.5.2 and Table 14.5.3. In both cases, four classes are introduced that refer to the field of application of the measuring equipment:
(1) Class L, the highest, for laboratory use;
(2) Class A, high, also for laboratory use;
(3) Class B, average, for practical applications;
(4) Class C, low, where no specification of the use is given.

Criterion	**Unit**	**Error limits for equipment class**			
		L	**A**	**B**	**C**
V_λ-correction	%	1,5	3	6	9
UV and IR sensitivity	%	0,2	1	2	4
cosine correction	%	1	1,5	3	6
linearity error	%	0,2	1	2	5
display error	%	0,2	3	4,5	7,5
fatigue	%	0,1	0,5	1	2
temperature coefficient	%/K	0,1	0,2	1	2
change in range	%	0,1	0,5	1	2
total error	%	3	5	10	20
lower frequency limit	Hz	40	40	40	40
upper frequency limit	Hz	10^5	10^4	10^4	10^3

Table 14.5.2: *Accuracy requirements for illuminate measurements.*
After Ris, 1992, table 10.2, p. 335.

Criterion	**Unit**	**Error limits for equipment class**			
		L	**A**	**B**	**C**
V_λ-correction	%	2	3	6	9
UV and IR sensitivity	%	0,2	1	2	4
stray light influence	%	2	3	6	9
linearity error	%	0,2	1	2	5
display error	%	0,2	3	4,5	7,5
fatigue	%	0,1	0,5	1	2
temperature coefficient	%/K	0,1	0,2	1	2
change in range	%	0,1	0,5	1	2
focus error	%	9,4	1	1	1
total error	%	5	7,5	10	20
lower frequency limit	Hz	40	40	40	40
upper frequency limit	Hz	10^5	10^4	10^4	10^3

Table 14.5.3: *Accuracy requirements for luminance measurements.*
After Ris, 1992, table 10.2, p. 335.

It should be noted that, although it is not clearly stated, we may assume that these tables agree with CIE (1987b) and DIN 5032 part 7, as quoted by Hentschel (1994, p. 85).

14.5.2 CCDs

(a) CCDs for taking pictures

Charge-Coupled Devices, or CCDs, are the most recent light detectors that are used on a large scale. They combine the capability of two-dimensional imaging of photographic plates with the linearity and the sensitivity of silicium photodiodes. They are at the heart of all video cameras; they are used in many modern amateur still photo cameras. For that purpose, they have several additional advantages. The picture can be seen and judged immediately after being taken; development and other chemical processes are not needed. If needed, it can be send, by cellular telephone, immediately to any place in the world, an advantage for professional press photographers. This means also that the same 'material' can be used over and over again, which is often considered as a way of saving money. Also, the picture, once taken, can be transferred to a computer, where a large variety of processes can be applied to change the original picture. This capability is used on a large scale by professional photographers, but it remains to be seen in how far amateurs actually do this. In the past, the limited resolution could be a disadvantage. Modern, top line cameras boast 3 or 4 million 'pixels' on their CCD. In a further part of this section we will explain what 'pixel' means. A top class 'chemical' camera, with $24 \cdot 36$ mm film and a resolution of 110 lines per mm, will be equivalent to 10 454 400 pixels, or almost 5 times as much. The gap is closing. Still, as is mentioned in sec 14.5.1.b, for large-scale astronomical survey purposes, the storing capacity of a photographic plate is still superior. 'Schmidt-plates' are equivalent to about one Giga-pixel. "Giga-pixel CCD's are still far away" (Sterken & Manfroid, 1992, p. 212). Their main advantage for astronomical observations compared to photographic plates is their sensibility. "CCDs can detect up to 70% of the light entering a telescope, photographic plates detect only 1/10th of 1%. CCDs are 30 times more sensitive to light than a photographic plate" (Lafferty & Rowe, eds., 1994, p. 112).

(b) The properties of CCDs

A CCD consists of an array of tiny photodiodes made of silicium (Sterken & Manfroid, 1992, p.192). The array is usually, but not always, two-dimensional. One-dimensional, or line scan CCDs have been used in measuring the luminance of road surfaces in road lighting (Schreuder, 1996; 1998, p. 71; Schreuder & Van de Velde, 1995). The individual photodiodes are called picture elements or pixels. Present-day CCDs generally come in sizes from 512 by 512 pixels to arrays as large as 4096 by 4096 pixels, totalling 262 144 pixels and 16 777 216 pixels respectively (Howell, 2001, p. 2).

In CCDs, the pixels may be regarded as capacitors, that are charged when exposed to light. The charge packets, one for each pixel, are caused to flow from one capacitor to another. This is why the array is called a Charge-Coupled Device. The charge packets pass through readout electronics, that detect and measure each charge in a serial fashion (Howell, 2001, Chapter 2). "Originally designed as a memory storage device, CCDs have swept the market as replacements for video tubes of all kinds owing to their many advantages in weight, power consumption, noise characteristics, linearity, spectral response, and others" (Howell, 2001, p. 7). Apart from these, the other main advantages of CCDs over other means to measure and store light are: the large dynamic range of about 10^{10} and the high quantum efficiency (Sterken & Manfroid, 1992, p. 191). A major disadvantage is bleeding. Bleeding occurs when a pixel is overexposed and overflows into neighbouring pixels (Howell, 2001, p. 17, footnote). It can be compared to irradiation in optical systems and to glare in visual perception.

CCDs have a number of essential characteristics, that are too specialized to discuss here. These characteristics are discussed in detail in Budding (1993, sec. 5.2.6, p. 129-132); Sterken & Manfroid (1992, Chapter 13) and Howell (2001, Chapters 2 and 3). We will discuss only two essential aspects: in sec. 14.5.2c, the quantum efficiency, and in sec. 14.5.2d, the sources of noise in CCDs that are already mentioned in sec. 14.2.3e.

(c) The Quantum Efficiency

CCDs are made from almost pure silicium. Ultimately, the detection of radiation of different wavelengths by a CCD depends therefore on the absorption characteristics of silicium. This aspect is expressed in the quantum efficiency or QE. It is the term used to describe the ability of a detector to turn incoming photons into a useful output (Howell, 2001, p. 5). Photons of different energy levels – different wavelengths – can penetrate further or less far into the material. Photons that are not absorbed, can never be detected. This is illustrated in Figure 14.5.7.

The absorption length is defined as the length where 63 % of the incoming photons will be absorbed. The value of 63 % equals (1/e). From Figure 14.5.7 it can be seen, that light with a wavelength under some 300 nm will pass right through the crystal, or will simply be reflected (Howell, 2001, p. 27). Thus, the quantum efficiency of a CCD depends strongly on its thickness and on the wavelength. In Figure 14.5.8, some examples are given of the typical quantum efficiency of different detectors.

It should be noted, that the graph gives examples only, and that within a certain family of detectors, quite large differences may occur. As regards CCDs, it must be stressed that there may be considerable differences between the individual pixels in the array (Howell, 2001, p. 28). Also, there is always a small number of pixels that is defective. Sometimes, defective pixels are called warm pixels. Normal, high class, commercially available CCDs may have between 0,3 % and 0,6 % defective pixels (Schmidt & Krüger, 2000, p. 4).

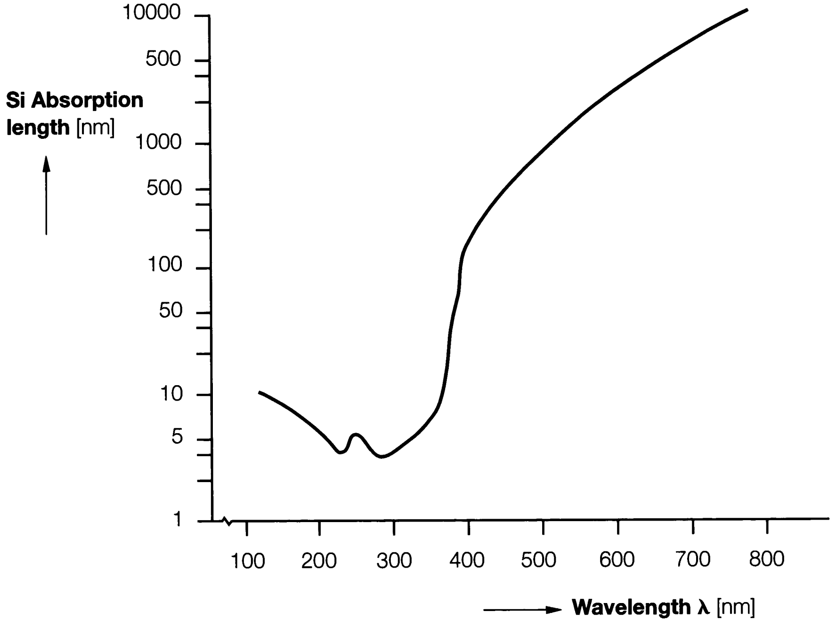

Figure 15.5.7: The photon absorption length in silicium versus their wavelength. After Howell, 2001, Fig. 3.1, based on Reicke, 1994.

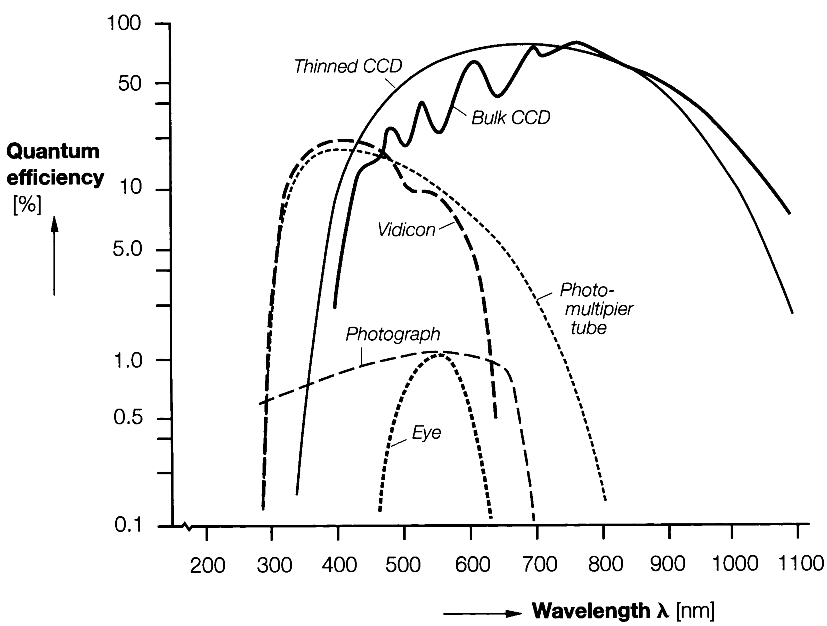

Figure 14.5.8: The quantum efficiency of different detector types. After Howell, 2001, Fig. 3.2. Most information is also given in Sterken & Manfroid, 1993, Figure 13.4, based on data from Kristian & Blouke, 1982.

(d) CCDs in photometry

In the past, photometric data were written down and stored in printed, sometimes in published, form. Some examples, that may, historically speaking, be interesting, are Kaiser (1888); Plaszmann & Pohle, eds. (1910); Thomas (1944). This, of course, was the case for all quantified data that were collected in science and technology. A major problem was, when other researchers wanted to use the data, the only way to do so was to copy them all. Digital storage systems changed all that. Nowadays, it is difficult to imagine any other way than to use digital data, often available through the internet. Examples, particularly for use in developing countries, are given in Batten, ed. (2001).

The most important characteristic of CCDs is, that they can be attached directly to a computer, and thus to the internet. It requires, however, specialized software, that will be discussed in brief in the next part of this section. See sec. 14.5.2e.

Before CCDs became available, digital data about celestial objects could be produced by detectors such as photodiodes, video tubes of the vidicon type, photomultipliers etc. Some of them are discussed in sec. 14.5.1. Many of them, if used correctly, could provide accurate and reliable data. The data referred only to individual celestial objects. For many studies, the amount of information was overwhelmingly large. CCDs not only could produce data from many celestial bodies simultaneously, but, being connected directly to computers, the data retrieval and analysis could be highly automated (Howell, 2001, p. 77). It is, for example, possible to record the spectra on many stars in one single wide-field exposure, and analyze the data automatically (Howell, 2001, p. 124-127.

A different type of application of CCDs is in the measurement of luminance. In this type of application, a digital camera is used; basically, any type of commercially available camera could be used. For reasons of calibration, as well as for the application at low luminances, special cameras have been developed. Appropriate, dedicated software allows a number of manipulations that are essential to assess the luminance and the luminance distribution of lighted surroundings. To name a few: the luminance of individual points can be measured, similar to the measurement with a 'spotmeter'. The same can be done, of course, for a great many points in the same surroundings. This allows one to asses the average luminance in any area of the field, as well as the non-uniformity of the luminance distribution. Also, it is possible to select single lines in the picture, as is done in 'line scan photometry'. Finally, lines of equal luminance can be assessed , and added to the picture.

The performance of a CCD luminance measuring system depends primarily on the luminance range one is interested in. For surroundings, where the overall luminance levels are high, such as the lighting of offices or tunnels, the measurements are straight-forward. They have been used on a large scale for more than a decade now. See e.g. Anon. (1996; 1997a,b; 1998); Frank & Damasky (1990); Huijben (2002); Rossi, ed. (1996); Schreuder (1998, p. 71) and Serres (1990).

In modern equipment, low luminances can be measured by using long integration times and by adding up the result of neighbouring pixels. This is called 'binning', (Howell, 2001, sec. 3.4, p. 36). The related concept 'exposure' is discussed in sec. 14.1.3a. The consequences are clear: long exposure times allow only the measurement of static scenes, and binning reduces the resolution. The effects can be dramatic, however. See Table 14.5.4. For further details, see Gall et al. (2002) and Schmidt & Krüger (2000).

Integration time	L_{max}		L_{min} (including binning)			
		binning	1×1	3×3	7×7	18×18
0,1 millisec	28 000	1400				
5 seconds	0,558		0,028	$9 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$1{,}6 \cdot 10^{-3}$

Table 14.5.4: *CCD measurements at low luminances. All values in cd/m^2.*
After Fischbach, 2001, Table 4.

In sec. 14.2.3e, when discussing the effect of sky glow on the precise measurement of faint, point-like celestial objects, the main sources of 'noise' in a CDD image have briefly been mentioned:
(1) The noise of the signal itself;
(2) The noise of the sky background;
(3) The detector readout noise.
Sources (1) and (2) are statistical noise sources, that follow, like as all shot-noise phenomena, Poisson-distribution. The signal-to-noise ratio (S/N) is given in equations [14.2.13] and [14.2.14] (Tritton, 1997).

(e) CCD data extraction and data processing

CCD imaging starts with the extraction of the information from the CCD. The information regarding the position on the CCD is already in digital form by means of pixel column and row. In consumer colour cameras, the colour information is contained in the three types of pixels for the three basic colours. Basically, the 'amount' of light per pixel is in analogous form. In the electronic hardware, this amount is digitized, e.g. in 255 levels. The comparison of the three types of colour yields the colour information. This is essentially enough to present pictures. Cameras usually are delivered with software packages that, together with one of the many computer software packages, allow further manipulation of the image. Sometimes, some of this manipulation is called 'cosmetics'. They are needed to get a beautiful, full colour picture that is worth showing. CCD imaging is discussed in detail in Howell (2001, Chapter 4, p. 47-74) and Unger et al. (1988, sec. 4.2, p. 77-85).

The following discussion about data extraction is bases in part on Howell (2001) and Vermaelen (2003). Data extraction includes several steps. Usually, the first steps are to get rid of all disturbances that are not coming from the heavenly bodies. This includes faulty pixels or faulty pixel lines, bias, thermal, UV, and cosmic ray noise etc. There are standard ways to take these out (Howell, 2001). The next step is to extract unwanted and disturbing information, like disturbing spectral lines, compensating for dark current, etc. The second step compensates for 'bias' like e.g compensating for offset, uncorrected dark current, etc. The next steps are to reduce image noise, e.g. by averaging a number of subsequent images, and to homogenize the field of exposure by comparing it to a homogene plane of reference. These compensations and corrections are more complicated and include complex mathematical procedures, like e.g. the deconvolution of Fourier and Bessel function. Such corrections are related to errors in the telescope optical system, like spherical aberrations and astigmatism, as well as bringing all exposures to the same scale in order to be able to compare them.

Recently, CCD imaging is used on an increasing scale for light measurements, particularly for luminance measurements in the field, e.g in lighting application, both indoors and outdoors. For this, some additional steps are needed. The first is, that locations in the field must be allotted to locations on the CCD. Further, the levels that are delivered for each pixel, must be calibrated in luminance values. This can be done in a variety of ways, the most common being a comparison with a luminance standard. When this is done, the luminance of any point in the field, that now corresponds to a specific pixel, can be quantified. Lines of equal luminance can be included by making all points of which the luminance equals that of the 'line' are made pure white. If needed, false colours can be added for luminance ranges. Special software is developed that allows arithmetic manipulations of the data, e.g. assessing the maximum, the minimum or the average of the luminances in the field, and that allow different ways to present the data. Usually, this sort of software is developed by the manufacturer of the measuring equipment, and is equipment-specific. In most cases, the process stops here. Lighting engineers, designers, planners and architects are in most cases satisfied with the type of data mentioned earlier, like the maximum, the minimum or the average of the luminances in the field, the glare, and the false-colour images.

In astronomical photometry, data extraction and data processing are much more complicated undertakings, because astronomers want to have much more, and much more detailed, information than the overall information which satisfies lighting designers. Basically, one makes a picture of part of the sky, and extracts data on all heavenly bodies in that part, like e.g. magnitude, colour, spectral characteristics, red-shift, etc. The end result is not a picture, but a set of digital data that can be used as the input for further data processing.

After the steps that have been described in the foregoing part of this section for data extraction in general, more specific steps are needed. One step is to clean the image of each individual body. If it about stars, this includes finding the centre of the star image by getting rid of optical errors in the telescope, overflow of charge from one pixel to the next, etc. This is described in detail in Howell (2001, Chapters 5 and 6). Then comes the most difficult step: pattern recognition.

(f) Pattern recognition.

Pattern recognition is a qualitative description of a vaguely defined area of research. It often seems to be not more than a bunch of algorithms and ad-hoc techniques (Krishnaiah & Kanal, 1982, p. 174). It so happens that biological systems – animals and humans, that is – are exceedingly good in recognizing patterns. Even when the information is random, like e.g. in clouds or Rorschach pattern may provoke some sort of 'recognition' (Gregory, ed., 1987, p. 686). "Biological perception and information processing mechanisms are very complex, mostly not understood and even, when partially understood, cannot be implemented. A replica of a biological pattern recognition system in not available" (Backer & Duin, 1989, p. 25). Pattern recognition is not defined any further. What is defined, however, is: "A pattern recognition system is an information processing system that allows to classify an amount of input data correctly into a number of classes; to describe them and to label them" (Backer & Duin, 1989, p. 25).

To begin with, all objects must be divided in two 'sets': the set of objects to be studied, and the set of objects not to be studied. The two sets, of course, are complementary: all objects in the universe belong to one, and only one, of them. The next step is to define a set of criteria that allows to decide with complete certainty, that a specific object belongs to the one or the other set. As mentioned earlier, human beings are exceedingly good at it: even a non-trained person can see at once whether any object in the sky is a star or not. Unfortunately, our clever companion, the computer, is very stupid in this respects. Therefore, pattern recognition is a major, but until now, a rather unsuccessful part of Information Technology ('just a bunch of algorithms and ad-hoc techniques'). Even the simple thing of recognizing a face, cannot be done properly yet in an automatic fashion. A paradigm must be established, that allows to decide whether an object is member of the set of objects that is to be studied, and not a member of any other set. This can be done only by looking at each object separately, and decide whether the set of criteria, that was mentioned earlier, does apply. In the case of stars, it is still rather simple. Stars are essentially point sources. As is explained in sec. 9.1.7, the star image is not, as a result of the inherent limitations of the optical system of the telescope. As mentioned earlier, a CCD response is even further from a point. It can, however, be described reasonably well by a Gaussian spread function (Howell, 2001, p. 81-83). If the objects to be studies are more complex, the success of the work is determined to a large degree on the definition, the selection, and the description of the set of criteria that makes it possible to decide whether a particular object is a member of the set of objects that is to be studied, and not a member of any other set. Some conditions for doing so are given in Backer & Duin (1989, sec. 3.5).

When all this is done, the actual work on data processing may begin. This subject is treated in detail in several other standard works. We will not go into that, but only mention a few references (Adams et al., 1980; Gilliland, 1992; Gullixson, 1992). The textbooks that are quoted by Backer & Duin (1989, p. 40-42) are all from before 1990. The complicated area of pattern recognition is dealt with in a number of publications. Because the area is developing very rapidly, probably in step with the rapid development of computer hardware and software, there seem to be no modern standard works in this area. Therefore, we will give only a few general comments, based on Backer & Duin (1989, Chapter 3).

- Sensors are essential, because they deliver the input data. When the input data are faulty, the result can never be correct. The requirements of sensors are discussed earlier in this section. The most critical are – obviously – the sensitivity and the S/N-ratio, as well as the calibration;
- Most modern pattern recognition systems are 'self-learning' systems. Learning means in this context that the decision making process for the classification of input data does become more efficient when more decisions are made. It learns from hits as well as from misses. The learning process is based on a 'teaching data collection', which is completely known. The test results are compared to the teaching data collection;
- The classes need to be well-defined. The teaching data collection should contain no errors. In order to arrive at an optimum, the classifying process needs to be based on the selection of the best as well as on the most effective characteristics, on the selection of an adequate learning model, and the selection of an adequate decision making model. i.e. statistical decision rules, syntactic decision rules, etc.;
- Essential is, of course, the evaluation of the system. Without an adequate evaluation, it remains guess-work as to whether the system really works.

14.5.3 Measuring photometric quantities

(a) Basic considerations

In sec. 14.1, the different quantities are defined that, together, constitute the set of photometric units and quantities. In sec. 14.1.2, it is explained that ISO defined the photometric system, using the luminous intensity as the primary quantity, its unit being the candela. The candela is one of the seven primary units of the SI-system. In further parts of sec. 14.1, it is explained that, for practical use, it is more convenient to define the description of the SI-system in the following order:

- the luminous flux;
- the luminous intensity;
- the illuminance;
- the luminance;
- the luminance factor.

Photometry is a specialized profession, that requires skill, good equipment, and a very large dose of experience. There are many things that can go wrong; there are many pitfalls. Here, it is not the place to go into detail, because we will deal here mainly with the measurements of urban sky glow, as well as with some other aspects of quantifying light pollution. We will refer only to a number of outstanding standard works, that deal with the different issues in great detail and with great authority: Baer, 1990; Budding, 1993; Cinzano, 1997; Helbig, 1972; Hentschel, 1994; Keitz, 1967; Moon, 1961; Reeb; 1962; Ris, 1992; Schreuder, 1967, 1998; Sterken & Manfroid, 1992; Van Bommel & De Boer, 1980; Walsh, 1958; Weigert & Wendker, 1989.

It has been stated earlier, that photometry is, in essence, just 'counting photons'. When a short summary is given about the measurement of photometric quantities, it is more convenient to start just there, at counting photons, and go from there to the other photometric quantities that are listed above. Counting photons, of course, is measuring the flow of energy. In other words, it is the measurement of energy per unit of time, or 'power' – expressed in Watts. We deal here only with photons out of the range of visual experience. These are quantums of electromagnetic radiation, weighted according to the V_λ-curve. In other words, counting such photons corresponds to the measurement of the illuminance. This is reflected in the 'toolbox', that is used by practical photometrists: its main tool is the device to measure illuminances – for short, the luxmeter.

(b) Luxmeters

Not only is the luxmeter the primary tool of the photometrist, the illuminance is also the main criterion to describe the characteristics of a lighting installation. When one knows the lighting level – or rather, the illuminance level – in a lighting installation, the other criteria of quality can, as an approximation, derived from it. More important, luxmeters are very simple instruments, that are easy to construct, as well as easy to maintain. In fact, the practical standard in an engineering photometric laboratory usually is a calibrated luxmeter, that is used to check all other equipment.

Luxmeters exist in all ranges of precision, size, handling and, of course, price. Simple luxmeters are of the barrier layer type that is discussed in sec. 14.5.1d. Usually, the photocell is made of selenium, and no external electric power supply is needed. Their range is usually from about 100 to about 100 000 lux, that is, they are suited for higher class interior lighting, and for daytime use outdoors. Usually, their overall level of error is at least 10%. They range in price from some 20 euro to a few hundred euro. More advanced luxmeters usually use silicium photodiodes, that require an external power source. They range from intermediate equipment, which can measure down to maybe 0,1 lux, with a precision of a few percent, and a price of one or two thousand euros, to the top levels, that measure from the microlux levels up to the megalux levels, with a precision better that 0,1%. They may cost up to 100 000 euro. They require, apart from a copious budget, expert operators to reach the top quality results. Precise photometry is not anybody's job. There are many manufacturers of such equipment in the world. No brand names will be given here.

Luminous intensities of light sources are usually measured with standard luxmeters. The only thing to do is to measure the distance between the meter and the source very precisely. The high precision is needed, because, according to the 'inverse square law', that is discussed in sec. 14.1.5d, a slight error in the distance will result in a large error in the measured value of the luminous intensity. The 'distance law', that is discussed in sec. 14.1.5f, requires that the distance between the meter and the source must be at least 5 times, and preferably at least 10 times, the dimensions of the source.

(c) Luminance meters

The measurement of the luminance requires a somewhat different arrangement of the equipment. Essentially, luminance meters are just plain luxmeters, where the angular range from which light is still taken into account, is limited and precisely restricted. This area represents the measuring field: the luminance is measured for all elements that show up within the measuring field. The only thing to do is to calibrate the meter in luminance values in stead of in illuminance values. Most luminance meters have silicium photodiodes, or in special cases, photomultipliers as a detector. As regards the optical system, usually luminance meters have a lens and diaphragm – 'stop' – system that limits the measuring field. This may be somewhere between 1 and 5 degrees in diameter. If the measuring field is much smaller, one may speak of a 'spot meter'. The measuring field may go dow to some 5, or even 2, minutes of arc. Because the narrow measuring field restricts the number of photons that may reach the detector, usually quite complicated electronic gear is needed. Medium priced luminance meters, costing several thousand euro, may go down to about 0,1 cd/m^2, which is not sufficient for most outdoor lighting installations. However, in road lighting, the requirements are usually much higher. In residential streets the darkest spots on the road may have an illuminance of about 0,1 lux, which corresponds to about 0,005 cd/m^2 (NSVV, 1990a, CIE, 1995b). Meters that can measure such low values accurately, must have a lower limit that is about a factor 10 better, that is a luminance of about 0,0005 cd/m^2. Particularly for spot meters, the number of photons that may reach the detector is very small, so that the requirements for the equipment is very high. Such meters are difficult to use, they need careful handling and frequent calibration, and are quite costly. Prices range to 100 000 euro or considerably more.

As is explained in some detail in sec. 14.5.2, more recently CCD cameras are often used for luminance measurements. It is explained that CCD cameras are very useful, both in engineering luminance measurements at high luminance levels, like e.g. office or tunnel lighting, and in astronomic photometry. It is also explained that CCD cameras are less suitable for measuring outdoor lighting installations.

(d) The measuring grid

In sec. 14.1.6f, when discussing the average luminance and the non-uniformity in road lighting, it is explained that the present definitions of luminances and illuminances that are used in CIE and CEN, are not fully satisfactory. In that section, the definition of the position of the observer is discussed, resulting in the conclusion that most measurements use a stationary observer, whereas almost all calculations are based on the concept of the 'moving observer'. In this section, the unsatisfactory situation as regards the measuring and calculation grid in road lighting is discussed, leading to some further suggestions. These considerations are based an unpublished report, prepared for discussion in CIE and CEN (Schreuder, 1995a).

In sec. 14.1.6f, it is suggested to define all luminance values in road lighting on the 'moving observer' concept. This would require some adaptations in the calculations methods, and much more adaptations in the measuring systems.

The measuring angle is, however, not the only instance where the present definitions of CIE and CEN, are not fully satisfactory. In this section, the differences in the systems used to define grid points, and the cross-wise position fo the observer in different conditions. Many aspects of the different considerations are given in publications about road and tunnel lighting (CEN, 2001; CIE, 1976, 1984, 1984a, 1990, 1990a, 2003a; Huijben, ed., 2003).

In view of what is suggested in sec. 14.1.6f about the angle of observation, it seems best to assess – measure or calculate – the road surface luminance and the illuminance on the road in all cases in points on the road. The average road surface luminance and the average illuminance, and the different measures of the non-uniformity are derived from the values of the points. In order to be able to compare measurements and calculations for the same road, the points must be located in a 'grid'. For straight, level and flat road surfaces, is seems logical to use a regular grid. As mentioned in sec. 14.1.6f, the usual photometric measures are not properly and uniformly defined for other – irregular – roads. CIE requires that measuring points – or grid points – are always on the intersections of equidistant lines parallel to and perpendicular to the length-wise road axis. The grid is therefore both rectilinear and homogeneous. The interdistance of the length-lines usually differs from that of the cross-lines. According to the application, the grids may differ in fineness. A fine grid always needs to contain all the grid points of any corresponding coarse grid. The grid points of a coarse grid form a 'sub-set' of the 'set' of the grid points of the fine grid. The calculations of the luminance and of the illuminance must always use similar grids, the fineness of which may differ. Otherwise, it is not possible to compare measurements and calculations from one and the same road directly.

As is mentioned in sec. 14.1.6f, and discussed in detail in Schreuder (1998, sec. 5.4.6, p. 68-69), a 'point' on the road always has certain dimensions. The dimensions depend on the distance between the observer and the point. Usually, a 'point' measures several centimeters in width and several decimeters in length. As far as visual observation is regarded, in the foreshortened perspective image of the road, such dimensions may be disregarded.

Each grid point belongs to an area on the road of which that grid point is the centre. There areas are called 'tiles'. Because tiles are considered as the smallest area to be considered, it is postulated that the calculated values of the luminance and of the illuminance are assumed to be equal to the average values of the 'tile' of which the point under consideration is the centre. In reality, of course, a 'point' has dimensions. These dimensions are disregarded, and the point is considered as a mathematical 'point'. Of course, the illuminance, as well as the luminance, may vary slightly, even over such a small area as a 'tile'. The size of the tile is determined by the pattern. The length- and cross-lines of the grid determine the centre of the tiles; the sides of the tiles are always halfway between the grid points. The tiles together determine the total area of measurement and/or of calculation.

There are several methods to spread the tiles over the surface. It is suggested here to put the 'points' in the centre of the 'tiles', whereas in some systems, the points are on the intersections of the length- and cross-lines of the grid. It might seem that, as long as the number of tiles is not too small, it will make little difference which system is selected. It is not possible to be very precise in stating 'not too small', but some 12 tiles seem to be sufficient. More important, different grids are used in different calculation systems and in different programs. And also, the grid points of a coarse grid do not always form a 'sub-set' of the set of the grid points of the fine grid. This implies that different calculations using the same data may lead to quite different results.

(e) The luminous flux; the light distribution

The luminous flux can measured in exactly the same way as the luminous intensity, more in particular the luminous intensity distribution of a light source, like e.g. the light distribution of a luminaire. At a certain distance, the intensity is measured. Actually, as is explained earlier, it is a measurement of the illuminance at that particular location. This is repeated for so many directions as is relevant for the type of light source. If the light distribution is needed, the values of the intensity in different directions are plotted. If the luminous flux is needed, all values are integrated. The integration process can, of course, also be made by integrating directly all light that is coming from the source. This is done by placing the source in a integrating photometric sphere, often called the Ulbricht sphere. If the inside of the sphere is covered by a material that reflects all incident light, by the action of multiple reflections, the luminance of the interior will be completely uniform over the complete surface, independent of the light distribution of the source. Measuring this luminance yields directly the total luminous flux of the source.

(f) Measurement of the luminance factor

As is explained in sec. 14.1.8a, the luminance of an object is proportional to the illuminance, the coefficient of proportionality being the luminance factor. It can be expressed simply as:

$$L = R \cdot E \qquad [14.1.12]$$

with:
L: the luminance;
E: the illuminance;
R: the luminance factor.

Relation [14.1.12] can be written as:

$$R = \frac{L}{E} \qquad [14.5.5]$$

In principle, the measurement of the luminance factor follows directly from its definition. All one has to do, is to measure the illuminance and the luminance in the way as is explained earlier in this section. This method can be used if the surface is a perfect – or Lambertian – diffuser. In that case, both the luminance and the illuminance are scalars. If the surface is not a perfect diffuser, the reflection will depend on the direction of the incident light and of the reflected light. Both quantities therefore show magnitude and direction, and can be described as a vector. As is explained in sec. 14.1.8a, they have a vectorial character, showing both without being, mathematically speaking, 'true' vectors, as vector summation usually is not valid. The product, or the quotient, of two vectors, is of course, a tensor. A tensor is described by five variables, the four angular variables of the illuminance and of the luminance together, and the fifth, which again describes the 'amount'. This again is a scalar; it simply is the quotient of the scalar parts of the illuminance and the luminance. See also Schreuder (1967a, sec. 3.3.1; 1998, sec. 10.4). As is mentioned earlier, the theory of vectors and of vector analysis is discussed in great detail in Feynman et al,. (1977, sec. I-11 and sec. II-12). The theory of tensor and tensor calculus is discussed equally detailed in Feynman et al,. (1977, sec. II-33).

In spite of the fact that we have to do with tensors, the measurement of the luminance factor still follows directly from its definition. All one has to do is to add the angular data to the measured values of the illuminance and the luminance.

If the reflection of a material shows a circular symmetry around the vertical – the normal – to its surface, it is said the be is isotropic. It is not important how the object is placed during the measurements. This is the case for most asphalt surfaces. Their reflection does not change when the surface is rotated around a vertical axis. Asphalt is the most common surface for traffic routes.

If, however, the material is not isotropic, one more variable must be added to the five we have mentioned already, the position of the sample. This is the case in many non-asphalt road surfaces, such as the bricks, paving stones, or concrete blocks that are extensively used in residential streets, and in many cement concrete roads that are grooved or 'brushed' to help any rain water to flow away without causing splash-and-spray or hydroplaning.

In sec. 14.1.8b, it is described in detail how the luminance factor of road surfaces is characterized. Several assumptions simplify the description. These assumptions are:
- the direction in which the road is observed – that is the direction in which the luminance is measured, is taken to be always 1 degree downward from the horizontal;
- the road surface material is considered as isotropic;
- the luminance factor is always linearly proportional to the value that is measured in one particular direction; usually, the vertical light incidence is used for this ($q_{0,0}$ or q_p).
- the road axis has no preferential status; the angles between the directions between the incident light, respectively the reflected light and the road axis, can be replaced by the angle between the incident and the reflected light.

With these assumptions, the five variables are reduced to only two, and the results can be represented in a plane. As is explained in sec. 14.1.8b, this table is called the R-table.

The methods that are used to measure the luminance factors of road surfaces, follow again directly from the definition. The R-tables, that are used at present, are based on laboratory measurements that have been made in different laboratories in Belgium, Canada, Denmark, France, Germany, and the Netherlands. In these laboratories, the equipment that was used, had the same layout in all cases. A road sample was placed horizontally. The light could strike the sample from many directions. The reflected light was measured by a luminance meter, that was aimed at a small part of the sample. The luminance was recorded for many directions of light incidence. The direction were divided over half a sphere, in such a way that it was easy to construct a R-table. See CIE (1984), Erbay (1973) and Kebschull (1968). R-tables of road surface materials that were common in the 1970s, are collected in Erbay (1974). See also Erbay & Stolzenberg (1975). An example of these measuring methods is described in detail in Schreuder (1967a, sec. 3.3.2, p. 111-112), and in summary in CIE (1994) and Van Bommel & De Boer (1980, sec. 14.2.5, p. 221-222). See also Jung et al. (1983).

The main disadvantage of these methods was, that the reflection was measured on samples. It is well-known, that taking samples out of the road, transporting them, and waiting until the measurements and made, will change the reflection properties considerably (SCW, 1974, 1984). So, one never will know precisely, what the reflection characteristics of the actual road are. Furthermore, the methods are very expensive, as a result of the complicated equipment and the time-consuming measurements. Because, as is explained later on, the samples need to be quite large, the holes in the road are large as well. Many road authorities do not like their roads to be studded with large holes. Consequently, such measurements are not made any more on a large scale. The standard R-tables that are used in road lighting calculations, are based on measurements from the 1950s and 1960s (CIE, 2001). Measurements of this type are only made for special purposes. See e.g. De Haan (1996); Gillet & Rombauts (2001, 2003); Laporte & Gillet (2003).

A number of attempts have been made to measure the road reflection on the road itself. A system that allows to measure individual reflection values, is described in Range (1972, 1973). See also Van Bommel & De Boer (1980, sec. 14.2.5, p. 221-222). Another device, where eight measurements were made simultaneously, is described in Anon (1979) and Obro & Sorensen (1976). See also Van Bommel & De Boer (1980, p. 221) and Schreuder (1998, p. 72-73). The attempts were not successful, primarily because normal road surfaces cannot be described by very small samples of only a few centimeters. Also, at that time, the electronic circuitry needed for the data processing were not available. More recently, a proposal has been made that may overcome these problems. The principle is described in Schreuder (1991a). Measurements, using a prototype, are described in Schreuder (1992).

Also, a method is developed, that could measure the integral value of the reflection values. It has been described in some detail in Schreuder (1967, sec 8.5, p. 468-473). See also De Boer & Vermeulen (1967). Also here, the small sample size and the restriction in the data processing, made further development of this system unfeasible.

Finally, a few words about the measurement of the reflection of retroreflecting devices. Again here, the illuminance on the surface and the luminance of the lighted surface are measured. Because these measurements are usually done only in laboratories, mainly in certified test houses, we will just mention a few CIE documents, where further information may be found. CIE, 1980, 1987, 1988, 1995, 2001a).

14.6 Measuring light pollution

14.6.1 The values of the sky glow

The following section is in part based on Schreuder (1993, 1993a, 1994). See also Schreuder (1994a). Many aspects have been subsequently used in the drafting of the CIE Guidelines for Reducing Sky Glow (CIE, 1997, summarized in Schreuder, 1997). Several more recent publications have also been taken into account. See also CIE (1978, 1993, 2001, 2003).

The level of the sky glow, even at the same location, is not a constant in time:
- it changes with time, not only throughout the night, but also seasonally and with the solar cycle;
- it changes with haze level – meteorological visibility –, a.o. as a result of changes in water content of the air;
- it varies with altitude and azimuth;
- it is a non-constant function of wavelength;
- the actual values may also depend upon the way of assessment.

Many practical recommendations for the measurements of the sky luminance can be found in specialized textbooks, like e.g. Budding (1993, sec. 5.1, 5.3); Cinzano (1997, sec. 3.2.6); Crawford, ed. (1991); Howell (2001, sec. 1.2); Isobe & Hirayama (1998); Schwarz, ed. (2003); Sterken & Manfroid (1992, sec. 15.1, 15.6).

For different purposes, different systems and methods are in use. At present, none of these systems is standardized. It is proposed to standardize a number of different methods for different applications, but efforts have had little success so far (CIE, 1993, 1997; Crawford (1991, 1997), McNally, ed., (1994), Mizon (2002). A proposal for a standard method to measure sky luminance is described in sec. 14.6.2e. The different methods that are in use, are described in the following sections:
(1) For simple area surveys: limit star assessment, star counting, photographic surveys (Sec. 14.6.2);
(2) For continuous surveys: monitoring (Sec. 14.6.3);
(3) For site selection: wide angle telescope systems (Sec. 14.6.4);
(4) For accurate site monitoring: standard telescopic photometry (Sec. 14.6.5);
(5) Global measurements; satellite methods (Sec. 14.6.6).

14.6.2 Simple area surveys

(a) Use of surveys

Walker's law, that is discussed in sec. 5.1.3, directly suggests several methods to measure sky glow. Such systems are widely adopted, although in many applications it is felt that the elevation angle of 45 degrees is too large to represent the reduction of visibility of objects near the horizon. For other applications, like the establishment of the disturbance for residents near intense lighting like sports stadiums or greenhouses with assimilation lighting, an angle of 30 or 15 degrees is often used (Van Berghem-Jansen & Vos, 1991).

For many reasons, surveys over large areas may be required. Some major reasons are:
- the selection of non-sky glow zones, or 'dark zones';
- the monitoring of the situation on region-wide or even nation-wide scale;
- the selection of sites for amateur astronomers;
- studies of influence of sky glow on public health;
- studies of influence of sky glow on animal and plant wildlife.

The method must be simple and cheap, and the assessments must be made by amateurs or even by lay persons. Three systems, that are used presently at a large scale, deserve to be standardized: limit star assessment, star counting and photographic surveys.

(b) Limit star assessment

The most obvious method, and also the method that comes closest to the actual question of sky glow, is the establishment of the magnitude of the stars that are 'just' visible – the limit stars. Stars of known magnitudes are looked for and the faintest to be seen determines the sky limit. Obviously, the method is subjective in part, as the visual acuity of the observer comes into play. When due account is taken, e.g. by using the well-known epidemiological data on visual acuity distribution, the method may be used on a large scale. The use of binoculars is not recommended, because there are no general data on the optical quality of binoculars available.

As is explained in sec. 9.1.7g, Hipparchus, in about 120 B.C., classified the stars that can be seen by the naked eye in six classes, called magnitudes. The magnitudes represent equal steps in visual perception (Sterken & Manfroid, 1992, p. 23). As is explained in that section as well, the 'traditional' value for the limiting magnitude for stars is about 6,0 magnitude (Schaefer, 2003). See also Schaefer (1993).

In sec. 14.3.6c, when discussing the number of visible stars, three different surveys are mentioned, stemming from very different sources and from different times. They are summarized in Table 14.3.8. Although one may safely assume that neither the stars, nor the visual systems of people did change much in 150 years, the differences in the published numbers are striking. The data are included to serve as a warning, not to rely too much on data about limiting magnitudes

Just as with the method of 'star counting' that is explained in the next part of this section, care must be taken in regions near cities. The sky brightness is usually very uneven and the limiting magnitude can be a function of the position in the sky, and perhaps also of the time of night and season as much or more than it is a measure of sky clarity (Upgren, 1997, p. 21). Another form of this method is to observe relatively bright stars near the horizon. "The method is of use only on the very clearest of nights" (Upgren, 1997, p. 22). It determines the limiting magnitude as a function of elevation and it can be used to monitor the changes in sky brightness over time. One example shows the importance of high-level aerosols. At a specific location in the USA, the effect of the volcanic eruption of Mount Pinatubo in the Philippines could be estimated. The difference 'before and after' was about 0,45 magnitude. It seems that the lighting did not change very much in that period, because the limit came back after a few years back to the original values, when the atmosphere was cleared of the Pinatubo debris (Upgren, 1997, p. 23).

Several important conclusions have been presented by comparing zenith data at two locations, 3,5 km apart. One is a suburban location in a small town (Middletown, Connecticut, USA), the other the relatively dark location of the Van Vleck Observatory at the campus of the Wesleyan University. The zenith sky brightness for the two locations were calculated as being 18,7 mag per square arcsec and 20,1 respectively (Garstang, 1989, 1992, 1993). They were measured as being between 20,1 and 18,7 for the first location and between 20,5 and 20,1 for the second location.

The paper offers the following three conclusions:
(1) The calculated and measured values are in good agreement;
(2) "Since the two sites are so close to each other, the disparity between the zenith brightnesses indicate that very local lighting is relatively more predominant than is accounted for in many sky brightness models (e.g. Garstang, 1991);
(3) The densest layers of aerosols may be more limited in elevation than is commonly believed" (Upgren, 1997, p. 24).

This final statement seems to agree well with unpublished results of Soardo (2003).

(c) Star counting

Another method that is used in several countries, is the star counting method (Crawford, 1991; Kosai & Isobe, 1988; Kosai et al., 1994). Using a precise instruction, the number of stars visible to the naked eye in the Pleiades is counted. As the magnitudes of all stars in the Pleiades is accurately known, the limiting magnitude, and thus the level of the sky glow, can be assessed. A similar action in proposed in Austria. Details are given in sec. 15.2a. See also Anon. (2003a).

Both for limit star assessment as for star counting, it is necessary to know the relation between the magnitude of the limit star and the luminance of the sky glow. Also, the number of visible stars of different magnitude. In sec 14.3.2c, several tables are given for this; we will repeat here the table given by Schmidt (2002), based on the table of Mizon (2002). This table has been given earlier as Table 14.3.7.

Limiting magnitude	Number of stars visible	
+7	about 7000	
+6	about 2500	
+5	about 800	
+4	under 400	(Milky Way not visible)
+3	under 50	
+2	under 25	

Table 14.6.1: *Number of visible stars versus limiting star magnitude (Schmidt, 2002, Table 1; Mizon, 2002, p. 34.*

(d) Photographic surveys

Photographic surveys are made by inviting a large number of amateur observers, that need not be amateur astronomers, to take pictures with a normal camera in a fixed position, and with a normal slide film of the zenith area in their own neighbourhood. The camera must have a focal length of 50-55 mm and an aperture of 2.0 or more. The exposures are made on 400 ASA colour reverse slide films at a stop of 4 with an exposure time of 80 sec. From the relation in film density between the background and the track of known stars, the sky luminance can be assessed. Details are given by Kosai & Isobe (1988) and in Kosai et al. (1993). The results of the measurements are described in sec. 5.2.3b. In Japan, the sky glow in densely populated and heavily industrialized areas like the regions of Tokyo, Yokohama, and Osaka is about 4 magnitudes or even more than that in rural areas, corresponding to almost a factor of 100 (Kosai et al., 1994). In the Netherlands, similar measurements have been made. Even over large areas the average varies more than 0,5 magnitude (Schreuder, 1994, 1999). A similar set-up is described in Cinzano (1996 p. 122, quoting Foti, 1992). Finally, we may mention the measurements made in the surroundings of the Van Vleck Observatory in the USA (Upgren, 1997). In sec. 14.5.2a, it is mentioned that, most probably, similar measurements can be made with digital cameras. The organization can be simplified, as thus the costs, because the results can be send by electronic mail.

(e) A proposal for a standard measuring method

In order to compare the measurements of sky glow from different locations and different moments in time, the following standardized geometry is proposed (Schreuder, 1997). Within a cone that measures 2·5° around the zenith, which means a total opening angle of 10°, the average luminance of the sky is measured. In addition, six more measurements are made, each in a cone of 2·5°, that join the cone around the zenith. The lowest of these seven measurements is considered as the appropriate value of the sky glow at that place and time. The measurements may be supplemented by a number of cone measurements in other directions to assess the sky glow distribution over the sky.

For more precise measurements, the measuring field is restricted to 1° or even to several seconds of arc. In this way, the influence of background stars may be reduced. However, such measurements require a high-class telescope and the direction, or the location in the sky, has to be recorded separately.

All sky glow measurements are made at an elevation higher that 15°. The reason is that only in very exceptional cases, observations are made with an elevation of less than 15°. The sky glow close to the horizon is primarily an aesthetic disturbance as it does not interfere with observations. Any 'light smudges' from distant cities that are seen near the horizon, need to be considered, but not on the grounds of any disturbance of astronomical observations. As is explained in sec. 3.4.4, the effect is usually referred to as horizon pollution. It can be a problem in daytime, as well as during the night. It should be noted, however, that light emitted by distant sources under angles below 15° may contribute considerably to the sky glow and cannot be disregarded (Cinzano & Diaz Castro, 2000).

14.6.3 Continuous surveys and sky glow monitoring

A continuous survey of the sky glow can be made by monitoring the sky brightness. Several companies market sky scanners for daylight measurements. As an example, we give here a short description of the PRC sky scanner of that is marketed by Krochmann GMBH in Berlin. It is a photometer for the fast measurement of the sky luminance distribution for continuous, maintenance-free usage. The sky luminance distribution is measured in 145 nearly equidistant directions. The luminance is measured with a 10 degree view angle. Obviously, these specifications would fulfill the requirement for the measurements of sky glow. However, the sensitivity of the apparatus must be adapted to the low levels of the night sky, e.g. by using a photo-multiplier tube. Experimentally, this has been done, allowing a sensitivity of 0,01 cd/m^2 (Özver-Krochmann, 1993). This sensitivity is, of course, not enough to measure sky luminances in really dark areas. As is explained in another section of this book, the value that usually is taken for the practical minimum of the natural background radiation, is 21,6 magnitude per square arcsec, which corresponds to $3{,}52 \cdot 10^{-4}$ cd/m^2. (CIE, 1997).

Another method is mentioned in Cinzano (1996, sec. 3.2.2, p. 122). Without giving further details, it is mentioned that photographic measurements of sky glow can be made with a fish eye camera. No data are given about film sensitivity or exposure times, but it is likely that they will be similar to those for use of normal cameras, as is described in an earlier part of this section. In several publications, fish eye photographs are used to explain sky glow effects, more in particular to explain the horizon pollution, that is mentioned in another section of this book. See e.g. Cinzano (1996, figure 4.2, p. 144).

A number of detailed 'technical' aspects of site monitoring are given in Cinzano (1996, p. 125-126). As is mentioned earlier, also many more general useful recommendations about the measurement of sky glow are given by Cinzano (1996, p. 117-120).

In order to do accurate site monitoring at existing observatories, normal astronomical telescopes can be used with the standard equipment to perform photometry. This is done in many observatories on a routine bases. An instrument in use at the Observatory of the Canary Islands is described by Diaz Castro (1993) See also Diaz Castro & De la Paz (2003).

14.6.4 Site selection

Probably, the most useful type of instrument that can be used for site selection is the wide angle telescope system. Wide angle transportable telescopes are available on a very wide scale. Most can be adapted, some even with standard equipment, to do the type of photometry required to assess the sky glow at different sites. Usually, the accuracy seems to be quite adequate. There is, however, no standardized method to do the measurements. The proposed standard measuring method that is described in sec. 14.6.2e might be useful, but there is not yet any practical experience.

14.6.5 Accurate site monitoring

In order to do accurate site monitoring at existing observatories, normal astronomical telescopes can be used with the standard equipment to perform photometry. This is done in many observatories on a routine bases. As an example, the instrument that is in use since 1995 at La Palma observatory in the Canary Islands is described here briefly. The description follows the design as reported by Diaz Castro (1993). See also Diaz Castro & De la Paz (2003). The equipment consists of:

- a photo-electric photometer model SSP-5A1 (OPTEC Inc) with the R4457PMT. In order to achieve the requirements, the Fabry-type lens of the SSP-5A will be adapted;
- an alt-azimuth mounting system with system model LX-200 (Meade) with an RS-232 port for interfacing with a PC;
- a 6-position filter slider with UBVR and 588 nm Na filter (OPTEC, Inc). It comes with an SSP3CARD computer interface;
- a telescope with an aperture of at least a 50 mm, and a 1 degree field.

14.6.6 Global measurements; satellite methods

As is described in considerable detail in sec. 5.3, Cinzano and his colleagues have spent the last decade in establishing of 'The First World Atlas of the Artificial Night Sky Brightness'. This atlas will be published in the near future; a preprint is already available (Cinzano et al., 2001a). Some recent extensions of the efforts are mentioned in Floor (2004); Smith (2003) and Petrakis (2003). It is difficult to overestimate the importance of this endeavour; the widespread attention in the scientific press as well as in publications for the general public is therefore fully justified. A few examples: Cinzano (1994, 2002); Cinzano et al. (1999, 2000, 2001).

As is explained in great detail in Cinzano et al. (2000), the Atlas is based on measurements that are made on a continuous basis by the Defense Meteorological Satellite Program (DMSP). In the description of the technical aspects, extensive use is made of this publication, more in particular of the Chapters 2 and 4 (Cinzano et al., 2000). The predecessor of the Atlas was the image produced by Sullivan (1989, 1991). These images had a considerable impact, but because they were based on analogue pictures, they could not be used in a quantitative way. This became possible when the DMSP data could be treated digitally (Elvidge et al., 1997, 1997 a,b).

The results of the satellite measurements are discussed in detail in sec. 5.3.1 and 5.3.3, more in particular in relation to the population for different cities and to the population of different countries. See also Petrakis (2003).

It is also explained that, for the application of satellite data for actual lighting design, more detailed data sets are required. An example of such detailed sets is given by Isobe & Kosai (1994, 1998). As mentioned in that section, nation-wide contour maps of the whole of Japan are given. In addition, for two cities, much more detailed data are given.

14.6.7 Measuring light trespass

The requirements that are made on light trespass, are expressed primarily in the vertical illuminance. In some standards, it is required that the measurements have to be made at the property border (CIE, 1995a, 2003; IESNA, 1999). In other standards, the facade, or the windows in it, of the building where the people that are bothered by light intrusion, do live (NSVV, 1999, 2003; LITG, 1996; Assmann et al., 1987, 1991; Hartmann, 1984; Hartmann et al., 1984; Anon, 1990, 1998a, 2000a). Usually, the illuminance limits refer to the maximum. The limiting values are usually somewhat above 1 lux. There is no special problem in measuring it. It can easily be done by any reasonably accurate luxmeter. When the average illuminance is included in the requirements, a higher accuracy to about 0,1 lux is needed (Anon, 2000a). This implies a luxmeter of at least medium quality, but nothing fancy.

In many standards or recommendations, limiting values of the luminance of the surfaces that may cause the disturbance, are included. For facades, the limits are usually at least several cd/m^2, for signs often at least 10 times higher. These values are easy to measure with a spot luminance meter of medium quality. A spot meter is needed, because the limits are often expressed in the maximum within the area, or the average over the area, implying rather small angles. Again, no fancy requirements.

According tot the recommendations issued in the Netherlands (NSVV, 1999), the following requirements are given:

(1) Light trespass to be measured at a height of 1,5 m, at the border of the premisses including buffer zones, also if those are the responsibility of other authorities; in lux (vertical) including the full installation;

(2) Glare to be measured directly in the line of sight pointing into the most glaring of the luminaires; using the standard disability glare formula;

(3) Sky glow to be assessed allowing for the total upward flux (direct and reflected) taking into account the size (area) of the installation.

The matter is rather different for the case where limiting values are given concerning the luminous intensity of luminaires, or concerning their luminance. This is sometimes done for the lighting of sport facilities (NSVV, 1999). Usually, the data provided by the manufacturers are not sufficient, because the recommendations usually refer to the situation as is found in practice. Furthermore, in many cases, the directions in which the luminous intensity or the luminance must be assessed, is precisely prescribed. In principle, the luminous intensity can be determined when the illuminance and the distance are known. This is explained in sec. 14.1.5e, where photometric distance law is described. In practice, this means that the luxmeter must be screened precisely, so that only light from a particular luminaire is received, and the meter must be aimed precisely at that luminaire. With common luxmeters, this can hardly be done. Furthermore, in case the luminaires are far away, the resulting illuminance may be very low. And finally, the distance must precisely be known, because the square of the distance shows up in the photometric distance law. Another way is to use an accurate spot luminance meter, when it is calibrated as a luxmeter. This is also difficult, because the luminance distribution over the luminaire, as well as its projected size, must be known. Also, the distance must be known. When the luminance is required, again the luminance distribution over the luminaire must be known. It can be measured, but this requires a spot meter with a very small measuring angle, when the distance is large. And finally, in all field measurements, the absorption of light in the atmosphere can be considerable at a large distance. This is depicted in Figure 14.6.1.

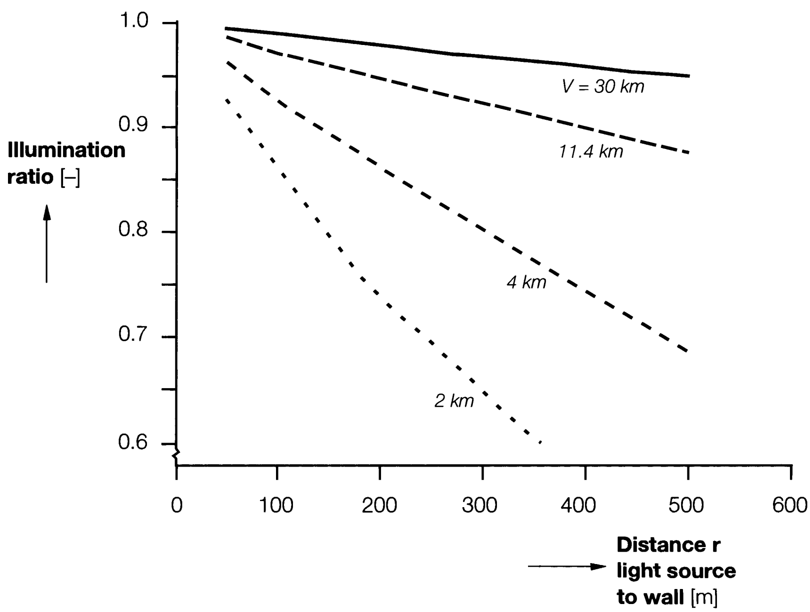

Figure 14.6.1: *The absorption factor against the measuring distance for various values of the meteorological visibility. After NSVV, 2003a,d.*

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15 Public aspects

Astronomy is a World Power. The famous TV coverage of the space module Giotto passing the Halley comet in 1987, attracted about 1 000 million viewers in over 37 countries – about the same amount as the finals of the soccer football world championships. Astronomy is only a few centuries old. Before that, there was only astrology. Astronomy is 'clean', contrary to biology, medicine or physics. However, astronomy is an endangered science. The aims of astronomy are nothing less than to search for the origins of the Universe. This is inextricably linked with the need for mankind to understand its place in the Universe.

Astronomy is a human intellectual endeavour which runs throughout the history of civilization. Astronomy is facing a crisis – the observation of faint astronomical objects may soon become impossible because the spread of 'civilized' lifestyles. Astronomy, an exponent of the modern lifestyle is threatened by extinction by the same civilization.

Not so long ago, many astronomers considered lighting engineers as greedy misers who had no other goal in life that to sell as many lamps and as much electricity as possible. On the other hand, many lighting engineers considered astronomers as absent-minded theorists who used lots of taxpayers' money to study, from the tops of distant mountains, matter that is without any significance whatsoever. The relation between astronomers and lighting engineers has been strained in the past, but did improve considerably since then.

A major source of difficulty at urban as well as the best observatory sites is the rising level of pollution from the increasing level of outdoor lighting. No wonder that the two professions are not always on a good footing. It is one of the major goals of this book to repair this situation, to explain the needs and possibilities of each profession to the other, and, essentially, to try to create mutual respect between the two professions.

A major problem, insofar as light pollution is concerned, is the education of the public. Outreach is the conscious and concerted activity of the members of *organizations, to go out, and distribute and clarify the essential message of their organization to the general public. The International Dark-Sky Association, or IDA, provides information that can be the basis for outreach programmes.*

Training, teaching, and education have one thing in common: they all refer to the transfer of information from a sender to a receiver. Training is related to the acquisition of basic skills. Teaching involves a systematic transfer of information from the teacher to the student. Teaching means the acquisition of knowledge and insight. Education is aimed at the acquisition of a certain attitude. Education involves moral and spiritual aspects.

Light that goes where it does not belong, represents economic losses; it is an assault on the natural environment, and may have negative public health effects. Light is often considered as a pollutant. Also, the intrusion itself is often regarded a legal infringement of property.

When public benefits and personal profits collide, usually the private profits win. Legislation and regulation are needed, both as regards civil and penal legislation. Site selection and protection requires local ordinances. This chapter gives frameworks for lighting codes. Finally, examples of local ordinances, of outdoor lighting projects and in general, of activities that are happening around the world.

15.1 Astronomy and lighting engineering in the world

(a) *Astronomy as a World Power*

Not everybody, even not all astronomers, are conscious of the place of astronomy as a scientific endeavour in society. One might speak of a 'World Power'. As an example, the famous TV coverage of the space module Giotto passing the Halley comet in 1987, attracted about 1 000 million viewers in over 37 countries – about the same amount as the finals of the soccer-football world championships (Schreuder, 1990). One might speculate about this special place of astronomy in the general opinion. One point might be the apparent antiquity of astronomy; however, astronomy is only a few centuries old. Before that, there was only astrology, an activity that is vehemently rejected by most scientists – probably unjustified.

More likely is the general opinion that astronomy is 'clean', contrary to biology, where genetic manipulation of plants and animals is promoted, medicine that wants to clone humans, and physics that built atom bombs. Nonsense of course, but the public opinion is both irrational and strong. Astronomy seems to profit from that. Scientists in most other disciplines look somewhat jealously at the funds that are made available for astrophysical research. It is one of the objectives of this book, to interest the general opinion in such a way that the restriction of light pollution is treated just as generously. It is essential to note that the public opinion is the driving force behind taking political decisions; the main tool is the impact of the media on public and politics alike. These points will be discussed in the further sections of this chapter.

(b) Astronomy as an endangered science

The following considerations are based on a quotation of parts of paper given by Paul Murdin, at that time of the Royal Observatory in Edinburgh, at the LuxEurpa Conference on 'Urban sky glow, A worry for astronomers', held on Saturday 3 April 1993 at the Royal Observatory in Edinburgh (Murdin, 1993). See also Murdin (1994).

The aims of astronomy are nothing less than to search for the origins of the Universe, and of its constituent stars and galaxies. The contemplation of the origins of the Universe has been the aim of astronomy for thousands of years and over many cultures. This is inextricably linked with the need for mankind to understand its place in the Universe. The subject matter of astronomy in the twentieth century is the nature of everything outside the Earth, including the Moon and planets, the stars, the Milky Way and the Universe of galaxies.

The planets, stars and galaxies are the celestial stage on which human life and mundane affairs are set. Astronomers of the past, the present and the future, study astronomy to understand the context of mankind's own place and origins.

By our understanding we place ourselves in the environment of the Universe. In the first place, we give ourselves a physical setting, like a stage set. We discover our relative insignificance, comparing our physical dimensions and those of the bodies most important to us – the Earth, the Sun and the Solar System. We discover that the material of which we are made is identical to the material of the heavenly bodies, indeed was once inside other heavenly bodies – stars, supernovae, nebulae. With discoveries like these we satisfy our innate curiosity about our ultimate origins.

We also realize that we are a part of the Universe – not apart from it. This is true, not only in material terms, or in terms of space and time, but also in a more sophisticated sense – we are a part of the Universe within the forces of nature. By our understanding of astronomy, we generate confidence in our human abilities of comprehension and what we can achieve for ourselves. It is not perverse of astronomers to want to study faint things, when there are so many brighter things in the sky; it is essential, it is our destiny.

Large and powerful telescopes are required to gather large amounts of light from whatever source; they are equally excellent in gathering light from distant galaxies, but they gather light from any interfering dazzle just as well. So astronomers build the biggest telescopes on the most distant dark mountain sites away from interference. However, it is well-known that the dazzle of bright lights has the potential to overpower the faint signals of distant galaxies and quasars. It is this potential for interference which endangers astronomy.

Astronomy is a human intellectual endeavour which runs throughout the history of civilization. Its aim is nothing less than the understanding of the origins of the Universe. It has the potential at the present time, from the scientific and technological advances which have been created in recent times, to fulfil these aims. To progress in doing so astronomy must be protected from its dangers!

(c) The relation between astronomers and lighting engineers

The considerations given by Murdin, that were quoted in the preceding part of this section, point out one aspect clearly. It is worded by McNally as follows: "Astronomy is facing a crisis – the observation of faint astronomical objects may soon become impossible because the spread of 'civilized' lifestyles. Now, and in the foreseeable future, mankind will continue to consume great amounts of energy, to extend the working day to a full twenty-four hours and rely heavily on rapid worldwide communications. Such a lifestyle is the norm for the developed world and is the goal of the developing world" (McNally, 1994, p. 3). The working day extends not only to 24 hours a day, but also to 7 days a week – known as '24/7'. It is ironic that astronomy, an exponent of the modern lifestyle, of the modern civilization if one would wish to call it so, will be threatened by extinction by the same civilization (McNally, 1994, p. 3). One can think about the blessings of modern civilization in different ways, but two things must be made perfectly clear. First, the civilization is here to stay for quite some time, and second, astronomy would be impossible without that same civilization. Not only would there be no technology for all the paraphernalia of the trade, but without civilization, there would be no interest in the heavenly bodies. So, all suggestions of a controversy between astronomy and civilization are difficult to marry with considerations of clear thinking or common sense!

But there is more to it. "A major source of difficulty at urban as well as the best observatory sites is the rising level of electromagnetic pollution from the increasing level of outdoor lighting" (McNally, 1994, p. 4). In this one sentence, the problems in the relation between astronomers and lighting engineers is made clear. Astronomers sometimes fancy that their science could exist without civilization, and furthermore, they consider that outdoor lighting as the culmination of the civilization, and of its technology. No wonder that the two professions are not always on a good footing.

It is one of the major goals of this book to repair this situation, to explain the needs and possibilities of each profession to the other, and, essentially, to try to create mutual respect between the two professions.

Not so long ago, many astronomers considered lighting engineers as greedy misers who had no other goal in life that to sell as many lamps and as much electricity as possible; some went even further and suggested that lighting engineering as a profession, was an enemy of astronomy. At the other hand, many lighting engineers considered astronomers as absent-minded theorists who used lots of taxpayers' money to study, from the tops of distant mountains, matter that is without any significance whatsoever. What makes thing worse, many astronomers seem to pretend to be an expert on all aspects of outdoor lighting, although they are completely ignorant about even the first principles of illuminating engineering. This might seem to be a caricature, but, alas, many publications prove it to be almost true. For obvious reasons, these publications are not mentioned here.

The issue is further complicated when the role of architects is taken into account. In many cases – engineers and astronomers tend to feel in far too many cases – architects have a large influence on how an outdoor lighting installation should look. Some architects deliver fascinating projects, but many disregard, not only the functional aspects of the installation, but also the impact on light pollution. The fact that there are people who want to involve another discipline – viz. the lighting designers – does not help (Pasariello, 2003).

(d) Political aspects

Fortunately, the relation between astronomers and lighting engineers did improve very much during the last one or two decades. As is explained in the introduction to this book, organizations like CIE, IDA, IAU, UNESCO and many others, did achieve a lot in this respect. Gradually, the opinion is gaining ground, that outdoor lighting is both necessary and complicated, and that by mutual effort of the astronomical and lighting engineering professions, compromises can be found which leave the benefits of lighting unaffected, and which leave plenty of opportunities for astronomers to do their work.

The main problem is, that well-designed optimal solutions cost money. That money stems in most cases from the public domain, that is governed by politicians. Now, it seems that the first thing that many politicians have in mind, is to be re-elected next time. Difficult things that do not give spectacular results, are not popular by that kind of politicians. Furthermore, the priorities of many politicians tend to shift rapidly. The environment, high on many lists only a few years ago, is replaced by the Information Superhighway, by the economic slum, by terrorism, by SARS, etc. In order to bring the interest of politicians back to environmental problems and issues, like the Kyoto protocol, or like light pollution on a somewhat smaller scale, it is essential that the two main disciplines involved, work close together.

It is one of the goals of this book to explain to politicians, to decision makers, and to other authorities the fact that light pollution may present many problems, both for astronomers and for others, but that, when the appropriate organizational and technical measures are taken, the damage and the hindrance can be reduced considerably.

15.2 Outreach, public awareness

(a) Outreach

When writing about light trespass, Tanner remarked that light trespass is a real problem to astronomers, and, to some extent, to the general public. “This means, that a major problem, insofar as light pollution is concerned, is the education of the public. The public is ignorant about many things that affects their environment. But they have even greater difficulty comprehending that anything as good and useful as light can be a pollutant" (Tanner, 1991, p. 85). This is definitely true, but, in referring to ligating organizations, it is mentioned that: "Most members earn their living selling light" (Tanner, 1991, p. 85).

These two quotes make clear the need, and the objectives, of what often is referred to as outreach. Outreach is the conscious and concerted activity of organizations, or rather of the members of organizations, to go out, and distribute and clarify the essential message of their organization to the general public. The second quote refers to the fact that most lighting people are selling light. It seems therefore, that professional lighting salespeople are probably not the best qualified to undertake the outreach activities in the area of light pollution. Here seems to be a need for 'educating the educators'. Education aspect are discussed in sec. 15.3.1.

Not all people seem to be satisfied with the 'soft' outreach approach to environmental problems. Sperling for one seems to agree with the 'hard' approach (Sperling, 1991). Many environmental activist organizations like Greenpeace apply violence in their approach. Recently, the Government Attorney in the Netherlands compared, in a televised official statement, animal right activists to terrorists (30 September 2003). Also, using personal pressure is advocated (Sperling, 1980). It is pointed out that: "Astronomers most often succeed when they exercise personal connections with government officials – a very depressing conclusion for societies so proud of their democracy" (Sperling, 1991, p. 104). It seems that, in this and in the preceding parts of this section, it is made clear that violence or political pressure are not the best means to find any long-term improvement in the light pollution situation.

A more positive, useful approach is advocated by Chester (1991). With he expansion of urban areas and their associated artificial illumination, amateur astronomers must travel further into the countryside to find dark skies. "By discouraging the amateurs, an important educational resource is lost to the public" (Chester, 1991, p. 109). This remark relates, of course, to those parts of the world where dark skies still do exist. As is explained in sec. 5.2.1, this is not the case any more in many regions of Western Europe and Asia. See e.g. Cinzano (2002), Schreuder (1999). The point is, however, that the value of the night sky as an educational tool is emphasized. See also Pikall et al. (2003).

As is explained in sec. 1.3.4, the International Dark-Sky Association, or IDA, provides information that can be the basis for all sorts of 'outreach' programmes. "IDA is formed to serve the public and the amateur and professional astronomical communities by providing information, education, and research on light pollution and related topics. IDA will share knowledge of the issue on a local, national, and international basis and will assist with members' problems. It was organized for the purpose of preserving dark skies for astronomy and for the general public" (Hunter et al., 1991, p. 110). By means of their many excellent publications, like their Information Sheets, they reach many more people than just the astronomers and that part of the general public that is interested in experiencing the night sky.

(b) International aspects

Light pollution is not restricted to one country only. It is a world-wide problem. But just as most other matters of environmental pollution, it is the industrialized countries, and particularly the densely populated countries that suffer most. Furthermore, there sometimes is an 'overflow' from one country to the next. Examples may be found in the 'World Atlas' that is referred to earlier (Cinzano, 2002). There are, however, even in these regions, specific areas that are relatively 'free' of light pollution. The connoisseurs guard these locations like a treasure, so that they will not be spoiled by housing, industry – or even worse – the 'tourist industry'. Just like wild life, the dark nights can easily be endangered by well-intended but clumsy attempts of eco-tourism.

The protection of the environment begins to be an important political issue in many countries, particularly in industrialized North-West Europe. The downfall of Communism confronted the West with the appalling situation that resulted from decades of mis-management. Usually, it takes some time before politicians wake up, but when they finally do, their force is – obviously as they form the government – considerable. In North-West Europe, this did lead to a serious environmental consciousness. As most measures to protect the environment are expensive, it is natural that governments begin with those measures that give the highest returns in cost/benefit terms, where the benefits may be monetary or electorial. Light pollution is not a direct threat to human life, and therefore most governments give toxic waste, nuclear fall-out, water pollution, and noise a higher priority. Nevertheless, there are many examples of national or regional governments that show interest in reducing the impact of light trespass and light pollution, e.g. as 'dark areas' in natural parks. More details are given in sec. 4.2.1.1; some examples of dark areas near astronomical observatories are briefly described in sec. 15.6.2a.

(c) Cultural aspects

There are other aspects as well. In 1992, the UNESCO hosted a conference 'Adverse environmental impacts on astronomy; An exposition' (McNally, ed., 1994). This conference concentrated on a number of cultural aspects of restricting light pollution. It was suggested that the few remaining pollution-free locations in the world, that are suitable for astronomical observatories, should be included in the Register of World Heritage Sites, giving them additional protection from intentional or unintentional damage (McNally, ed., 1994). See also Anon. (1997) and Schreuder (1993). However, it is not certain at all that these recommendations will have any follow-up. In some countries, there are specific legal measures and regulations. These are discussed in sec. 15.5.1.

(d) Awards for 'good lighting'

In the process of improving dark skies, it is customary to pay a lot of attention to lighting installations that contribute a lot to the light pollution. This is such a common trait, that one might come to think that most outdoor lighting is no good. Fortunately, this is not true. Experience of decades has shown that one usually has to look long and hard to find a really bad lighting installation. In spite of the fact that many people criticize the skills and the professional level of lighting engineers, the great majority of outdoor installations is designed up to a reasonable standard. The efforts that are mentioned in sec. 5.3, aimed at an improvement of the skills and at an increase of the professional level of lighting engineers, would help to get many more really good outdoor lighting installations.

It never helps to pay too much attention to the bad things in lighting – or in life in general. The situation does not improve; the only result is that many people end up in depressions. It is one of the ground rules of modern education, that rewarding desirable behaviour reinforces that behaviour, whereas punishing undesirable behaviour has little effect. In many cases, it may have even a negative effect, because punishment is also a form of reinforcement. The 'carrot and the whip' type of education has failed. Modern education is based on rewarding desirable behaviour, and ignoring undesirable behaviour.

One way to make people, particularly professionals and public authorities, aware of the problems of light pollution and the ways to restrict them by promoting quality lighting, is to institute prizes or awards. This is done in several countries in a variety of subjects. Many countries have an award system on lighting in general; such systems could easily be extended toward awarding low pollution lighting schemes. If the awards are widely publicized, the prize-winning schemes will become well-known, and may serve as an example for other similar schemes. The awards need not to be combined with huge amounts prize money. For most professionals, being honoured for their efforts, and being praised in public, is reward enough. And it never hurts a curriculum vitae!

(e) Handbooks and textbooks

Modern classroom and individual education makes generous use of handbooks and textbooks. In the past, this, of course, was different. In sec. 15.3.1, the distinction between training, teaching and education is mentioned; pointing out that training is about skills, and is based on teachers providing examples. This still seems to be the only way to learn to play a musical instrument. For general education, the method became obsolete when school books became available. Only in some religious institutions, pupils memorize their sacred text by endless repetition. The same is still the case in choir practice.

For teaching specific professional knowledge and insight, and for higher education in general, many outstanding textbooks are available on almost every subject one can think of. In recent times, these textbooks are supported by publications on the Internet. As regards teaching astronomy, many examples are discussed in the Proceedings of the IAU conference on astronomy for developing countries, that is mentioned in sec. 15.1.3b (Batten, ed., 2001).

Handbooks and textbooks on illuminating engineering are less abundant. A number of fine examples is listed at the end of this section; a number of other books that might evoke further reading, are added. This list is not a comprehensive bibliography. As said, it contains a number of examples only. Some works are in less common languages, which might help some people who are less familiar with English or German. Most works quoted in the list have been referred to in various chapters of this book.

The fact that several of them are not recent publications, is not much of a draw-back, because the principles of illuminating engineering do not change that rapidly. What changes is the technology of light production, and the methods for the design of lighting installations.

What is missing, are two things. The first void is a thorough and comprehensive work on the different aspects of light pollution. This is one of the aims of this book to fill that gap. The second thing that is dearly missed, are simple, short primers on the subjects of astronomy, outdoor lighting and light pollution. Such primers should be available on a world-wide scale, and they need to have a standard high enough to be used as textbooks for secondary schools, for dedicated secondary courses, and for college level courses for astronomers, engineers, and public decision makers.

(f) A selection of handbooks and textbooks

Here, the handbooks and textbooks are referred to in full, in spite of the fact that they are also included in the bibliography at the end of this Chapter. Thus slight duplication is accepted in view of clarity.

(1) Astronomy

- Batten, A.H. ed. (2001). Astronomy for developing countries. Proceedings of a Special Session at the XXIV General Assembly of the IAU, held in Manchester, UK, 14-16 August 2000. San Francisco, The Astronomical Society of the Pacific, 2001.
- Budding, E. (1993). An introduction to astronomical photometry. Cambridge UP, 1993
- Howell, S.B. (2001). Handbook of CCD astronomy, reprinted 2001. Cambridge (UK). Cambridge University Press, 2001.
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(2) Lighting in general

- Anon. (2000). Handboek verlichtingstechniek (Llighting engineering handbook). Loose-leaf edition. Deventer, Kluwer Techniek, 2000 and following years.
- Baer, R. (1990). Beleuchtungstechnik; Grundlagen (Fundaments of illuminating engineering). Berlin, VEB Verlag Technik, 1990.
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15.3 Education

15.3.1 Training, teaching and education

(a) Goals of teaching and education

Training, teaching and education have one thing in common: they all refer to the transfer of information from a sender to a receiver. It is well to keep this in mind, when planning activities in this area. Matters of coding and decoding, that are discussed in sec. 10.3, must be taken into account, and so must matters related to the signal-to-noise ratio, that is explained in sec. 14.2.3b.

It is generally understood that training is related to the acquisition of skills, usually basic skills. A 'trainer' gives the example, and the 'trainee' follows it. In many cases, the acquisition involves many repetitions of the task. The results of the training can be assessed by a performance. As regards astronomy and related subjects, such as light pollution, it seems that training as only a limited place.

Teaching involves a systematic transfer of information from the 'teacher' to the 'pupil'. The subject matter of teaching is also the acquisition of skills, but much more the acquisition of knowledge and insight. The means are explanation from the part of the teacher, and solving problems and making exercises from the part of the pupil. Usually, teaching is understood as 'classroom teaching' with one teacher and a number – sometimes a large number – of pupils. In some countries, a classroom may mean the shadow of a large tree! In teaching, usually textbooks are followed, which gives teaching an objective and rational slant. The results can be measured to a reasonable degree in objective terms by exams. As regards astronomy and related subjects, such as light pollution, teaching has a major role to fulfill:

- first, teaching pupils of general schools the first principles of astronomy. The aim is to evoke interest in the subject itself and the dangers to it from pollution;
- second, to teach college astronomy students the details of the science. The aim is to form astronomers who can do the research, and can teach astronomy at schools, but also to understand the intricacies of light application and the consequences of light pollution, as well as the workings of the countermeasures;
- third, to teach professionals in different disciplines the value of astronomy and the first principles of the science, as well as the need for adequate outdoor lighting and the principles of the 'tricks of the trade'. This teaching can be incorporated in the curriculum of other college studies, like those of future decision makers, electrical engineers, economists, corporate managers etc., but also as a part of a 'permanent education'

scheme that is aimed at active professionals, mainly in refreshing courses. This is the sort of teaching that was hinted at in sec. 15.3.1, where the lack of insight in astronomy and in light pollution problems by some lighting sales people was mentioned.

Education is usually understood to involve much more than training or teaching. Education also involves, to a degree, a systematic transfer of information from the teacher to the pupil. Education is aimed, however, not at the acquisition of knowledge and insight, but much more to the acquisition of a certain attitude. Education is not only an intellectual endeavour, but it involves moral and sometimes even spiritual aspects. This makes education, on the one hand, a powerful tool to raise individuals, who are adjusted to the needs of society and to their own needs in that society, but on the other hand, may easily degenerate to a method to promulgate hero-worshipping, bigotry, and hatred, and to promote stupidity and indoctrination in the people. For both, ample evidence exists in the present and in the recent history. This touches on the main problem of education, a problem for which no general solution exists: how to leave education free enough to fulfill its primary task, and to guard it, so that excesses are avoided. Education may involve an appointed teacher or textbooks, but need not. It can be given to groups in classrooms, but it can also be given individually. The basic tool of education is to give the 'good example' and to promote that the students will follow that example out of free will. The 'Guru status' of some educators is not easily compatible with that aim. The results cannot be measured; they will show in the long run. As regards astronomy and related subjects, such as light pollution, education has a major role to fulfill:

- first, to explain the wonders of the 'starry sky' to all people, pupils of elementary schools or high schools, and college students included. Also, to explain that it is wrong to spoil it by pollution;
- second, to explain that the starry night is just one aspect of the Cosmos, and that the Cosmos must be guarded against pollution and degradation. The human species is the only species that can do real damage to the Cosmos, but at the same time, it has the duty to safeguard the Cosmos.

Two remarks must be made:

- first, the terms 'teaching' and 'education' are not always clearly defined. In many publications, the two are used more or less as synonyms. This is not always avoided in the following section;
- second, it is mentioned in sec. 15.1c, that the relation between astronomers and lighting engineers has not always been based on mutual respect. Disrespect is, of course, not a favourable ground for positive education.

(b) Astronomy teaching and environment education in developing countries

In 2000, a Special Session on Astronomy for developing countries was held during the XXIV General Assembly of the IAU in Manchester, UK. The proceedings are published in Batten. ed., 2001. Most presentations were on education of astronomy students, and on undertaking astrophysical research in developing countries. A survey of the problems was given in Batten (2001). Almost all papers were written from the Western point of view, even by people from the developing world, both as regards astronomy and education. Only Eenens (2001) points out that, in promoting astronomy in a country, the cultural heritage of that particular country must be taken into account. In no paper, except Schreuder (2001), was any mention made about the problems of light pollution. This is very striking, because in many developing countries, light pollution is severe, particularly in or near the many cities with many millions of inhabitants, that abound in the developing world. One may suspect that in many developing countries, mass-transportation and mass-electrification receive more interest than matters of the environment.

One other point should be mentioned. In some countries, maybe in many countries, astronomy is considered not relevant for high school and college education, because it has no direct bearing in future employment needs. Therefore, astronomy is at the bottom of the priorities for education subjects (Munyeme & Kalebwe, 2001).

Most subjects of this important session fall outside the framework of this book. We will, however, mention a few, that may have a link to the subject of the reduction of light pollution. One is the need to 'teach the teachers'. In Spain, summer schools are organized the promote the exchange of astronomy teaching experiences (Ros, 1991).

Further, several activities are reported that aim at reaching out to high-school students and also to the general public, and try to arouse interest in astronomy. Although is does not seem to have been done until now, it is probably feasible to introduce interest in light pollution, in its causes and in its remedies, in such activities. In Vietnam, a planetarium for school classes and for the public has been opened recently (Wentzel, 1991). In the Philippines, an 'Astro Olympiad' for highschool students is organized, where, after a number of qualifying rounds, five students are examined about their contributions (Celebre & Soriano, 1991).

In Chile, that belongs to the group of countries that are highly industrialized in some parts, but 'developing' in other parts, a major effort has been started under the auspices of the large international observatories that are located in that country (Smith, 2001, 2003). In this respect, it may be noted that a considerable part of the national income stems directly or indirectly from these observatories; it is estimated to be at least 100 million US$ (Smith, 1991, p. 451). The school activities include an internet project, called 'Astronomy on line'. Presently, more that 100 schools with in total more than 10 000 students are involved in that project (Smith, 2003).

(c) Education of political decision makers

It seems that a major barrier to solving light pollution problems is the lack of knowledge of the authorities. One should try to convince the authorities of the cultural and scientific value of professional and amateur astronomy. The cause for the astronomers is a legitimate one, as much so as the cause for other interest groups. Furthermore, one should try and persuade the authorities that the means to fulfill the requirements of the astronomy are available, that they are within reasonable limits of what one can do – and pay –, and, finally, that in a number of cases the solutions that are preferable for the astronomy are, economically speaking, advantageous as well (Schreuder, 1995). As many authorities have only vague ideas about the benefits of high quality outdoor lighting, it is important to explain that as well. Again here, the situation in Chile may serve as an example. In spite of the fact that astronomers are 'guest' in that country and have no formal place in the political scene of the country, their influence is great, also in matters of legislature. In seems to pay off, when the astronomical community is actively engaged in improving the situation, in stead of just 'sitting and waiting', until someone else takes the initiative. Details are given in Smith (2001, 2003). In this respect, it is worth-while to point to the activities of IDA and CIE, that are summarized in sec. 1.3.

One interesting way to bring not only the quantitative aspects of light pollution under the attention of local decision makers, but also to inform them about the effects of any measure for the reduction of light pollution, i.e. put in effect, is given by Isobe et al (2000). Using the DMSP-satellite data, that are described in secs. 5.3 and 14.6.6, they are able to give, for any city everywhere in the world, the data about the energy that is emitted upward (expressed in kWh /km^2). By comparing the data from one year to the preceding year, any changes in the energy emitted upward that occurred in that year, can be found. Provided the city authorities keep precise track of all building and lighting activities in their city, the effect of the measures that are taken to reduce light pollution, can be found. One remark must be made. As is pointed out in sec. 1.2.2, it is not correct to designate all upward energy as 'Light Energy Loss', as is done in the paper. Most of the energy is used in useful lighting, before it is emitted upward.

The means to explain precisely what is going on, should be based on mutual respect. Most political decision makers have a sincere wish to provide good and fair government, just as most astronomers have a sincere wish to do 'good' science, and most lighting engineers sincerely try to do their job as well as possible. This mutual respect and trust should be the basis to try to improve the political decision making process. Cynical remarks, that politicians are only interested in being re-elected, that astronomers are only interested in the tenure at their university, and that lighting engineers are only interested in maximum profits, are not helpful, even if they are, to some extent, not far beside the truth.

(d) Educating lighting professionals

Good lighting design ensures that the light comes where it is needed, and does not fall elsewhere. If not, the light is spilled, which may cause considerable economic and environmental losses. The light, the money and the energy are simply wasted. Furthermore, spilled light often may cause light trespass. Light trespass may cause a restriction of astronomical observations. A major part of the answer is quality lighting. "Dark skies are compatible with quality lighting, they require such lighting, in fact. Poor lighting has many adverse effects, including glare, clutter, light trespass, energy waste, and light pollution. None of these are evident when quality lighting is used. Dark skies are compatible with a safe, secure, and functional nighttime environment. As with astronomers, the public needs and deserves a quality nighttime environment. Solutions are possible and they work. Lets achieve them, and have a Win/Win/Win situation: quality nighttime environment, energy saving and dark skies" (Crawford, 1991). This description of the benefits of quality gives a nice tool for the education of lighting professionals.

The low level of expertise of many lighting engineers poses a problem. The scientific level of the lighting field as an engineering discipline is quite high, but unfortunately, even in industrialized countries, the people in the field who have to take care of the lighting installation, are often not educated to a high technical level. This is even more the case in many developing countries. Also, the education at all levels of schooling in lighttechnical skills and sciences is quite limited, in spite of the fact that the environmental and social aspects of good versus excessive lighting are within the awareness attention of both the general public and the political and administrative bodies world-wide (Begemann, 1986; Schreuder, 1986). Further details are given in CIE (1997); Crawford, ed. (1991) and McNally, ed. (1994). A related problem is that most astronomers know little about lighting, just as most lighting engineers know little about astronomy.

This looks, in effect, more like a matter of teaching than of education. As is mentioned earlier in this section, this teaching can be incorporated in th curriculum of other college studies, like those of future decision makers, electrical engineers, economists, corporate managers etc., but also as a part of a 'permanent education' scheme that is aimed as refresher courses for active professionals.

(e) *Standardizing work.*

A related aspects is the set-up of standards. A number of countries have national standards or codes-of-good-practice for the reduction of obtrusive light. Many cities or regions, particularly those with major astronomical observatories in the neighbourhood, have local regulations or ordinances. Such standards and regulations are effective in reducing obtrusive light because they are obligatory, and have a further reach than recommendations, particularly when economic factors are prevalent. Legal aspects are discussed in sec. 15.4.

In sec. 14.6.2e, the need for standardized methods to measure light pollution, and to interpret the results of these measurements, is pointed out. To do this effectively, should also involve aspects of education about astronomy, lighting and light pollution. Setting up standardizing committees is usually a joint effort by industry, related organizations, and authorities. Most effective standards are drafted on an international basis. Here, international organizations, like UN, IAU, and CIE, have an important role to fulfill.

15.3.2 Classroom teaching of astronomy

The following discourse is based in part on several papers of Dr Margarita Metaxa, from Athens, Greece (Metaxa, 2002, 2002a, 2003).

Education is important to astronomers because it affects the recruitment and training of future astronomers, and because it affects the awareness, understanding, and appreciation of astronomy by taxpayers and politicians. Astronomers have an obligation to share the excitement and the significance of their work with students and the public. There are other reasons why astronomy education should be part of the education system and human culture. Astronomy is deeply rooted in the history of almost every society, as a result of its practical applications and its philosophical implications.

Astronomy education happens in many places beside the formal classroom. It happens in planetaria and museums. It happens in the media, when someone reads a newspaper, or in front of television and radio sets. It happens when someone is engrossed in a popular book on astronomy. It happens on the Internet, it happens in youth groups taking an overnight hike. The above reinforce the science of astronomy, but also certify that students are influenced as well by 'informal' education.

If astronomy is so interesting and important, and if it is available in so many places, why is it not taught in more schools? Why are there so many misconceptions about astronomical topics? The reasons for this can be found in the following:

- the traditional way of teaching astronomy;
- many teachers have misconceptions about the teaching of astronomy, as well as about the actual contents of astronomy, which might discourage them from teaching it;
- teachers are not always aware of all the educational material that is available;
- however, the most important problem is that most governments do not sufficiently support education – not only the education of astronomy, for that matter.

These barriers apply, to a greater or lesser extend, at all levels of education, and in all countries of the world.

When designing courses in astronomy, there is a tendency to assume that the students who are addressed, are younger versions of the teachers. But this is not always the case. Many young people have different passions, a different way of thinking, and different interests. Many will follow different careers, and, in addition, they grow up in a different environment. Probably the greatest difference between the generations is the natural way the young got acquainted with computers. They are born in a digital world, whereas many teachers grew up in an analog world and had, often with great difficulty and with tremendous effort, to adjust to the digital. If the teaching methods are not adjusted accordingly, the students will unhook. However, this problem will solve itself automatically when time proceeds, and the students of today will become the teachers of tomorrow.

Research shows that by introducing technical innovations into the classroom, the traditional roles for teachers and students could be redefined in a dramatic blurring of the boundaries between the processes of teaching and learning. Use of technology in the classroom can foster an environment that more closely reflects the processes scientists use in doing research. However, the criteria and goals should be realistic and the prerequisite notions should be explained to the students, prior to the more exotic ones, so that student learning may be optimized, in order to build up understanding and knowledge that outlasts the final exams.

To make the teaching and education in astronomy more effective, it should be based on the following concepts, which should include collaboration between teachers, researchers, and students. The reasons are:

(1) Each partner work in the area of their specialty.
(2) A framework is established where scientists can contribute their unique assets with potential large impact and multiplier effect, taking in advantage of an existing end-user support structure.

Educating the world about astronomy is a major challenge which can be met, if the work is done together with interested organizations, using modern pedagogical concepts.

This type of teaching and education need not be confined to one single country. Particularly if the possibilities if the Internet are used in full, international projects are feasible. One project of this kind is described in summary in Anon. (2002) and Metaxa (2003). In the Netherlands, high schools include a course in 'General Natural Sciences'. In the context of this course, they will receive 12 lessons on astronomy, in which they will be able to direct a telescope in Australia via internet. The purpose of this is to activate interest in cosmology in students. It should be added that there is a chance that this project will fall victim to the urge of the Government to cut spending – what they prefer to call 'saving money'. In Australia, professor David MacKinnon is involved, in the Netherlands the Teachers Education Programme ELAN from the University of Twenthe in Enschede. The project is very much like that which is described by Baruch (1998). See also Jones (2000). Another programme of this kind is described briefly in the next part of this section.

15.3.3 International School Education Networks

The following discourse is again based in part on papers of Dr Margarita Metaxa, from Athens, Greece, that describes in detail the 'International Schools Education Networks for Light Pollution Control' (Metaxa, 2002a, 2003).

As is explained in the Chapters 3 and 5 of this book, the problem of light pollution exists almost everywhere, and is still growing rapidly. The maintenance of dark skies at prime astronomical locations as well as in other locations, depends very much on the awareness of the public, and particularly of key decision makers responsible for developments, including lighting engineers. It is necessary to continually promote awareness of light pollution and its effects. Thus the preservation of the astronomical environment requires effective education. The model described here is part of the educational programme of the IAU Commission No. 50. Some results as well as future plans are discussed.

Fortunately, solutions do exist to reduce the impact of light pollution, and control programmes are underway now in a number of communities. Outdoor lighting codes and ordinances are essential to the long term success of astronomical research and for the preservation of humanity's view of the universe. However, there is much more to be done everywhere, and most people are not yet even aware of the issue. It is often felt that a lack of awareness, rather than specific resistance, is generally the biggest problem in controlling light pollution.

Educating the public, government officials and staff and lighting professionals is a major aspect of many education activities. Education is essential. A programme is set up to enhance the education at schools. It proved that 'Light Pollution' is a good educational aspect to introduce the topic to the general public, to government officials and staff, and also to lighting professionals.

The programme is characterized by the following points:
(1) It covers all levels of education, formal and informal;
(2) It is Multi-Disciplinary; it involves: physics, astronomy, technology, the environment etc.;
(3) It stresses both scientific and social components;
(4) It is aimed at an international audience.

The main aims of the programmes are:
(1) Students and the general public may familiarize themselves with the problems of light pollution, while making use of astronomy, physics, and computer sciences;
(2) To take into account the cultural and social dimensions of the impact of light pollution;
(3) To raise the awareness for the preservation of the heritage and environment throughout the countries of the participants;
(4) To promote international cooperation and the awareness of being in One World;
(5) To focus on training of teachers.

Regarding the last point, it is stressed that the programme is based on the collaboration between teachers, researchers, and students. The reasons are:
(1) Each partner work in his/her area of specialty;
(2) A framework is established where scientists can contribute their unique assets with potential large impact and multiplier effects, taking advantage of an existing end-user support structure;
(3) Activities connected with light pollution can be used in an introduction to astronomy or environmental education.

Through the various activities in the programme, the students and the general public will be encouraged to become familiar with the night sky. Additionally, it is intended to increase the awareness of the effects of light and air pollution, and to attempt to influence planning authorities to produce efficient and effective lighting schemes. As is explained in sec. 1.2, well-designed luminaires will not only cut down light pollution, but are also likely to save energy.

The students and teachers, who participate in the activities, should open their results to the public. They may communicate with their local authorities, local environmental associations, and local scientific societies on the light pollution problem. In that way they may form the 'critical mass' that, in the long run, will influence planning authorities to produce better building schemes that should include efficient and effective lighting.

The theoretical framework of the programme is based on the following considerations. Contemporary teaching requires a connection with events in our everyday lives. This is very successfully provided by models for environmental studies. These models require that each project should be placed in the natural, historical, social and technological environment.

The goal of such models is described as: "The development of citizens/people with knowledge, sensitivity, imagination, and an understanding of their relationship with their physical and human environment, ready to suggest solutions and participate in decision making and implementation".

15.4 Legal aspects

15.4.1 Light as a pollutant

Most of the interference by light from which both astronomers and others suffer, results from poor lighting design, both as regards the equipment and the installation itself. The result is, that a considerable part of the lamp light flux ends up where it should not be. People may suffer from glare, obtrusive light, and loss of darkness, but also plants and animals may suffer from excessive light. This is often called obtrusive light (CIE, 1997, 2003), or light intrusion (Schreuder, 2001), or light immission (Anon., 1998, 2000a).

In Chapter 3 of this book, it is explained that light, that goes where it does not belong, represents economic losses with negative monetary effects, is an assault on the natural environment, and may have negative public health effects. Because of the last point, light is often considered as a pollutant, as will be explained later on. Also, the intrusion itself is often regarded a legal infringement of property. This will be discussed in a further part of this section.

Obviously, a better quality of the lighting is the answer, not only to enhance the benefits for the environment and to reduce the wastage, but also to avoid legal complications. A description of what is to be understood by 'quality lighting' is given by Crawford (1991, p. 10).

Several nations, states, or regions that have important astronomical observatories within their boundaries, have set up regulations to restrict light pollution. In the UK, the following criteria are used to decide whether any influence on the environment is classified as a 'pollutant':

(1) Is it a hazard to safety (i.e. for motorists)?
(2) Does it produce ecological disturbances?
(3) Does it produce environmental and visual nuisance?
(4) Does it represent energy wastage?

The same arguments are used to define noise as a 'pollutant' (Gray, 1993).

In Germany, similar criteria are used. Light is considered by law as an 'immission', as well as an 'emission' (Anon., 1998). "Light immissions belong according to the law, to damaging influences on the environment, if they, as a result of their nature, intensity or duration, may cause danger, considerable disadvantages or considerable burden to society in general, or to the surroundings' (Anon., 2000a, sec. 1).

The matter of light as a potential pollutant is also addressed in the comprehensive study of McManus (2001): "There is no all-embracing definition of 'nuisance'. The emphasis should be on the of invasion of interest and on the unreasonable interference with the use of the land. There exits a wide variety of different circumstances capable of ranking as a nuisance. A hierarchy of pollutants is not defined. Courts seem to use, however, an emotional hierarchy of pollutants. Light is a less emotional pollutant than e.g. fumes, or even noise. It is not every slight interference that constitutes a nuisance but it must be sensible and material in nature. A Light Pollution Act should embrace the concept of annoyance, as opposed to nuisance. This seems to be a general feeling in courts. In the UK, The 'Environmental Protection Act 1990' would need to be amended in order to make light a statutory nuisance. Regarding civil law, only few, if any, court cases are known on the subject as to whether intrusion of light could rank as infringement. Probably it would". (McManus, 2001). Further, light is an aspect of human rights. The European Convention of Human Rights (ECHR) Article 8 provides: "Everyone has the right to respect for his private and family life, his home and his correspondence" (McManus 2001).

Over the years, attempts have been made to persuade the European Union, to put light pollution on the agenda. One of these attempts has been a petition, drafted by the Campaign for Dark Skies, an organization associated with the British Astronomical Association. The petition was send in on 7 December 1994 (Mizon, 1994). The petition is discussed here briefly. More details are given in sec. 4.5.7a. The main issue is the need that stemming light pollution cannot be left completely to private initiative, but that regulatory action is needed. It was, and still is, the point of view of several governments, that market forces are sufficient to find the best solution, and that regulations would mean an infringement of freedom, particularly of corporate institutions. In the petition, it is pointed out that the European Union has the possibility to promote regulatory actions on the basis other EC-regulations, like e.g. the regulations 89/364/EEC on the efficient use of electricity and regulation 91/565/EEC on the promotion of energy efficiency in the European Community.

Petitions like these seem always to drown in the EU bureaucracy. However, the contents are often used in other contexts or in other international considerations. There are some signs, that the European Commission is willing to take a standpoint regarding light pollution and the preservation of the dark sky. At present, a draft CEN Technical Committee is in the process of drafting regulations for the lighting of work spaces. For outdoor lighting work spaces, maximum admissible values of light pollution are included. These values are identical to those that are adopted by CIE (1997, 2003) and NSVV (1999, 2003, 2003a,b).

The petition mentioned earlier, may have had an effect, as well as the statements made by UNESCO (Anon., 1992a). Concrete measures have, however, not yet been taken.

15.4.2 Enforcement of limiting values

(a) *The need for regulations*

It is well-known that, when public benefits and personal profits collide, usually the private profits win. This is the more so, when the profits are related to the large corporate and financial organizations. However, it is also well-known that, when the situation is getting really intolerable, human solidarity prevails, and decisions are made that do not favour private profits. These insights may sometimes take decades or even centuries to form, but they also may strike at lightning speed. Although falling outside the scope of this book, an example of each of these extremes is given, in order to illustrate the process. It took centuries to come to the insight, that slavery must be abolished; it took about five minutes for the Rumanian people to realize that communism must be abolished. One prerequisite of this process, where the human solidarity is getting the upper hand, is that the situation is considered as intolerable. In a great number of human activities that relate to the environment, the 'point-of-no-return' has been passed. There are, however, considerable differences between countries in the speed of these processes. We will give three examples. Controlling chemical and household waste, and controlling air and water pollution, are world-wide topics. Protection against noise, and preservation of plant and animal life, are not world-wide, but widespread notions. Protecting the astronomical electromagnetic window, both at visible and at radio frequencies, is regarded as a topic only in a few countries. The reason for this is not difficult to find. The first costs many thousands of lives each year, the second costs great fortunes, whereas the third has little public health or financial consequences. As is explained in the introduction of this book, keeping the astronomical window open, has primarily spiritual benefits, allowing humanity to keep contact with its spiritual basis in the Cosmos. Additionally, it has scientific benefits as well. A different approach must, therefore, be found to let the human solidarity find its place in this aspect. In secs. 15.2 and 15.3, the awakening of public awareness and of education are explained in some detail.

In sec. 4.2.2.2, it is explained that the Netherlands is one of the most densely populated countries in the world. It is among the most affluent, it is heavily industrialized, but it has a large and productive agricultural sector. It is one of the largest producer of natural gas in Europe. Also, it has a number of world-wide known cultural monuments, and some of the most crowded beaches in Europe. But it has also the largest area of protected wetlands in the world, and the largest natural inland sand dunes in Europe. As is explained in that section, the Government is very conscious of these facts. It requires a considerable amount of clever policy making, to have both affluence and environment guaranteed. It is likely that, therefore, it has established one of the most comprehensive, nation-wide legal system of land preservation, land and urban planning, and nature preservation to be found in the world.

Still, there is much to be desired, particularly in the underestimated area of light intrusion. In the workshop 'Working together for darkness', that is quoted in sec. 4.2.2.2b (Anon., 2002a), it was stated: "A wider policy is needed to reduce obtrusive light: centralized, nation-wide approach; collaboration between authorities regarding the environment, the land management and the nature and landscape policy; establishing regulations for areas where they do not yet exist like e.g. floodlighting, advertisement lighting; designation of 'dark areas' guarantee the preservation of the primeval quality". (Van Den Berg, 2001, p. 12-13).

In March, 1998, the governmental environmental agency of Japan published the 'Guidelines for light pollution – Aiming at good lighting environments' (Isobe, 2001). "This is the first governmental guideline in the world that deals with reduction of light pollution" (Isobe, 2001, p. 117). The special feature of these guidelines is the check list, to be used when outdoor lighting is prepared. "It is a perfect list, therefore if one follows this list, we may minimize light pollution" (Isobe, 2001, p. 118). In most other aspects, the guidelines follow closely the CIE Publication No. 126 (CIE, 1997).

In the United Kingdom, the need for further regulation is felt quite hard when new data about the upward light emission became available (Anon., 2003a, Petrakis, 2003, Smith, 2003) "On the land area of England experiencing severe light pollution grew by 17% between 1993 and 2000. Over the same period, the rural areas where there are truly dark skies and unimpeded views of the night sky in all its majesty and mystery shrank by 27%. On average, the light shining upwards at night from each square kilometre in England rose by 24% over those seven years" (Anon, 2003a). As a result of these figures, a committee was established, that recommended a.o. to set up a 'Planning policy guidance'; to urge local authorities to realise their responsibility. Legal measures are considered for the future (Anon. 2003a).

(b) The Sustainable Society

The function of road lighting is to promote road safety, to reduce criminal activities, and to enhance amenity. Road lighting costs money, and money is, economically speaking, a 'scarce commodity'. There is always less money available than needed. Additionally, road lighting requires electric energy, and the production of electric energy leads to environmental pollution. For many years, the effect of road lighting in the Netherlands was measured in the reduction of road accidents, and the costs in energy consumption. For many years, the yardstick for energy consumption was money. Some twenty years or so ago, a further yardstick was added: environmental load. The implication was that energy consumption was about the only environmental aspect that was taken into account for road lighting.

Around 1990, here was a change in thinking about the environmental policy in the Netherlands. The key concept was the desire for a 'sustainable society'. In practical terms, this would mean two things:

(1) The polluter pays. Costs on the production, made to protect the environment, are to be considered as normal production costs, to be paid by the end-user.
(2) Environmental aspects are part of an integral chain policy. This means that in environmental matters, the complete chain from raw materials to waste removal is taken into account.

The 'sustainable society' concept stems from the National Environmental Policy Plan (NMP). In 1990, this was detailed in Environmental Policy Action Plan (MAP). On the basis of these documents, many municipalities did set up their own environmental policy plans. The bottom line was, in most cases, still energy saving (Schreuder, 1992, 2001c).

(c) Environmental Effect Reports

Over the years, the public opinion in the Netherlands was not satisfied any longer with the special focus on energy saving. Many people suffered in their daily life from environmental problems, like noise, stench, dirty water etc. These problems, and the ensuing complaints, were the impetus for a wider approach by the government. Environmental Effect Reports were introduced. An Environmental Effect Report has to be presented in all cases where any construction, activity, or establishment is planned (Schreuder, 2001a). The report must be presented, before the work starts, to the authority that is entitled to give permission for the work. This can be the central government, the province, or the municipality. The report must contain proof that the construction, activity or establishment will not cause more environmental load than prescribed in the relevant legislation. The proof must be delivered by certified research or testing establishments. Until now, the legislation includes environmental loads caused by noise, stench, vibrations, electromagnetic interference, physical dangers and air and water pollution. It is one of the aims that are described earlier in this section, to have light pollution included in this list. The fundamental data are available; it is explained in sec. 15.4.1, that light can be considered to be a 'pollutant'.

(d) The benefits of the Environmental Effect Reports

Some people complain about these procedures. The procedures take a lot of time and they cost a lot of money. The benefits, however, are clear to see, when countries like the Netherlands, and a few others, are compared with many countries where little or no protection of the environment exists. In many countries, both rich and poor, one might find mines, oil fields, factories, logging activities, prisons, or harbors right in the middle of areas that, in a more careful society, would classify as national parks. The argument that some countries do not have the means to set up national parks and to maintain and protect them, is not true. In many countries, and in particular many developing countries, tourism is the main source of income. Tourists come to enjoy themselves, to see national parks, but not to visit oil fields, logging activities, or harbors and the like.

The same sort of visit will show, however, that the protection of dark areas and the restriction of light pollution are not yet successful in the same way. It should be added, that the legal activities that are described here, are particularly aimed at new installations. Obtrusive light from existing installations must be restricted by other types of legislation.

One more thing must be added. There are large differences in the legal systems of different countries, even between countries that are close together geographically or culturally. This implies that it does not make any sense at all to try and formulate some sort of 'framework for light pollution legislation'. This is also clear, when, in sec. 15.5, lighting ordinances are discussed.

15.4.3 Light intrusion; liability

(a) *Written law*

Modern legal systems vary considerably from one cultural region in the world to another, and even between countries, that live within the same cultural context. It should be noted that, in the traditional view of Western Europe, the European culture is based on the early cultures of Mesopotamia and Egypt. As regards the Western civilization, undoubtedly there is some truth in this. When, however, we would consider the whole world, this point of view is rather restricted. This fact was realized by Western scholars only a few decades ago, and it is far from being generally accepted in school and college education. However, almost all industrialized countries either belong to the Western European tradition, or lean heavily on it. And because light pollution is usually regarded as the fall-out of industrialism, and consequently is regarded as exclusively a problem of the Western European tradition. In spite of the fact that even a cursory glance at the World Atlas, that is discussed in sec. 5.3, shows that this is not correct, the legal considerations that are briefly discussed here, are those of the Western European tradition as well.

Probably the legal systems that are based on a direct relation to Divine Powers, are better suited for moral questions, but for liability questions related to light intrusion, probably the secular legal systems of the West are more suited. To understand the working of that system, but also the internal differences, it might help to explain, very briefly, the evolution of the Western legal systems.

The following discourse is based in part on Fockema Andeae (1950). "In the history of human consciousness, all human actions are under the government of the Gods. In the ancient Near East, it was generally accepted that laws are gift of the Gods. The God that guards the laws is the personification of the world order that applies to nature as well as to society. The king or the judge executes the law, and therefore guards truth as well, because truth and law belong together" (Fockema Andeae, 1950, p. 119). It should be noted, that in many countries, the function of King and Judge were combined in one person, who often acquired a godlike status. In such a system, there was no need for written laws: all was in the hands of the Gods.

(b) Civil and penal legislation

The famous Code of Hammurabi, King of Babylon in what it Iraq today, from about 1700 years before the birth of Christ, is the first recorded breach in this unity. The law is considered as a general rule that applies to society, and that is upheld by secular judges. There was, of course, a need now to write the law down. Religious matters were still referred to the temples and their priests. (Fockema Andeae, 1950, p. 119). The next and final major step was to split up secular law into civil and penal legislation, as was done in the final days of the Roman Empire. It was Emperor Justinianus (527-565 AD), who gave the final touch in the 'Corpus Iuris' (Fockema Andeae, 1950, p. 121). So there were three bodies of legislation: religious matters, matters of damage between civilians, and matters involving criminal acts. All criminal acts were considered as being acts against the State or the society. This principle is still fully applicable in Western legislation right up to this day.

(c) Jurisdiction

Jurisdiction has one common trait; it is always in the hands of specialists. This is not only the case in countries where the laws are written down, but also in communities where natural, unwritten, laws prevail (Fockema Andeae, 1950, p. 126).

The jurisdiction within the Western legal systems varies considerably between countries. In the Middle Ages, it was the King or his deputy, who announced the verdict, after consultation with the experts and the fellows in law. In modern terms, this would mean the judges and the jury. Often the judges were separately appointed (Fockema Andeae, 1950, p. 126). In some countries, remains of Germanic law may be seen, but they refer mainly to services to be made by free men, like e.g. in the maintenance of dykes and polders (Romein & Romein, 1961).

Gradually, a further distinction grew out of this system. In many countries, the judges give the verdict, when basing themselves exclusively on the written law. In other countries, the jury has a crucial function, basing itself on 'equity' or fairness, and not alone on the letter of the law (Fockema Andeae, 1950, p. 126). All sorts of transition forms between these two may be seen.

There is still one more thing in common. Going to court is always a costly affair. So, in order to avoid a large part of these costs, mediation is a common procedure. Here, the parties involved in the conflict come to an agreement about the indemnity. This is mainly, but not exclusively, applied in the case of liability cases that belong to the civil code, because here the two parties are private persons or private institutions. In penal cases, it is still the State who acts as the injured party.

As regards light pollution, these considerations can be summarized as follows:
- the responsibility of perpetrators – the polluters – is dealt with in the Penal Code;
- the damage of the light pollution is dealt with in the Civil Code.

(d) Light intrusion

Light intrusion is usually described as the effect of light, i.e. it originates from the premisses of one party, and it intrudes into the premisses of another party. On these grounds, some publications use, as a criterion for light intrusion, the amount of light – usually the illuminance – that falls on a plane, real or imaginary, at the location of the property limits (CIE, 2003; Anon., 2002b). Other publications refer to the disturbance that is experienced by the 'second' party, and use the illuminance that falls on a plane where the disturbance is effective, usually the facade of buildings etc., as a criterion for light intrusion (NSVV, 1999; Anon., 1998; 2001a)

It is usually clear who is the injured party and who is the perpetrator. As regards the application of the considerations, the first thing to find out is, whether the transgression is a matter of civil or penal legislation. In some countries, according to civil law, a party is liable for all damages caused by his actions or by the actions of persons or constructions that belong to his field of responsibility. The penal code comes into effect only if malicious intent or gross negligence can be proved. This is only seldom the case, so most problems related to light intrusion and light pollution will be covered by the civil code.

In most practical cases, it is difficult to describe the damage, let alone to quantify it in monetary terms. In some cases, however, the costs of the damage may also be clear. As an example, the case where an astronomical observatory has to move to another location, because a major lighting installation is erected nearby. The costs of moving can be very considerable. Sometimes, a court decision can sentence the owner of the lighting installation to pay the damage. Usually it is better to relay on mediation or arbitration. However, in most cases, such problems can be avoided when the Environmental Effect Reports are used, that are described sec. 15.4.2c (Anon., 1994; Schreuder, 2001a).

(e) Light intrusion by assimilation lighting

In sec. 7.2.1e, the use of light in greenhouses to simulate daylight during the winter, is discussed in detail. Because the idea is to help plants to assimilate radiation, and to grow when natural daylight is weak, this application of light is called assimilation lighting. One might argue that, because it is inside the greenhouse, it would classify as indoor lighting, but, because the greenhouses are made of glass or transparent plastic, it seems as if the lighting is outdoors, it is common to regard it as outdoor lighting.

The idea is to simulate daylight. Therefore, special high-pressure sodium lamps are used, with a slight adapted spectral emission, and levels of many thousand lux are applied. For most vegetables and flowers, about 5000 to 7000 lux is sufficient, but tomatoes require at least 15 000 lux.

As is mentioned in sec. 13.2.3e, in the Netherlands, many square kilometers are covered with lighted greenhouses. This did lead, in the early years, to complaints, and even to court cases. One example is that of a certain farmer who grew cucumbers. Growing cucumbers is done in greenhouses, but additional lighting is not needed. At a certain moment, the neighbour of this farmer installed assimilation lighting in his greenhouse. A fair amount of it leaked out of the sides of his greenhouse, into the property of the cucumber farmer. Because of the very high light level in the greenhouse, even the leak light was fairly intense; at any rate, intense enough to let all cucumbers grow crooked into the direction of the light, as plants normally do. Now, cucumbers need to be straight, so they can easily packed, and easily handled in the kitchen. Crooked cucumbers are almost worthless. The cucumber farmer filed a complaint, and won his case. From then on, a national regulation is in force, that restricts the light emission out of the sides of greenhouses.

The regulation is a Ministerial Decision. These are, as appendices, attached to laws. This one is from 1 May 1996. It became into force in 2000, and a revision is considered (Anon., 2000b). The main requirements are:

(1) The sides of greenhouses must be shielded in such a way, that no more than 5% of the light escapes, unless a wall or a row of trees is within 10 m from the greenhouse. This sounds nice, but the requirement means that the installation must be measured with and without side shieldings. This is, of course, possible when existing installations are adapted. For new installations, however, it is not always possible to do so. There is no elegant solution to this;
(2) Between 20:00 h and 24:00 h, it is not permitted to use the assimilation lighting, unless the top of the greenhouse is shielded. The lawmakers considered that, after midnight, decent people are asleep, so that they are not bothered by the light. This disagrees, of course, with the point of view of astronomers and naturalists, that it is particularly important to have dark surroundings after midnight.

Although the provision is far from ideal, as is made clear in the remarks at the different requirements, it can be seen already at first glance that they are quite effective. A greenhouse with an unshielded assimilation installation can easily be seen from many kilometers at night. Although the number of lit greenhouses still increases sharply, as is mentioned in sec. 13.2.3e, the night visibility conditions have improved over the last five years or so in a dramatic way.

15.4.4 Legal aspects of laser applications

The following paragraph is based in part on McNally (2002). There are some concerns about the use of lasers in the optical or near infrared regions in satellite communication. Should the technology prove successful, it will offer an escape from the strict control of the radio bands. If that happens, the growth of the technology might have considerable consequences for astronomy. At the moment is not easy to predict the effects. Probably, faint photometry will suffer, as would be deep sky imaging in bands which include the laser frequency. Possible, the effect could be filtered out with appropriate spectroscopical means.

In more general terms, lasers are considered as dangerous equipment. When the beam hits the eye directly, severe damage can be the result. With this in mind, the IEC has drafted extensive a safety regulations (Schmidt, 2001). The most important is IEC 60825: "Safety of laser products", consisting of several parts:
Part 1: "Equipment classification, requirements and user's guide"
Part 2: "Safety of optical fibre communication systems"
Part 3: "Guidance for laser displays and shows"
Part 4: "Laser guards"
Part 5: "Manufacturer's checklist for IEC 60825-1"
To this, "Technical Specifications" are added:
Part 6: "Safety of products with optical sources, exclusively used for visible information transmission to the human eye."
Part 7: "Safety of products emitting infrared optical radiation, exclusively used for wireless "free air" data transmission and surveillance"
Part 8: "Guidelines for the safe use of medical laser equipment"
Part 9: "Compilation of maximum permissible exposure to incoherent optical radiation".

15.5 Standards, laws and regulations

15.5.1 National and international regulations.

It has been pointed out on several occasions in this book, that the loss of the dark night sky is a world-wide problem. Densely populated, industrialized countries suffer most, but there are few places left in the world, where the night sky visibility is not affected in some way by artificial light. It has also been pointed out, that outdoor lighting is essential for the survival of the society as we know it. Without outdoor lighting, most people on Earth probably would perish.

In sec. 15.4.2a, it is explained that, when public benefits and personal profits collide, usually the private profits win. This is the more so, when the profits are related to the large corporate and financial organizations. Also, it is mentioned that protecting the astronomical electromagnetic window, both at visible and at radio frequencies, is regarded as a topic only in a few countries, mainly because there is not much profit to be made, and there are no severe, spectacular public health risks involved. It is concluded in sec. 4.5.7a, that stemming light pollution cannot be left completely to private initiative, but that regulatory action is needed. Environmental problems, light pollution included, do not affect the direct survival of individuals, so stemming light pollution cannot be left to private initiative, to market forces, or the like.

It can be concluded that.in order to make a real step forward, two things are needed:
(1) A set of regulations that requires users to reduce the upward light;
(2) The activities must be world-wide.

15.5.2 Frameworks for lighting codes

As has been pointed out in the Introduction to this book, the night sky has been a canvas of our hopes and inspirations since we have been aware enough to raise our eyes from the ground. Bad lighting is one of the major causes that our children may be robbed of this inspiration of the ages (Anon., 2002b, p. 2). There are many tools, that can be used to avert the most serious consequences of poor outdoor lighting. As is explained in sec. 15.3.1, ongoing education in outdoor lighting is one of them. See also Anon. (2002b, section 6). Another is the institution of lighting codes or lighting ordinances. General lighting codes and recommendations, that are aimed at nation-wide use, are described in Chapter 7 of this book.

The International Dark-Sky Association published a set of guidelines to assist local people to set up lighting codes that help to reduce light pollution. It seems that the guidelines are more directed to private citizens than to authorities, but both may use the guidelines to their own, and to the general, benefit. "There is nothing good that comes from bad lighting. Most bad lighting can be blamed on the fact that the user is unaware of the issues of visibility and utility, how they are enhanced by good lighting and compromised by bad. A lighting code is a vehicle for a community to express its expectation for quality lighting and dark skies" (Anon., 2002b, p. 3). Lighting codes are presented here as a major tool to improve the situation at local levels. Often, these local codes will lead to 'lighting ordinances'.

The IDA publication presents an 'USA Pattern Lighting Code' (Anon., 2002b, section 7). "The USA Pattern Lighting Code is intended only as a guide to writing a code suitable for your community. Issues and priorities will be to some extent different for every community, and the Pattern must be adapted to reflect your own community's concerns and desires" (Anon., 2002b, p. 23).

The Pattern gives a framework only. As is indicated earlier, each community has to adapt it to its own concerns and desires. For this, the Pattern provides all the material. In general terms, it is an excellent piece of work. As will be clear when details are discussed, it is, as the title clearly indicates, particularly aimed at communities within the USA. It is tempting to suggest that a similar framework might be drafted, aimed at the international market. However, as is indicated earlier, the differences between the legal systems of different countries, even between neighbouring countries, is far too great to make such a work feasible. The best thing one could do, is to set up a few very broad main lines. The Pattern might be of help. Because the Pattern gives so much valuable detail, and because it is the only work of its kind, we will give here a brief summary of the main items.

The Pattern follows the usual set-up of a low-pollution outdoor lighting design. (Anon., 2002b, table 4.1). First, environmental zones are described. The five zones are similar, but, unfortunately, not identical to the zones that are introduced by CIE (CIE, 1997, 2003). Next, for each zone, a number of lamp types and luminaire shielding factors are designated (Anon., 2002b, table 4.1). The shielding is reduced to two steps only.
(1) No shielding;
(2) Full cut-off.
This is maybe not the best solution for an optimal outdoor lighting design. It is shown in sec. 7.1.4, that different degrees of cut-off have different fields of application.

Next, requirements are given for the total lumen output of all outdoor lamps per net unit of area. The area is understood as the property of a specific land user, be it a commercial or industrial estate, or a private home. Buildings are not taken into account. Again the same five zones are used, but now subdivided in commercial and industrial areas, and residential areas. Further, a separate maximum is given for unshielded lamps. Because the requirements apply only to properties, it is not possible to compare the maximum permissible luminous flux with the proposals that are given in Chapter 7 of this book. Sections 5 and 6 relate to signs and other outdoor lighting, where curfew requirements are listed, again different from CIE proposals (CIE, 1997; 2003). Section 7 gives a brief description of the procedure that could be followed for the application of permits. Section 9 lists several prohibitions, the most interesting being:
(1) The sale of non-conforming equipment is prohibited;
(2) The use of lasers, searchlights, and other high-intensity beams for advertising purposes and for entertainment is prohibited.

The final sections give some, very brief, information about exemptions, appeals, conflicts, violations, and penalties. A complete set of definitions is added at the end. The definitions do not always comply with the CIE Vocabulary (CIE, 1987).

It is mentioned earlier in this section, that the 'USA Pattern Lighting Code', presented by IDA, is aimed in particular at the USA. It is also mentioned that it might prove difficult to draft a similar framework that could be applied on an international scale, because the differences between the legal systems of different countries, even between neighbouring countries, often is considerable. Furthermore, it is suggested that a broad framework, based to some extent on the Pattern, might be of help.

A framework for national, regional, or local legislation or regulation should, as far as possible, be based on recommendations of internationally renowned organizations. Obviously, both IAU and CIE classify as such. The relevant publications of these organizations have been discussed elsewhere in this book. The most important are: Anon. (1978, 1984, 1985, 1985a, 1997a), CIE (1978, 1980, 1993, 1997, 2003) and IAU/CIE (1984). There are many regional and local regulations and ordinances that may give additional information. A number of them is summarized in sec. 15.6. The recommended values that are proposed in Chapter 7 of this book, can be used as the basis for the numerical requirements.

Finally, we will mention again the two aspects that are the cornerstone of most recommendations and regulations:
(1) Zoning. Details are discussed in sec. 3.4.1;
(2) Time limitations or curfew. Details are discussed in sec. 3.4.2.

15.5.3 Examples of national legislation.

(a) Italy

Some time ago, a proposal for an Italian national bill on pollution by outdoor lighting, was briefly described by Blanco (1994). The outlines of that proposal are described, focussing on the control of energy consumption in private and public exterior lighting, as well as on the prevention of light pollution of the sites where professional and non-professional astronomical observatories are located, including their surrounding area.

The proposed law is aimed at municipalities where such observatories are located. The proposal focusses on luminaires. They need to have a G-factor better than 6,5. The G-factor is described in sec. 9.2.3. Luminaires must be equipped with sodium lamps, either high or low pressure, and be provided with dimming devices that can reduce the light output down to 30-50% of the full output. High polluting equipment like globe luminaires must be shielded down to 45^0. Refractor type luminaires, such as are described in sec. 11.4.2, are prohibited. Floodlights on monuments and historical buildings must be aimed in such a way, that the beam reaches only up to one meter from the top.

It is not known whether these proposals got any further than the paper of Blanco (1994). They do not seem to be very complete, and if adopted, would do not very much to reach their goal. Presumably, they have been superceded by the proposed Italian standard that is discussed in sec. 5.2.3 (Fellin et al, 2000; Broglino et al., 2000).

Further developments are described in Zitelli et al. (2001). The activities regarding legislation and standardization are discussed in combination. As regards the standards, there is some overlap with the studies mentioned earlier (Fellin et al., 2000; Broglino et al., 2000).

The following paragraph is based in part on Zitelli et al. (2001). To avoid a proliferation of local laws, a national Italian bill has been submitted to the Italian Parliament, designated as Bill No. 751. It is presently under discussion. The law provides specific guidelines to avoid unnecessary upward illumination and to reduce glare. In particular, it intends to limit 'sky pollution' over the entire nation, and it provides for reduction of luminous flux when traffic on the roads is reduced (i.e. night time). The Bill specifies requirements for several technical parameters:

- the upward light emission over the horizontal plane is restricted. The Upward Light Ratio ULR is explained in sec. 6.2.3c. For road lighting, ULR most be zero. For ornamental and other outdoor lighting, ULR must be less than 15 cd/klm, and for the lighting of large areas, less than 10 cd/klm;
- it is forbidden to illuminate monuments and buildings in an upward direction;
- search-lights for advertising are forbidden;
- luminous signs, that are not necessary for nocturnal activities like e.g. for hotels, hospitals etc., must be turned off at 23:00 h in winter and at midnight in summer.

In 1999, the Technical Standard UNI 10819 has been established. This standard is discussed in sec. 5.2.3. See also Fellin et al. (2000).

Even if one allows for the fact that the information given here, is only a summary, the requirements are severe, if they were to adhered to in full. In the paper, the way the government plans to deal with the costs, is not discussed.

(b) Spain

"Possibly the strongest legislation for the control of light pollution and other forms of activity which potentially interfere with optical astronomical observations is the formidable array of international treaties and laws associated with the Roque de los Muchachos Observatory on la Palma and the Observatory of Teide on Tenerife, both of which are in the Canary Islands, part of Spain" (Murdin, 1992, p. 164). In 1988, a law was adopted in Spain, governing the conditions of optical astronomical observations in the Canary Islands (Anon., 1988). The original Spanish text is given in Annex 6 of Murdin (1992, p. 200-203). A flawed translation into English is added (Murdin, 1992, p. 204-207). The starting point is Article 7.3 of the Agreement on Cooperation concerning Astrophysics, that guarantees the protection of research activities at the Institute of Astrophysics of the Canary Islands. The agreement was signed on 26 May 1979 in Santa Cruz by Spain, Denmark, the UK, and Sweden, later joined by Germany and other countries (Murdin, 1992, p. 204). In 1982, an international consortium was installed by law 7/1982, ratified on 11 May 1982. Earlier legislation was passed in 1982 (Anon., 1982). The law of 1988 refers, amongst others, to all exterior lighting, that could degrade the quality of the observation. It contains, amongst others, the following articles:

(2) All exterior lighting, except air navigation beacons, must avoid light emission above the horizon;
(3) The Institute of Astrophysics of the Canary Islands gives obligatory information regarding all exterior lighting and the establishment of all installations and activities that could cause light or air pollution over 1500 m above sea level.

The 1500 m level is included because in normal weather conditions, an inversion layer is present at that height. (Murdin, 1992, p. 165). Later, a revision of the law of 1988 is published (Anon., 1992; see also Diaz-Castro, 1998, and Diaz Castro & De la Paz, 2003).

(c) Belgium

In October 2003, an environmental policy plan 2003-2007 for the region Flanders in Belgium, has been adopted (Anon. 2003b). It covers all environmental aspects that are recognized by the government. For the first time, light pollution is included. As regards obtrusive light, it is stated that:

- in 2007, even the brightest areas shall have, between 00:30 h and 05:00 h, a sky luminance not more than 9 times the natural background luminance;
- the replacement of high-pressure mercury lamps shall be speeded up;
- overhead road lighting on rural roads shall be replaced by reflectorized road markings;
- dark areas will be introduced in important natural areas as well as near eco-tunnels;
- regulations will be established to restrict disturbing lit advertisement signs;
- the general population shall be more involved in the different processes.

(d) Chile

The efforts that were described earlier, did result in the adoption in 1999 of lighting regulations with the force of law. These refer to the three regions in Northern Chile, where all the major observatories are located (Smith, 2001, p. 43). In the future, all cites in Chile will have to comply with the regulations (Smith, 2003).

15.6 Site selection and protection

15.6.1 Local ordinances

(a) Characteristics of local ordinances

In sec 15.5.2, frameworks for lighting codes have been discussed, in particular the 'USA Pattern Lighting Code', published by IDA (Anon., 2002b, section 7). The Pattern gives a framework only, but it provides all the material needed for local communities to set up their own local ordinance. Most local ordinances follow the scheme that is described in the Pattern Lighting Code.

First, environmental zones are described. Next, for each zone, a number of lamp types and luminaire shielding factors are designated. Next, requirements are given for the total lumen output of all outdoor lamps per net unit of area. Further, a separate maximum is given for unshielded lamps. Curfew requirements are listed. Also, signs and other outdoor lighting are dealt with. Finally, procedures, prohibitions, exemptions, appeals, conflicts, violations, and penalties are touched upon.

When looking at the history of reducing the light pollution effects on astronomical observation, it is clear that the earliest and the most frequent activities took place in the State of Arizona in the USA. No wonder; several of the largest and most famous astronomical observatories in the world are located in that state. A list, published in 1992, shows that, from 1958 onwards, 16 counties and 33 cities in Arizona had established enacted local outdoor lighting control ordinances (Crawford, 1992, table 2.5).

It is often suggested that the ordinances of Pima County and that of San Diego are not only some of the earliest, but also some of the most relevant ordinances. They have been used as an example, that was followed by many other laws and regulations, such as the Law of the Canary Islands and the USA Pattern Lighting Code, that are discussed in sect 15.5.

The Pima County ordinance stems from 1972 (Crawford, 1992, table 2.5). It is, in revised form, included in Murdin (1992, Annex 2). The San Diego ordinance is given in Murdin (1992, Annex 1).

(b) *Siding Spring*

A second set of local regulations, worth discussing, relates to the Anglo-Australian Siding Spring observatory in Australia. In 1979, a plan is issued by the Province of New South Wales that aims to preserve optimum conditions for astronomical observations at the Anglo-Australian Siding Spring observatory (Anon., 1994a; Murdin, 1992, Annex 3).

One point is that the plan specifies critical conditions. The situation is considered critical if the artificial sky glow reaches 10% of the natural sky glow at 30 degree elevation and 3% straight up. The natural sky glow is that at the minimum of solar activity. It is not indicated what is the consequence of the situation being critical.

It is stipulated that within 18 km of the observatory, only constructions without outdoor lighting and without electric supply are permitted.

It is also stipulated, that lighting installations over a specific lumen value require that the comments of the director of the observatory must be taken into account. In Table 15.5.1, the corresponding lumen values for different distances are given.

Distance (km)	Lumen value
3	0
8	1 000
12	2 000
18	4 000
30	12 000
100	1 000 000

Table 15.5.1: *Lumen values for different distances where comments are needed. After Anon., 1994a, p. 170.*

It is difficult to estimate the significance of these data, because it is not indicated whether the data refer to upward lumens or to total lumens, and whether they refer to individual light sources or to complete lighting installations.

(c) Examples of local ordinances

The number of local ordinances is very large indeed. As was mentioned earlier, Crawford (1992) gave a survey up to about 1990, and that for the state of Arizona only. At that time, several dozens were in effect. Since then, the number inside and outside the USA, did increase rapidly. As a example, we will quote a few from one of the most recent issues of the IDA Newsletter from September 2003, issue 55. The following legislation is reported from within the USA: a new Arizona law, two Connecticut laws, and ordinances for Tooela County, Utah; Fairfax County, Virginia; and the city of Madison in Wisconsin. It is striking, that all seem to favour full cut-off (FCO) luminaires for new road lighting installations. Unfortunately, it is not clear, which definition of FCO is used. In sec. 12.4, it is explained in detail, how a small change in the definition, which has only a small effect on the luminaire upward light emission, may have a considerable effect on the installation upward flux, as well as on the costs of the installation.

In a 1995 publication, a summary list of local light ordinances is given (Isobe & Sugihara, 1995, Table 1). The list includes the following cases:

1958	Flagstaff, Ariz., USA.
1972	Richmond, Wash., USA.
1972	Tucson, Ariz., USA.
1972	Itapetinga Radio Observatory, Brasil.
1973	Coconino County, Ariz., USA.
1974	Hawaii County, Hawaii, USA.
1967	Jefferson Davis County, Texas, USA.
1978	Weis Observatory, Tel Aviv, Israel.
1978	Karl Schwarschild Observatory, (East) Germany.
1979	Tenerife, Izaya and Palma, Canary Islands, Spain.
	Ondrejov Observatory, Czechoslovakia.
1989	Bisei, Okayama, Japan.

Here, we will also give some details of a Provincial Motion that is adopted on 4 July 2003 by the Provincial Government of the province of Zeeland in the Netherlands (Anon., 2003c). The following considerations were used:

- the negative effects of nighttime lighting on nature, landscape and humanity are generally accepted;
- the province Zeeland is relatively dark, compared to surrounding areas;
- public lighting in rural areas may have sometimes a negative effect on road safety.

In view of these considerations, the Provincial Government is invited to develop in a short time a clear lighting policy that takes into account Nature, the environment, road safety and the regional and national regulations regarding public lighting. It is also stated, that new assimilation lighting in greenhouses is permitted only if total shielding is ensured.

It should be noted that this is the first, but by no means the last, decision of this kind that is taken in the Netherlands.

(d) The number of observatories

It might be interesting to know the world-wide number of astronomical observatories, both for professional and non-professional observations. It seems that the number is not known. We will make an estimate on the basis of the observatories that are located in the Netherlands. See Table 15.5.2.

Province	Name	Location	Telescope (cm diameter)
Friesland	Eise Eisinga	Franeker	
Friesland	Volkssterrenwacht	Burgum	20
Drenthe	Planetron	Dwingeloo	60
Overijssel	Nutssterrenwacht	Ommen	
Overijssel		Twente	60
Gelderland	Bussloo	Bussloo	30
Gelderland	Corona Borealis	Dieren	
Gelderland	Nijmegen	Nijmegen	30
Gelderland	Phoenix	Lochem	35
Utrecht	Sonnenborgh	Utrecht	40
N-Holland	Copernicus	Haarlem	
N-Holland	De Jager	Texel	
N-Holland	Saturnus	Heerhugowaard	35
N-Holland	Vesta	Oostzaan	
Z-Holland	Sterrenwacht	Leiden	20
Z-Holland	Mercurius	Dordrecht	
Z-Holland	Rijswijk	Rijswijk	35
Z-Holland	Tweelingen	Spijkenisse	
Zeeland	Philippus Lansberg	Middelburg	
N-Brabant	Halley	Heesch	
N-Brabant	Jan Paagman	Asten	
N-Brabant	Simon Stevin	Hoeven	
Limburg	Schrieversheide	Heerlen	

Table 15.5.2: *Astronomical observatories in the Netherlands.*

From Table 15.5.2, it follows that, in total, there are more than 24 observatories. The list contains only those that are member of the organization of astronomical observatories, and that are open to the general public. It should be stressed, that the observatories in this organization all have a number of telescopes. Table 15.5.2 lists the largest, so far as that information was available. They all have educational facilities, and they are frequently visited by groups of amateurs, schools, etc. In short, they are important educational facilities. The number of private observatories in not known.

Now, we will assume that in the industrialized world, the observatory-density is the same as in the Netherlands. For 16 million people, there are 24 observatories; or 1,5 for each million people. In the industrialized world, there are about 1000 million people, or 1500 observatories. For the developing world we assume an observatory-density of 0,15 for each millon people. In the developing world, there are about 4000 million people, or 600 observatories. World-wide, this would mean about 2000 observatories!

15.6.2 Outdoor lighting projects

(a) *Lighting near observatories*

In sec. 15.6.1, the set-up of local ordinances is discussed. In this section, the results will be discussed. Some examples will be given about observatories and other facilities, where careful planning and skilled design are combined with relevant regulation and legislation. In all cases, the enthusiasm and dedication of the people involved, is a striking aspects. One may safely assume that without skill, enthusiasm, and dedication, no facility will be successful.

(b) *The Canary Islands observatories.*

This section is based in part on (Diaz-Castro,1998), and also in part on unpublished information from Diaz-Castro (2000). The atmosphere above the summits of the Islands of Tenerife and La Palma offers exceptional conditions for astronomical observations. The main climatological feature is that both islands are in the trade-wind areas of the Northern hemisphere subtropics, and that the summits are well above the inversion layers that characterize many trade-wind regions. Above the inversion layer, the prevailing winds exhibit laminar air movements, which helps to have good 'seeing'. For this reason, a large number of important telescopes, and a variety of detectors have been placed in the internationalized Canarian astrophysical observatories.

An increase in light pollution from outdoor lighting could cause a deterioration in these conditions. To prevent this from happening, an Act of Parliament was drawn up, in accordance with the guidelines established by the IAU's Committee 50, and passed into Law (31/1988) to protect the Astronomical Qualities of the Observatories of the I.A.C. This has now been implemented through the regulations of Royal Decree 243/1992.
These regulations are discussed in sec. 5.2.2g.

This regulation covers obligatory modifications to the existing outdoor lighting installations in an effort to further improve the observing conditions. Under the auspices of the Instituto de Astroficica de Canarias, La Laguna, Tenerife (IAC), an organization created to monitor and analyze potentially polluting activities (Oficina Technica para la Proteccion de la Calidad del Cielo O.P.S).

One of the first activities of the O.P.S. was to carry out the First Project of Lighting Modifications on La Palma, financed by the Spanish Government, which was completed during 1993. A second project has been carried out during 1994.

In the first project of lighting modification, the O.P.S. has built up a database registering all light sources on the Island of La Palma and has analyzed the lighting fixture and type of lamp for each single light point. For this, the formula that was used to estimate the light pollution, had to be adapted to be able to incorporate the upward light emission and the downward light emission of the luminaires separately, the reflection factor of the ground, and the lamp type that was used. The original formula only considered the total lamp flux installed in towns and the distance to the Observatory.

In the first project was to modify the luminaires that did cause most light pollution. It affected 16% of the total number of light points on La Palma island. The original paper does not include details about the actual improvements, but in general, better lighting designs and more appropriate light distributions were used, and more efficient lamps were applied. The modification did give the following results:

	Before midnight	After midnight
Average whole island		
– luminous flux	2	13
– light pollution	21	34
– power (W)	4,3	14,2
– energy (Kwh)		10,2
Barlovento county		
– luminous flux	32	41
– light pollution	79	83
– power (W)	26	37
– energy (KWh)		33
Barlovento, design only		
– luminous flux	0	0
– light pollution	0	60

Table 15.6.1: *Reduction found in la Palma after the modifications of the first project.*

Notes to Table 15.6.1:
- All reductions are in %;
- The modification affected 16% of the light points; the results were averaged over the whole island;
- Barlovento county: 198 lanterns in the town and 300 scattered security lights over the rural area;
- Design only: improved light distribution, with the same wattage and the same lamps.

(c) *Bisei Town*

In 1989 a lighting ordinance was set up for Bisei Town. Bisei Town is a small mountain town in Okayama prefecture in Japan. The special case was that Bisei Town is renowned in Japan for its clear, starry sky at night; the municipal authorities wanted to keep that special feature, although there is no major astronomical observatory in the vicinity. It this respect, Bisei Town could be regarded as an important example for other small towns to follow, not only in Japan, but also world-wide. The tools of the Bisei Town ordinance were:

(1) To guarantee a level of lighting necessary for daily life and to protect the beautiful starlit skies;
(2) To keep the night sky brightness within 10% of the natural conditions;
(3) To turn out all outdoor lights after 22:00 h, except important safety lights;
(4) To ask citizens to comply with the restrictions
(after Isobe & Sugihara, 1995, abridged).

(d) The need for education of experts

In sec. 15.6.1c, examples of local ordinances are given. It is mentioned that the number of local ordinances is very large indeed. See e.g. Crawford (1992, table 5.2), Isobe & Sugihara (1995, Table 1) and the IDA Newsletter from September 2003, issue 55.

National parks, many of which house astronomical activities, are still more frequent. Some are discussed in sec. 4.2.1. Also, in that section, the 'dark areas' or 'dark refuges' are discussed. They exist in many countries, e.g. Australia, the Canary Islands, Canada, Italy, Japan, Mexico, South Africa, Slovenia, the Netherlands, the USA, to name a few. Some of them have been mentioned in this book. A complete lists would be unyieldingly large. That does indicate immediately the main problem. Not only the large number of parks and the like, but also the number of organizations that deal with them. There is a lot of international cooperation, but still, it seems that the effect would be much larger if the many organizations would work more closely together. Here again, a problem is the fact that these subjects are dealt with by specialists, who are quite capable to do their own job, but do not always understand the needs and motives of other professions. As in many other cases, this is again a clear indication of the need of cross-disciplinary education. In sec. 15.3.1, the different aspects of education of experts have been discussed, particularly as regards those that are related to the reduction of light pollution.

(e) A list of activities

In spite of the remarks, that have been made in the preceding part of this section about the proliferation of national parks, dark sites and the like, another list will be given here. The list is based on a personal communication (Alvarez del Castillo, 2003). It was used for drafting a paper for he CIE Session in San Diego, USA, in 2003. Almost all the material that shows up in the list, had been published earlier (Alvarez del Castillo et al., 2003). The list is included here, because it is not restricted to observatories, parks, dark sites and regulations, but it mentions all sorts of activities that are happening around the world. As with the earlier lists, many items are dealt with in different sections of this book. The list is, obviously, not comprehensive. The original paper mentions in a number of cases, the e-mail addresses. These are omitted here, because they are changing too rapidly to be useful in a book like this one. A few additions have been made to the original lists, notably as regards the Netherlands.

Australia and New Zealand

- National Standards for Obtrusive Light;
- AS 4282-1997 'Control of the obtrusive effects of outdoor lighting';
- AS/NZS 1158., 1997 & 1999, on Road Lighting;

- City of Sydney, 2000. Exterior Lighting Strategy as part of a plan to establish the city as Australia's premier city;
- International Dark-Sky Association Office near Sydney.

Austria

- Nationwide Star Counting Activity. Raised awareness and measured limiting magnitudes in as much of the country as possible;
- The IDA Austria has published the 2nd edition of "Die Helle Not", a glossy, colour brochure describing the problems of light pollution (in German);

Belgium

- National Light Pollution Awareness Day;

Brazil, Costa Rica, Greece, the U.S.A. (e.g. Florida, Hawaii)

- Programs and laws to protect Sea Turtles. Sea turtle nesting and hatching behaviour is adversely affected by artificial nighttime illumination. Programs seek to keep obtrusive lighting off the beaches during the relevant seasons in order to protect endangered turtles;

Canary Islands, Spain

- Protecting a Premier Astronomical Site;
- 1988 legislation protecting the quality of the night sky for observatories of the Instituto de Astrofisica de Canarias (IAC);
- 1992 establishment of the OTPC (La Oficina Tecnica para la Proteccion de la Calidad del Cielo), an office to control and evaluate activities that could contaminate the astronomical research;
- 1998 establishment of an ecologically protected zone for the area around the observatories;

Canada

- Dark Sky Preserves:
  - In 1999, Torrance Barrens Conservation and Dark Sky Reserve, about 150 km North of Toronto, Ontario;
  - In 2000, McDonald Park Dark Sky Preserve in Fraser Valley, near Abbotsford, British Columbia;
- General Educational Activities: The Royal Astronomical Society of Canada has a tradition of light pollution education activities. Lighting professionals promote good lighting practices through strong participation in the Illumination Engineering Society of N. America (IESNA) and in the Commission Internationale de l'Eclairage (CIE);
- Calgary's EnviroSmart Streetlights Project. The city of Calgary is replacing about 30 000 residential street lights with full cut-off (FCO) fixtures, generally going from 200 W to 100 W on residential streets and 200 W to 150 W on collector roads. Phase 1 is complete with 10 400 lights done. End of Project is expected to be in 2005. Calgary is actively investigating ways to retrofit its 40 000 other, non-residential streetlights;
- Expected outcomes include:
  - Electricity bill reduced by over $2 Million per year;
  - Carbon dioxide emissions reduced by 16 000 tonnes per year;
  - Reduced glare for drivers;
  - Reduced light trespass;
  - Reduced sky glow over Calgary.

Chile

- National Legislation, Applicable in Regions II, III, and IV (of its 6 regions, the 3 with professional astronomical facilities), to promote quality lighting and minimize waste and sky glow. La Officina de Proteccion de la Calidad del Cielo del Norte de Chile (OTPC) established to assist in coordination and execution of the law;
- March 2002 International Light Pollution Conference with attenders including engineers, astronomers, political representatives, manufacturers, etc. Proceedings published;

Czech Republic

- National Legislation: Protection of the Atmosphere Act (addresses light and air pollution). Signed into law in February 2002 and took effect in June 2002.

France/Switzerland/Germany

- European Symposiums on Light Pollution. First one in France, Second one in Switzerland (September 2002), Third one in Germany (Stuttgart, September 12-13, 2003);
- The IDA has sections and affiliates in all three of these countries and numerous educational materials are available in French and German;

Greece

- Education programs in Networks of Schools. Hands On, Interdisciplinary activities. Students learn how light pollution affects them and what they can do. Lessons include astronomy, technology, art, and sociology and build skills in observation, data analysis, computers, and communication. Programs network students in distant areas who learn how local action can make a positive difference addressing global concerns. Programs are being extended through UNESCO as well.

Hungary

- Hungarian National Railways wins Award. They won an IDA International Lighting Award for their project to convert 16 000 lights at 500 railway stations to full cut-off with power use reduced by nearly 50%.

Italy

- Regional legislation in several of its regions;
- First World Atlas of Artificial Sky Brightness, Released in summer 2001 by the Instituto di Scienza e Technologa Dell' Inquinamento Luminoso. Uses DMSP satellite images and adds modeling of light propagation;
- The Night Sky as the Heritage of Humanity. In March 2003, the Commission for Foreign Affairs of the Italian Parliament approved a resolution to promote this at UNESCO.

Japan

- Japan's Environment Agency published "Guidelines for Light Pollution: Aiming for Good Lighting Environments" in 1998;
- Calculations on Wasted Light. The calculations by Japanese researchers on wasted light for specific regions such as cities have been used worldwide to understand the value of better economies in lighting design and installation.

Malta

- How lighting affects our natural environment. In coordination with environmental groups, they are studying the effects of light pollution on flora and fauna. To promote education and awareness, they produce educational leaflets and good lighting guidelines and hold conferences pulling together experts from the relevant fields and government organizations.

The Netherlands

- 1997 Dark Night, which resulted in a sketch of a national light pollution atlas;
- actions of several Ministeries to add light to possible pollution effects;
- actions of several Ministeries to introduce 'dark areas' in natural parks, in analogy of 'silence areas';
- between 1999 and 2004, a comprehensive series of 'General directives for light intrusion in public areas' has been published. They are based on the relevant CIE Publications No. 126 and No. 150.
- 2003 the Platform Lichthinder (platform obtrusive light) is established. It serves as a National section of IDA.

United Kingdom

- General Educational Activities: The Campaign for Dark Skies of the British Astronomical Association group has a long history of raising awareness about light pollution; The Institute for Lighting Engineers publishes guidelines and has held symposia addressing good lighting practices and how to minimize obtrusive lighting;
- Legislation and Policies. The UK Environment Agency recently sought to include the issue of light pollution in the "London Plan." In spring of 2003, the Science and Technology committee of the House of Commons began an inquiry to "examine the effectiveness of measures taken to reduce the impact of light pollution on astronomy and to consider what further steps, if any, are required."

U.S.A.

- Legislation to Control Obtrusive Lighting. Numerous State-level ordinances in existence and proposed ones in more States. Hundreds of municipalities and counties seeking legislation. IDA working on a National Outdoor Lighting Code. Flagstaff, AZ awarded as IDA's 'First International Dark-Sky City';
- Dark Sky Preserves. National Park Service funds a Night Sky Team and monitors National Parks with special night sky programs. Michigan Dark Sky Park (Lake Hudson Recreation Area) first such preserve in the U.S.A. and preserves continuing to be established in parks and on local levels;
- First International Conference on the Ecological Consequences of Artificial Night Illumination (Feb. 2002).

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