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Night-time traffic in urban areas

A literature review on road user aspects

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Title:
Night-time traffic in urban areas – a literature review on road user aspects

Abstract (background, aim, method, result) max 200 words:

The aim of this literature study is to review recent research on night-time traffic from a road user perspective. The report discusses road users' behaviour, needs and problems in relation to other road users as well as to traffic environment. The study includes 128 references from 1998–2008 and it mainly concerns urban areas.

The report begins with a chapter about accident statistics, followed by a theoretical background that includes lighting terminology, Swedish regulations on road equipment, and the human eye and night vision. The main part of the report has its focus on five road user groups – drivers, pedestrians, bicyclists, older people and visually impaired people – and their needs, difficulties, performances and behaviour in night-time traffic.

The literature gives relatively much information about drivers' situation in night-time traffic, but there is a lack of knowledge in some areas such as drivers' interaction with parts of the driving environment. Also, there is partly a lack of knowledge on pedestrians and older road users. Regarding bicyclists and visually impaired people, there is only very limited literature available.

Several areas that are interesting for further research are identified in the report.

Keywords:
night-time traffic, drivers, pedestrians, bicyclists, older people, visually impaired people, road equipment, accidents

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Syftet med den här litteraturstudien är att sammanställa aktuell forskning om mörkertrafik ur ett trafikantperspektiv. Rapporten tar upp trafikanters beteenden, behov och problem, både i relation till andra trafikanter och till trafikmiljön. Studien omfattar 128 referenser från 1998–2008 och är i huvudsak inriktad mot tätort.

Rapporten inleds med ett kapitel om olycksstatistik. Därefter ges en teoretisk bakgrund som tar upp ljusterminologi, riktlinjer och regler för utformning av vägutrustning samt människans synsinne och mörkerseende. Rapportens huvuddel handlar om fem trafikantgrupper – fordonsförare, gående, cyklister, äldre och personer med nedsatt syn – och deras behov, svårigheter, förmågor och beteenden i mörkertrafiken.

Litteraturen ger en förhållandevis god uppfattning om fordonsförares situation i mörkertrafiken, men det finns samtidigt kunskapsluckor inom vissa områden, bland annat när det gäller interaktion med delar av vägmiljön. Likaså saknas delvis kunskap om gående och äldre. När det gäller cyklister och personer med nedsatt syn är litteraturen mycket begränsad.

I rapporten identifieras ett flertal områden som är intressanta för fortsatt forskning.

Nyckelord:
mörkertrafik, fordonsförare, gående, cyklister, äldre, nedsatt syn, vägutrustning, olycksstatistik

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Preface

This literature review is the first part of a three-step project called “Road user support in night-time traffic”, which has been financed by the Swedish Road Administration. The second step will be a focus group study and in the third step road users’ behaviour and experiences in relation to alternative designs of road equipment will be investigated. The project will be finished by the end of 2010.

Lena Nilsson, VTI, has been project leader. Carina Fors, VTI, has written the chapters 1, 2, 5–7 and Sven-Olof Lundkvist, VTI and Ramböll, has written the chapters 3–4. Hillevi Nilsson Ternström at VTI Library and Information Centre has assisted with the literature search. Peter Aalto has been contact person at the Swedish Road Administration.

Linköping May 2009

Lena Nilsson

Cover: VTI/Hejdlösa bilder

Kvalitetsgranskning

Granskningsseminarium genomfört 27 april 2009 där Staffan Möller var lektör. Carina Fors har genomfört justeringar av slutligt rapportmanus 30 april 2009. Projektledarens närmaste chef Jan Andersson har därefter granskat och godkänt publikationen för publicering 27 maj 2009.

Quality review

Review seminar was carried out on 27 April 2009 where Staffan Möller reviewed and commented on the report. Carina Fors has made alterations to the final manuscript of the report. The research director of the project manager Jan Andersson examined and approved the report for publication on 27 May 2009.

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Night-time traffic in urban areas – A literature review on road user aspects

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Summary

Human vision is not well adapted to night-time conditions. Hence, road users need technical solutions, such as street lighting and retroreflective materials, in order to be able to drive, cycle or walk safe at night. Night-time traffic implies some certain problems, for example glare and difficulties with detecting obstacles and estimating distances. Different groups of road users have different prerequisites and needs, and the problems encountered may thus vary. In order to improve traffic safety and accessibility under night-time conditions, the needs and problems of all road user groups must be taken into consideration. It is also important to adapt the technology that aims to facilitate night-time traffic to the road users who will use it.

The aim of this literature study is to review recent research on night-time traffic from a road user perspective. The report discusses road users' behaviour, needs and problems in relation to other road users as well as to traffic environment. The study includes 128 references from 1998–2008 and it mainly concerns urban areas.

Accident statistics show that pedestrians are at a greater risk of having an accident at night than during daylight conditions. For drivers, research indicates that there are no substantial differences in accident risk between darkness and daylight, when the influence from other factors such as alcohol and drowsiness is controlled for.

A problem that is frequently discussed in literature is drivers' difficulties in detecting pedestrians. One explanation given is that the ability to steer a vehicle is not affected by darkness, which results in the driver not being aware of the reduced visibility and thus not adjust the driving to the present conditions. In addition, pedestrians tend to overestimate their own conspicuity, which may cause them to expose themselves to potential risky situations.

Many older drivers avoid night-time driving. Increased sensitivity to glare and age-related visual impairment may be some of the reasons, but literature does not provide a complete picture.

Bicyclists' needs and problems in night-time traffic are not well documented. Accident statistics indicate that bicyclists may be at an increased risk of having an accident in darkness, but besides that almost no information is available from literature.

Also, there is very little literature on visually impaired people and their experiences of night-time traffic. Some eye diseases are very common, especially among older people, and research shows that many of those affected continue to drive. Knowledge about these road user groups is thus important.

Regarding the interaction between road users and road environment, mainly studies about street lighting were found. Among other things, the studies report about new lamp types that both improve visibility and have lower energy consumption. Other studies indicate that the visibility of road markings seldom meets the road users' demands. Literature on traffic lights and traffic signs was limited to a few studies, while no information at all about road surfaces was found.

An area interesting for further research is visibility and detection of pedestrians, which includes behavioural aspects as well as technical solutions. Other areas that are interesting for further studies are older and visually impaired road users' experiences and problems in night-time traffic, and also bicyclists' visibility and needs.

Mörkertrafik i tätort ur ett trafikantperspektiv – en litteraturstudie

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Sammanfattning

Människans synsinne är inte särskilt väl anpassat till mörker. Trafikanter är därför beroende av tekniska lösningar, såsom vägbelysning och reflekterande material, för att kunna vistas säkert i trafiken under dygnets mörka timmar. Mörkertrafik medför en del speciella problem, bland annat med bländning samt svårigheter med att upptäcka föremål och korrekt bedöma avstånd. Olika trafikantgrupper har olika förutsättningar och behov, och vad som upplevs som problem kan därför variera. För att kunna förbättra trafiksäkerheten och framkomligheten i mörker behöver man därför ta hänsyn till samtliga trafikantgrupper och deras olika behov och problem. Viktigt är också att den teknik som syftar till att underlätta för trafikanter i mörkertrafiken är väl anpassad till dem som ska använda den.

Syftet med den här litteraturstudien är att sammanställa aktuell forskning om mörkertrafik ur ett trafikantperspektiv. Rapporten tar upp trafikanters beteenden, behov och problem, både i relation till andra trafikanter och till trafikmiljön. Studien omfattar 128 referenser från 1998–2008 och är i huvudsak inriktad mot tätort.

Olycksstatistik visar att gående har en större risk att råka ut för en olycka i mörker än i dagsljus. För fordonsförare visar studier inga betydande skillnader i olycksrisk mellan mörker och dagsljus om man tar bort påverkan från andra faktorer, såsom alkohol och trötthet.

Ett problem som ofta tas upp i litteraturen är förares svårigheter med att upptäcka gående. En förklaring som ges är att förmågan att styra ett fordon inte påverkas i någon större omfattning av mörker, vilket leder till att förare inte inser att synbarheten är kraftigt försämrad och därför inte anpassar sin körning till de rådande förhållandena. De gående, å sin sida, tenderar att överskatta sin egen synbarhet, vilket gör att de riskerar att utsätta sig för potentiellt farliga situationer.

Många äldre förare undviker att köra i mörker. Ökad känslighet för bländning och en allmänt försämrad syn kan vara orsaker, men litteraturen ger ingen fullständig bild.

Cyklisters behov och problem i mörkertrafiken är inte väldokumenterade. Olycksstatistik tyder på att cyklister kan ha en ökad risk att råka ut för en olycka när det är mörkt, men utöver det finns nästan ingen information om cyklister i litteraturen.

Likaså finns väldigt lite litteratur om trafikanter med nedsatt syn och deras upplevelser av mörkertrafiken. Vissa ögonsjukdomar är mycket vanliga, framförallt hos äldre, och forskning visar att många av dem som drabbas fortsätter att köra bil. Kunskap om dessa trafikantgrupper är därför viktig.

När det gäller trafikanters samspel med vägutrustning och trafikmiljö finns en del studier om vägbelysning, bland annat rapporteras om nya lamptyper som både ger bättre synbarhet och lägre energiförbrukning. Det framgår även att synbarheten hos vägmarkeringar sällan motsvarar trafikanternas behov. Litteraturen om trafikljus och vägmärken är begränsad och studier om vägbeläggning saknas helt.

Ett område som är intressant för fortsatt forskning är upptäckbarhet av gående, vilket inkluderar både beteendeaspekter och tekniska lösningar. Ytterligare områden som är intressanta för vidare studier är äldres och synsvagas upplevelser och svårigheter i mörkertrafiken samt cyklisters synbarhet och behov.

1 Introduction

This report is a literature review on night-time traffic from a road user perspective. In this introductory chapter, the background of the project and the aim of the study are presented, and also the method and the literature databases that were used are described.

1.1 Background

Fundamental for safe and efficient traffic is the interaction between road users, vehicles and road environment. The information needed by road users to support their behaviour must be easy to perceive and understand, and obtained in time. Darkness raises particularly high demands on a good visual traffic environment. Visibility, legibility and identification of persons and objects, in order to achieve correct expectations and behaviours, are important components in a good visual environment.

Different road users have different needs and take part in traffic under varying conditions. These differences tend to be intensified in night-time traffic. Especially older road users may experience problems with glare from lighting and road signs. Drivers need help to discern unprotected road users, which can be very difficult under certain light and illumination conditions. From an equality aspect, vehicles, roads and road equipment must be designed in order to enable all road user groups to use the road and its immediate surroundings in a safe way, also during night-time conditions.

1.2 Aim

The aim of this study was to review literature on road users' needs, problems and experiences in relation to night-time traffic. The main focus is on traffic in urban areas. The study includes aspects such as road user behaviour, human vision, accident statistics, road equipment and issues related to older or visually impaired road users. The term "night-time" here refers to the dark hours of the day and thus, dawn and dusk are not included. However, night-time traffic comprises a range of light conditions, from small unlit roads to well-illuminated urban environments. Excluded from the review are problems and solutions mainly related to rural areas, for example animal accidents and road marker posts, and also vehicle-based solutions such as night vision systems and adaptive headlights.

1.3 Method

The literature search was done by VTI Library and Information Centre. Five databases were used:

TRAX – VTI library catalogue. Holds about 125 000 references within the field of transportation.

ITRD – International Transport Research Documentation. A world-wide database, containing more than 400 000 references.

TRIS – Transportation Research Information Services. Contains more than 600 000 references to literature and on-going research.

PsycINFO – Holds about 2.5 million references to international literature in psychology and behavioural and social sciences.

Scopus – Covers 36 million references in scientific, technical, medical and social sciences.

The search focused on night-time traffic (using words such as dark/darkness/night-/night-time/nocturnal) in combination with different road user groups such as driver, pedestrian and cyclist. Also words for visually impaired, disabled and older people were included in the search. In addition, the words human factors, vision and accident were used. The search was limited to a time period of ten years, i.e., from 1998 to 2008.

The search resulted in approximately 1 100 references. From this, about 140 references were selected. The main selection criterion, besides night-time traffic, was that the reference should have a road user focus, i.e., technical reports were excluded. References about rural-related areas and vehicle-based solutions were also excluded. The selected references were reviewed together with some other literature on eye physiology, traffic safety and road equipment regulations. Also a few references older than ten years have been used. Finally, 128 references were included in this report.

The report begins with a chapter about accident statistics (chapter two). Chapters three, four and five give a theoretical background about lighting terminology, road equipment regulations and human vision and can be read as an introduction to chapter six, which is the main part of the report. Chapter six deals with road users' problems needs and experiences in night-time traffic and it is divided into five sections: drivers, pedestrians, bicyclists, older road users and visually impaired. In the end of chapters two and five, and also in the end of each section in chapter six, there is a summary of the most important and/or interesting results of that chapter/section. The summaries are followed by the authors' comments and suggestions for further research. In the last chapter (seven), the results from the study are briefly discussed and some areas that are identified as interesting for further research are summarized.

2 Accident Statistics

Nearly one fourth of all personal injury traffic accidents in Sweden occur during the dark hours, Table 1. The distribution of injury severity is shifted towards more severe injuries and fatalities in low light conditions compared to daylight, particularly for roads without lighting. About 29% of all fatalities occur in dark time periods and another 10% during dawn/dusk. These figures include all roads, both urban and rural.

Table 1 Percentage of personal injury accidents by light condition, grouped by severity of injury, 2007, both urban and rural roads, Sweden [1].

	Percentage of accidents by light condition			
Lighting conditions	Fatal	Severe	Slight	Total
Daylight	57.5	61.9	61.9	61.8
Darkness	28.6	24.8	23.8	24.1
No lighting	*18.5*	*11.8*	*11.0*	*11.3*
Lighting	*10.1*	*13.1*	*12.9*	*12.9*
Dawn/dusk	9.6	7.9	6.9	7.2
No lighting	*8.7*	*5.7*	*5.2*	*5.3*
Lighting	*0.9*	*2.2*	*1.8*	*1.8*
Missing data	4.2	5.4	7.3	6.9
Total	100	100	100	100

Also in other countries, the accidents are more severe at night. In Great Britain, the severity of accidents (i.e., the number of fatal accidents per 100 accidents) is increased by a factor of 2 at night [2]. In Japan, about 55% of all fatalities occur at night, which is considerably higher than the total percentage of accidents at night – about 30% [3]. Also in the US the percentage of fatalities during the dark hours is higher than in Sweden – about 45% [4] – and the non-fatal accidents are more severe [5]. The fatality rate, corrected for mileage, has been estimated to be 3–4 times higher at night than in daylight [6, 7]. For pedestrians in certain urban areas, the relative number of fatalities (i.e., the number of fatalities/total number of pedestrians involved) is several times higher at night than during daylight conditions [8].

The relative risk of a motor vehicle accident with personal injuries during the dark hours in Sweden is 1.2–2.0, where a risk of 1.0 corresponds to daylight conditions [9]. In Norway, this figure has been estimated to 1.2 [10].

The distribution of different accident types in Sweden is shown in Figure 1. The relative frequencies of accidents involving a single motor vehicle, pedestrians and animals all increase in low light conditions, while accidents involving motor vehicles, mopeds and bicycles decrease. However, the light level alone does not explain the differences in accident distribution. Alcohol, drowsiness, weather conditions and driving behaviour (e.g., speed) are known to interact with light level, why these figures should be interpreted with caution [9, 11, 12].

In an attempt to reduce the influence of interacting factors, Johansson has investigated the accident pattern between 4 and 5 pm (dark from November to January) and compared it with the accident pattern between 1 and 2 pm (always daylight), where the influence of alcohol, drowsiness, weather and behaviour is assumed to be small or similar for the two selected hours [11]. By studying the accident patterns for four different types of accidents in urban areas, Johansson found that darkness was related to an increased risk of accidents involving pedestrians, with a relative risk of 2.2. The risk of accidents for bicyclists was also found to increase, but not as much as for pedestrians (relative risk of 1.4). The relative risk of accidents involving either a single motor vehicle or more than one motor vehicle did not differ significantly between different light conditions.

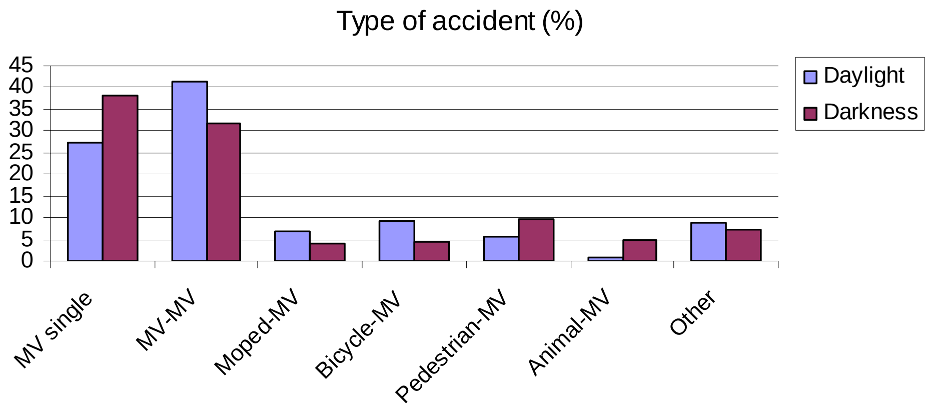

Figure 1 Distribution of different accident types during daylight and darkness expressed in percentage, 2007, both urban and rural roads, Sweden [1]. MV = motor vehicle.

Johansson has done the same analysis for rural roads and found no difference in relative risk for single motor vehicle accidents in dark conditions compared to daylight. It is therefore reasonable to assume that the increase in relative accident frequency for single motor vehicle accidents in darkness (Figure 1) mainly is related to other factors than the darkness itself.

In an American study – where influence from other factors was reduced in a similar way as in Johansson’s study – there were 1.3 times as many collisions between motor vehicles in darkness as in daylight [13].

The number of motor vehicle accidents involving pedestrians and bicyclists in Sweden 2007, is shown in Table 2. About 30% of all accidents involving pedestrians occur during the dark hours and another 6% during dawn and dusk. This could be compared to the number of pedestrian journeys in different lighting conditions. About 20% of all pedestrian journeys are undertaken at night time (1995–1997, Sweden) [14]. Furthermore, 85% of the pedestrian journeys at night time were undertaken at roads with illumination. Thus, assuming that the number of pedestrian journeys in different lighting conditions has not changed from 1997 to 2007, the relative number of accidents involving pedestrians is higher at night than in daylight conditions. Roads without lighting have the highest relative rate of accidents involving pedestrians (provided that the missing data in Table 2 does not have a considerable effect on the relative rates). Regarding bicyclists, about 17% of the bicycle journeys are undertaken at night time (1995–1997, Sweden) [14], which means that the relative number of accidents involving bicyclists does not differ substantially between day and night.

Table 2 Number and percentage of motor vehicle accidents involving pedestrians and bicyclists, 2007, both urban and rural roads, Sweden [1].

Accident type	Light condition					
	Daylight	Darkness, with lighting	Darkness, without lighting	Dawn/dusk, with lighting	Dawn/dusk, without lighting	Missing data
Pedestrians:						
n	662	328	106	43	46	216
%	47.3	23.4	7.6	3.1	3.3	15.4
Bicyclists:						
n	1037	157	48	30	68	196
%	67.5	10.2	3.1	2.0	4.4	12.8

The distribution of accidents involving more than one motor vehicle, during daylight and darkness in Sweden, is shown in Figure 2. The relative frequency of collisions with an oncoming vehicle is higher in darkness than in daylight. The same tendency can be seen for crossroad accidents, while the opposite is found for rear-end collisions and accidents with vehicles turning in intersections. In an American study of crashes on roadways without lighting, the types of crashes occurring more often during darkness than in daylight conditions were collision with pedestrians and fixed objects, and run off roadway [5]. Rear-end and intersection collisions had a lower percentage at night than during the day. However, Sullivan and Flannagan have found that when exposure level is taken into account, rear-end collisions are more than twice as likely to occur in darkness as in daylight [15]. In Japan, more than 20% of the total number of fatalities occur at intersections at night [3, 16].

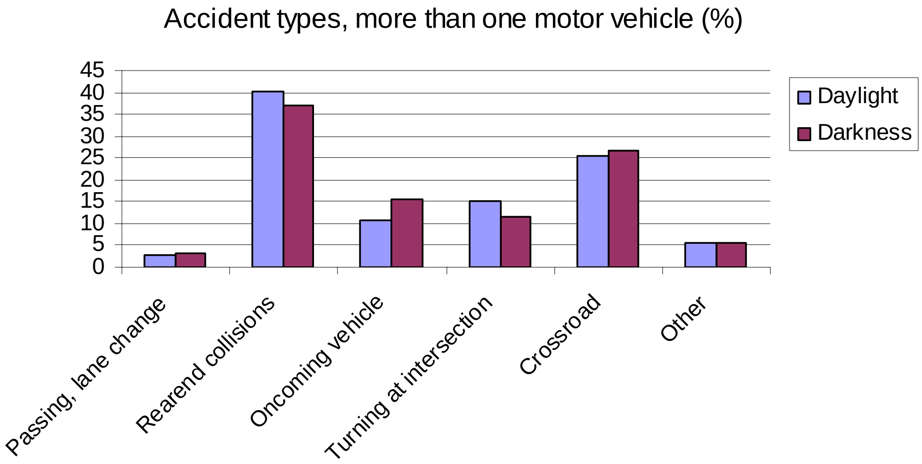

Figure 2 Distribution of accidents involving more than one motor vehicle, during daylight and darkness, expressed in percentage, 2007, both urban and rural roads, Sweden [1].

In the US, data from all night-time fatalities over a period of 11 years has been analysed [6]. Two categories were found: single- and multi-vehicle collisions with alcohol involved and crashes with low-contrast objects, such as pedestrians and bicyclists. In 2002, 65% of all pedestrian fatalities in the US occurred at night [17]. Alcohol was involved in nearly half of the total number of pedestrian fatalities. 34% of the victims and 13% of the drivers were intoxicated. The influence of ambient light level on pedestrian fatalities has been examined in a study, where the changeover to daylight saving time was utilized in order to reduce the influence from other factors (e.g., exposure, drowsiness and alcohol) [13]. It was found that there were about 4 times as many pedestrian fatalities in darkness as in daylight. The risk was highest on limited access-roads (6.75), followed by arterials (4.79) and local and collector roadways (2.97), i.e., the risk increases with roadway speed. On urban arterial roadways, where street lights often are present, there were about 3.4 as many pedestrian fatalities in darkness as in daylight. Arterials had the highest number of pedestrian fatalities and thus the greatest life saving potential. In a similar way (regarding the daylight saving time methodology) pedestrian fatalities in intersections were investigated, and it was found that the ratio of dark to light pedestrian fatalities varied between 1.4 and 4.7, depending of time of the year (spring, fall) and time of the day (a.m., p.m.) [13].

Summary, accident statistics

Statistics about accidents in night-time conditions should be interpreted cautiously, since there might be other explaining factors than the darkness itself, such as exposure level, alcohol, drowsiness, animals and weather conditions. In addition, not all statistics distinguish between urban and rural areas. Studies that attempt to take these factors into account indicate the following for urban areas:

- Pedestrians are at an increased risk of having an accident in darkness compared to daylight.
- Also bicyclists may be at an increased risk in darkness.
- There is no obvious increase in risk of accidents involving one or more motor vehicles in darkness. However, conclusions from different studies are not completely in agreement regarding the risk for motor vehicle drivers.

Authors' comments and proposals for further research

Pedestrians' increased risk of having an accident at night should be further investigated. With more knowledge of these accidents, it might be possible to decrease the accident rate, by for example improving road equipment or affecting pedestrians' attitudes and/or behaviours. Interesting research questions are:

- In what situations do these accidents occur?
- Are other factors, such as alcohol, often involved?
- Do night-time accidents happen more often to any particular group of pedestrians (e.g. older people)?
- What could have prevented the accidents from occurring?

3 Lighting Terminology

This section describes concepts that are of importance for the understanding of light, lighting and light measurements in the road environment.

Basically, a light-source emits **radiant flux**, Φ [W], which, when weighted according to the spectral response of the human eye, is called **luminous flux**, Φ_w [lm]. The luminous flux emitted within the solid angle, ω [srad], is named the **light intensity**, I [cd]. At a given distance from the light source, r [m], on a surface of area A [m^2], the light intensity implies an **illuminance**, E [lx]. Dependent on the reflection properties of the surface, the illuminance results in a **luminance**, L [cd/m^2], of that surface and, furthermore, dependent on the type of light source, a **colour**, which is described by the tri-stimuli coordinates, x, y and z, defined by the CIE-1931 System [18].

The above-mentioned reflection properties of a surface are generally characterized by the **retro reflectivity**, R_L [$cd/m^2/lx$], or the **luminance coefficient**, Qd [$cd/m^2/lx$]. The former parameter is mostly used to describe the performance of retroreflective material, like road markings, road sign sheeting, etc., while Qd generally is used in connection with road surfaces. The performance of small retroreflectors is described by the CIL-value [cd/lx], which is the retro reflectivity multiplied by the area of the reflector.

In the eye of a human observer, the illuminance will cause a **stray-light luminance**, L_s [cd/m^2], which is dependent on the illuminance at the eye, E, and the angle between light-source and direction of sight, Θ. This luminance occurs within the eye and is generally referred to as **glare**. The visual impairment caused by glare can be quantified by means of the **threshold increment**, TI [-].

When describing the visibility of a large object, like a pedestrian, the concept **luminance contrast**, C [-], is used. The contrast is dependent on the luminance of the object itself, L_o [cd/m^2], background luminance, L_b [cd/m^2], and the stray-light contrast, L_s [cd/m^2].

The most important light parameters and the relationship between them are shown in Table 3.

The **spectral response of the eye** during different light conditions is divided into photopic, mesopic and scotopic vision, see also Chapter 5.1. The luminance levels present in night-time driving are usually within the mesopic range (0.001–3 cd/m^2 [19]). Well-illuminated urban roads have a luminance of 1-2 cd/m^2 [20]. Wet country roads illuminated only by vehicle headlamps can have luminances down to 0.06 cd/m^2 while pedestrians and other objects typically have luminances in the range of 0.01–0.25 cd/m^2 [2] (citing several other authors).

In order to evaluate the effectiveness of lighting in the driving environment, the spectral sensitivity of the eye must be taken into consideration by weighting the light measures according to eye's spectral response, as mentioned above. For photopic and scotopic conditions, the spectral sensitivity of the eye is well-known (see Figure 4) and visual effectiveness can be evaluated by photometric instruments such as luminance meters. However, for mesopic conditions, there have been no suitable methods available, but mesopic models are currently under development [21–24].

In addition to measurement methods and instruments, methods for computer simulations of lighting conditions are being developed. For example, Delacour et al. suggest an approach for simulating surrounding lighting, display technologies, inside lighting and reflection in automobiles, using a model based on physiological aspects [25].

Table 3 Illumination and reflection parameters used for describing the performance of road equipment in night-time traffic.

Parameter	Denotations	Formula*	Application
Illuminance	*E* [lux, lx]	$E = \frac{\Phi_w}{A}$	Street lighting on minor streets, walking paths, etc.
Light intensity	*I* [candela, cd]	$I = \frac{\Phi_w}{\omega}$ $I \approx E \cdot r^2$	Traffic signals.
Luminance	*L* [cd/m^2]	$L = \frac{I}{A}$	Street lighting on major roads, traffic signals.
Stray-light luminance	L_s [cd/m^2]	$L_s \approx 9.2 \cdot \frac{E}{\Theta^2}$	Glare from road lighting.
Luminance contrast	*C* [-]	$C = \frac{L_o - L_b}{L_b + L_s}$	Visibility of objects.
Retroreflectivity	R_L [cd/m^2/lx]	$R_L = \frac{L}{E}$	Road markings, raised pavement markers, sign sheeting.
CIL-value	*CIL* [cd/lx]	$CIL = R_L \cdot A$	Small retroreflectors.
Luminance coefficient	*Qd* [cd/m^2/lx]	$Qd = \frac{L}{E_d}$	Road surfaces, road markings.
Colour	*x,y,z* [-]	**	Sign sheeting, road markings, traffic signals.

* *d*, diffuse (illumination); *o*, object (luminance of); *b*, background (luminance of); *s*, stray-light (luminance).

** Described by using the tristimulus values, defined by the International Commission on Illumination (CIE).

4 Swedish Regulations Regarding Road Equipment and Road Surface Performance in Night-time Traffic

In this chapter, the night-time requirements in the regulations of the Swedish Road Administration are presented by type of road equipment and surface.

4.1 Street Lighting

The most common concept used in street lighting is the luminance of the road surface. The Swedish regulations are based on EN-13201 [20], which divides roads into five luminance classes, dependent on e.g. type of road and speed limit. The lowest mean luminance requirement on dry road surfaces in built-up areas, 0.5 cd/m^2, is to be found on local streets, while the requirement on main roads might be as high 2.0 cd/m^2. Along with this requirement, there are also demands on wet road surface luminance, luminance uniformity and maximum glare from the armatures. It should be noted that the luminance of the road surface is dependent of the illuminance at, and the reflection properties of, the surface. This means that the required luminance can be obtained using light road surface and/or high illuminance.

On streets designed primarily for pedestrians and on cycle paths, there is no requirement on luminance, but instead on the illuminance at the surface. This measure is independent of the reflection properties of the surface.

A special regulation applies for pedestrian crossings. This regulation says that the luminance of the road surface at the zebra crossing should be at least 1.5 cd/m^2 or, if the speed limit is 30 km/h and there is no school or kindergarten in the surroundings, 1.0 cd/m^2.

In Sweden, road lighting is regulated in *Vägar och Gators Utformning*, (VGU) [26].

4.2 Road Signs

There are no physical optical requirements on road sign sheeting in Swedish regulations. However, indirectly, the performance of the road sign is regulated by which retroreflective material and which text size to use on different road signs. The handbook *Handbok Vägmärken* defines four types of sheeting and three sizes to be used, dependent on the road environment [27]. In most situations sheeting of type Super Engineering Grade or High Reflective is recommended. However, in some situations other materials can be used. As an example, prismatic sheeting may be used at pedestrian crossings.

4.3 Bollards

In Sweden, there are no requirements on the visibility of bollards, i.e. on the CIL-value of the retroreflector. However, at the time of purchase, the road keeper may regulate the performance in *Funktions- och standardbeskrivning, drift*, (FSB) [28].

4.4 Road Markings

The night-time performance of road markings in headlight illumination is described by the retroreflectivity, R_L, and on roads with street lighting by the luminance coefficient (generally called the *Qd*-value). This means that in built-up areas *Qd* is of more importance.

The Swedish regulations originate from EN-1436 and state average R_L > 150 mcd/m^2/lx and *Qd* > 160 mcd/m^2/lx regarding dry road markings [29]. On roads with average daily traffic (*ADT*) more than 4000, there is also a requirement on wet road markings, average R_L > 35 mcd/m^2/lx. Finally, not more than 20 % of the road markings may fail.

In Sweden, edge lines on motorways and semi-motorways are continuous. On larger two-lane roads the road authority can choose between using broken or continuous edge lines, while on small rural roads broken lines are always used.

The physical requirements are regulated in *Teknisk Beskrivningstext*, (TBT) [30], while the design of the road markings is found in VGU [26].

4.5 Traffic Lights

The visibility of traffic lights can be described by the light intensity. However, light intensity is difficult to measure, wherefore the Swedish requirement instead states a legibility distance: On streets and roads with speed limit up to 50 km/h, the signal must be possible to read at a distance of at least 70 metres. On all other roads, the corresponding distance is 120 metres.

The performance of traffic lights is regulated in *Vägverkets Författningssamling*, (VVFS) [31].

4.6 Road Surfaces

There are no requirements on road surface brightness in the Swedish regulations. The only demand is that, in road lighting, the surface must have a lowest luminance level. However, this may be achieved using luminaries with high light intensity instead of using light surface material.

5 The Human Eye and Night Vision

The human eye is not very well adapted to low light conditions. Both visual acuity and contrast sensitivity deteriorates as the amount of light decreases. In night-time traffic, road illumination and equipment must be designed to meet the demands set by the limitations in human night vision. This chapter describes the anatomy and physiology of the eye with focus on the eye's abilities to see and perceive things in the dark. Common visual impairments are also considered – both age-related, acquired and congenital – and how these impairments affect night vision. Unless otherwise stated, the contents in Chapter 5 are from the books *Medical Physiology* [32], *Adler's Physiology of the Eye* [33] and *Sensation and Perception* [34].

5.1 Anatomy and Physiology

The visual system in humans consists of a sensory receptor – the eye – and a signal processing unit – the brain. The eye forms an image and converts the image into a neural code, which is interpreted by the brain. In many ways, the eye resembles a camera, with its lens and adjustable aperture. Figure 3 shows a cross section of the human eye. Light enters the eye through the lens, which is covered by the transparent and protective cornea. Between the cornea and the lens is the iris, which forms the aperture of the eye – the pupil. The amount of light that is allowed to enter the eye is determined by the size of the pupil which, in turn, is automatically regulated by the intensity of the surrounding light. In dim light, the pupil grows larger. The incoming light is focused on the retina mainly by refraction at the cornea-air interface and partly by the lens. The lens is attached to the ciliary muscles, which can change the shape of the lens and accordingly its focal length, thus enabling focusing on objects at different distances. The ability of the eye to change focus is called accommodation.

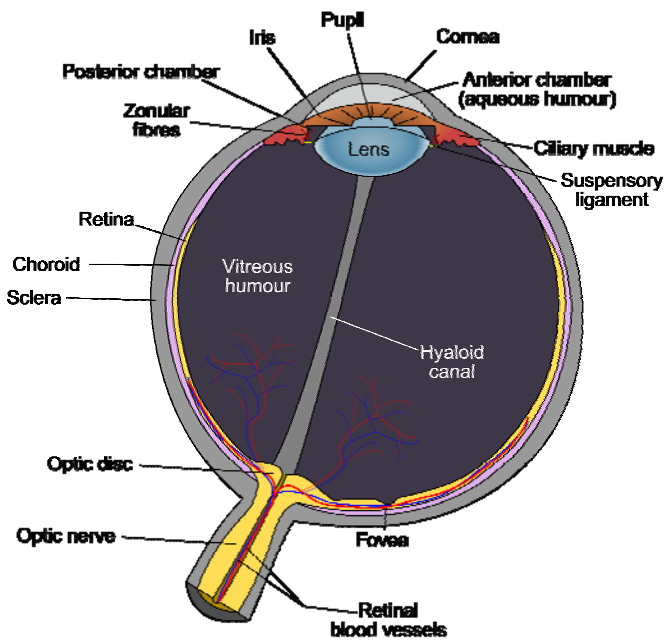

Figure 3 A cross section of the human eye. Image: www.wikipedia.org.

The retina is a thin layer of light-sensitive cells at the back of the eye, covering about two-thirds of the eye's inner surface. Two types of light sensitive cells are involved in vision: rods and cones. The rods are responsible for monochromatic vision in low light conditions – the **scotopic vision** – and they are highly sensitive to light. In fact, only a few photons are required to evoke a sensation of light. The rods are distributed across the retina with the highest density in the centre – except at the fovea and the optic disc (the blind spot) – and with a gradually decreasing density towards the edge of the retina. This means that the rods are responsible for the peripheral vision. Both the spatial and temporal resolution of the rods are relatively low, but they are very sensitive to motion, also at the edges of the field of view. The cones are responsible for the colour vision – the **photopic vision** – and they are mainly concentrated at the fovea, where the light from the centre of the gaze is collected, and more sparsely distributed towards the periphery of the retina. The cones are less sensitive to light than the rods and thus relatively bright light is required for the perception of colours. The visible spectrum, i.e., the colours or, scientifically, the wavelengths that can be detected by the human eye range from about 380 to 750 nm, Figure 4. There are three different types of cones, which have different spectral sensitivity, with peaks at 420, 530 and 560 nm, respectively, thus allowing for the detection of colours. The photopic vision, i.e., the vision mediated by the cones, is maximally sensitive at about 560 nm (green-yellow). The rods, on the other hand, can not distinguish between different colours but their light sensitivity varies with the wavelength as well, with a maximum at about 500 nm (blue-green).

The refractive indices are different for different wavelengths, meaning that their focal lengths are different. Thus, blue light will be slightly out of focus compared to green and red light. Furthermore, there are no cones of the 420 nm type in the fovea and as a consequence, intensely blue light will appear blurred.

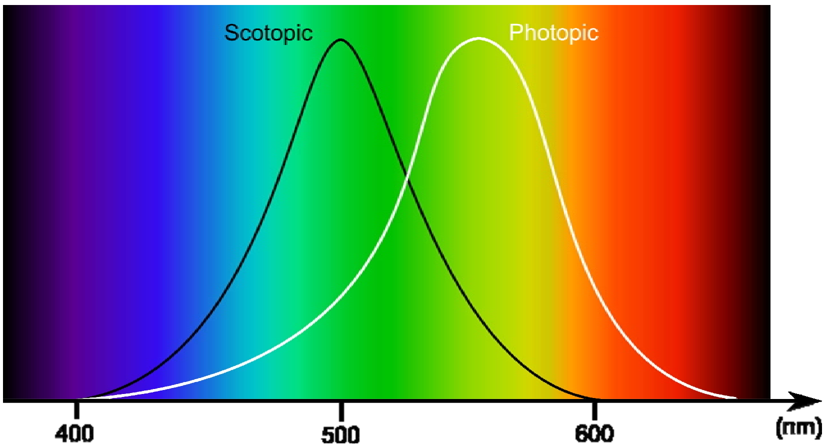

Figure 4 The visible spectrum and the luminous efficiency functions, i.e., the spectral sensitivity of scotopic (black) and photopic (white) vision, respectively. The luminance range between scotopic and photopic vision is called mesopic vision.

The high concentration of cones at the fovea results in a high visual acuity in the centre of the gaze, in bright light conditions. In dim light, the visual acuity thus decreases because of the relatively low light sensitivity of the cones. In scotopic conditions, there will actually be a blind spot in the centre of the gaze since there are no rods at the centre of the fovea. Instead, the highest acuity is found at about 17 degrees from the centre where the rods have their maximum density. However, even though the concentration of rods is high in the periphery, the spatial resolution is nevertheless relatively low, because the information from several adjacent rods is merged before being sent to the brain. As a result, the acuity of the whole field of vision is quite poor in dim light. Another factor that can impair the experienced visual acuity further is the decreased depth of field, which is a consequence of the large pupil during low light conditions.

In addition to the impairments in low light visual acuity described above, some people, mostly younger, experience a condition called night myopia. Myopia means near-sightedness and night myopia is near-sightedness that occurs only in low light conditions. The main cause of night myopia is the lack of clear objects to focus on during dark conditions, resulting in the eye accommodating on a constant distance of about 1 m or less, with some individual variations [6, 35–37]. Also aberrations from the large pupil are believed to contribute to night myopia. It has been suggested that night myopia should be corrected with suitable glasses when driving [35, 37–39], but there is no consensus about this. Some authors mean that the road and vehicle illumination prevent night myopia from occurring and that glasses would be of no benefit [40, 41].

Contrast sensitivity diminishes as the light level decreases and as a result, the peripheral vision also decreases and the ability to detect motion deteriorates. Contrast sensitivity tends to decrease with age, see also Section 5.2 [42].

Night driving involves both the scotopic and the photopic vision. The driver is in a dark environment that is occasionally lit up by road or vehicle illumination and he/she must be able to see illuminated bright objects in the centre of the gaze as well as dark objects in the periphery. The transitional range between scotopic and photopic vision is known as **mesopic vision**, where neither the cones nor the rods work optimally.

Important factors in mesopic conditions are dark adaptation and glare. Dark adaptation is mediated by several mechanisms. As mentioned above, the size of the pupil is quickly adapted to the present light conditions. The rods and the cones also need to adapt, but these processes are much slower. The adaptation of the cones takes about 5–10 minutes, while the rods need 30 minutes or more to become fully dark-adapted. Light-adaptation, on the other hand, is a much more rapid process and usually takes less than a minute.

Dark-adaptation will not be spoiled by red light, since the rods are not sensitive to red light.

Glare, i.e., difficulty in seeing in the presence of bright light, is frequently occurring in night-driving. The eye is not optically perfect, which in bright light conditions results in a large amount of stray light that is scattered within the eye and blurs the image. Bright light also causes the pupil to constrict and thus the ability to see the rest of the scene will be impaired. However, glare from for example an oncoming vehicle’s headlights, does not result in a full light-adaptation followed by a slow dark-adaptation. In fact, as long as the glare only affects some parts of the visual field, glare recovery time is more or less negligible, since only the rods and cones affected will have to adapt (i.e., different parts of the retina are adapted to different luminances at every given instant) [35]. Problems with glare are more pronounced among the elderly, because the optical deficiencies of the eye increase with age [42]. In addition to the temporary visual impairment, glare also causes discomfort and can lead to fatigue [35].

5.2 Visual Impairments

Age-related visual impairments affect a large part of the population and thus a large part of the drivers. Visual acuity, contrast sensitivity, visual field, adaptation, accommodation, pupil regulation, colour discrimination and the ability to tolerate glare decrease with age [12, 35, 43–45].

Visual acuity is expressed in different ways in different countries. In Sweden, decimal notation is used, where 1.0 corresponds to normal vision. In the US, visual acuity is usually expressed as a vulgar fraction, where 20/20 means normal vision. A visual acuity below 1.0 or 20/20 is worse than normal.

Myopia, nearsightedness, affects more than 2 billion people to various degrees [34]. People with myopia often complain of poor night vision, which partly depends on the apparent increase in myopic refractive error related to the spectral shift of night light towards the blue end of the spectrum in combination with aberrations from the large pupil [33]. In Sweden, a corrected visual acuity of 0.5 is required in order to be able to obtain a driving licence [46].

Cataract is a common condition among the elderly. A clouding gradually develops in the lens causing blurred vision and eventually vision loss, if untreated. The visual problems related to cataract may include poor night vision, seeing halos around lights and being sensitive to glare. Cataract can be treated surgically, often with good results. Approximately half of the people at the age of 65 have cataract. [47, 48]

Another age-related condition is **macular degeneration**, where the light sensitive cells in the central part of the retina decay, which causes a loss of central vision. There are different types of macular degeneration and the prospects of treatment and recovery depend on the type of degeneration. About 15–20% of people older than 75 years have this condition. [47, 48]

Glaucoma is yet another disease that mainly strikes old people and it involves loss of cells in the optic nerve. As a consequence, the visual field gradually decreases. Glaucoma also leads to poor night vision and blind spots in the visual field. The disease has a slow progress and can not be cured. [47, 48]

Diabetic retinopathy is a common complication to diabetes, where the blood vessels in the retina are damaged and causes blurred vision and floating spots in the visual field. Diabetic retinopathy can be treated with a laser method, which, in turn, may impair night vision. Almost all patients who have had diabetes for more than 30 years have diabetic retinopathy. [47]

The most common genetic visual disorder is **retinitis pigmentosa**, which is actually a group of eye conditions affecting the cells in the retina. Abnormalities and/or damages arise gradually in the cones and rods. Usually the rods are affected first and common symptoms of the disease are therefore impaired night vision, prolonged dark-adaptation and increased sensitivity to glare. As the disease progresses the visual field decreases and also blind spots can occur. Eventually, the patient might only be able to distinguish between light and dark. About 3000-4000 Swedes suffer from retinitis pigmentosa. [49]

About 8% of human population, mostly males, have some **defect in colour vision**, which is either genetic/congenital or acquired [34]. The most common type mildly affects red-green hue discrimination. In Sweden, colour vision deficiency is not an impediment to get a driving licence [46].

Further information about visual ability, visual impairments and the consequences for driving and obtaining a driving licence is given in *Trafikmedicin* (in Swedish) [46].

Summary, the human eye and night vision

Human vision deteriorates in low light conditions. Night-time driving involves a wide range of light conditions, where the deterioration in human vision varies with the light condition present. Aspects of human vision that may be affected during night-time driving are:

- Visual acuity and contrast sensitivity (decrease in low light conditions).
- Peripheral vision and the ability to detect motion (decrease in low light conditions).
- The sensitivity to different colours (shifted towards the blue spectrum in low light conditions).

Other aspects of human vision that are of importance for night-time driving are:

- Glare, which causes a temporary visual impairment.
- Dark adaptation, which is a relatively slow process.

Older people usually experience more problems than young people in low light conditions, because of age-related visual impairments. In addition, many older people also have cataract, glaucoma or some other eye disease that causes poor night vision.

6 Road Users in Night-time Traffic

Low light conditions lead to increased demands on people using the roads. The information needed in order to accomplish a driving task is mainly visual and as the light level decreases, the amount of available information decreases as well.

Visual acuity and contrast sensitivity deteriorate in dim light, see also Chapter 5. This has consequences not only for traffic safety but also for driving comfort and the possibilities for e.g., visually impaired to use the roads at night. In this chapter, the limitations in human night vision and their implications for night-time traffic are reviewed.

6.1 Drivers

This section presents a review of literature about drivers' experiences, needs and problems related to night-time driving, divided into the subsections visual performance and driving behaviour; detecting pedestrians and other objects; and interaction with road equipment and environment.

6.1.1 Visual Performance and Driving Behaviour

Vision deteriorates in several ways under low light conditions. Besides impaired visual acuity and contrast sensitivity, also reaction time, spatial resolution and accommodation response deteriorate [2, 34, 50]. To what extent decreased visual performance has an influence on night-time driving behaviour and traffic safety is not extensively covered in literature. Owens means that drivers are simply not aware of their poor night vision and presents a hypothesis that there are two modes of vision: focal and guidance [6]. Focal, or recognition, vision is responsible for visual tasks involving acuity, contrast and accommodation, while guidance vision is related to the sensation of motion. Owens means that focal vision deteriorates at night, while guidance vision remains highly efficient. Steering, which is of constant importance while driving, is suggested to depend heavily on guidance vision. Focal vision is partially enhanced by lighting and reflectorization. As a consequence, drivers do not realize that their ability to see low-contrast objects is markedly reduced at night, since they still can steer the vehicle and at least roughly perceive the scene. Owens has conducted some experiments that indicate that the hypothesis is correct. In a simulator study, it was found that steering accuracy deteriorated by visual field reduction but not by blur or low luminance [51].

The visual conditions while driving at night vary considerably. Vehicle headlamps, street lighting, traffic lights, commercial lighting, light from buildings, reflections and moon light all contribute to the total amount of light present in the driving environment, Figure 5. A user-centred approach – the twilight envelope – to describe illumination from vehicle headlamps at night is suggested by Andre and Owens [52]. During civil twilight, visual acuity and contrast sensitivity, which is essential for object recognition, degrade rapidly. At the dark limit of civil twilight (3.3 lux), acuity and contrast sensitivity are less than 20% of daylight levels. Andre and Owens use this limit to define a three-dimensional space in front of the vehicle to describe illumination from vehicle headlamps. The twilight envelope of 13 vehicles of 1999 models was investigated. For low-beams, it was found that along the right edge line, the shortest and the longest beams differed by about 70 m at ground level and more than 100 m at the driver's eye height. Vehicle headlamps thus play an important role in visual performance.

Figure 5 Vehicle headlamps, street lighting, traffic lights, commercial lighting, light from buildings, reflections and moon light all contribute to the total amount of light. The light level in the driving environment can thus vary a lot at night.

In addition to the impairments in visual abilities, research indicates that eye scanning behaviour may change in a non-beneficial way at night. Garay-Vega et al. have investigated eye scanning behaviour in different driving environments (including urban areas) in a simulator study [53]. Drivers, both experienced and novice, looked significantly less often in regions that had information of a possible risk (for example in a scenario where a truck blocks the view of a crosswalk) when driving at night than in daylight conditions.

The ability to estimate distance relies on a combination of several visual cues [34]. Most of the cues provide information on relative distance. In low light conditions, such as on roads without street lighting, not many objects will be visible and thus, the ability to estimate distances will be impaired. Castro et al. have found that at night, drivers' estimation of the distance to an oncoming car is related to the width between the headlights, but not to the headlight luminance [54], [55]. Widely separated lights resulted in more accurate estimations (with a tendency to overestimation) than lights that were closer mounted, which tended to lead to underestimated distances.

The reaction time for detection of targets increases with decreasing luminance, which, in turn, leads to longer stopping distances. Plainis and Murray have tested reaction times under different contrasts and luminances and found that the reaction time increased from about 200 ms in optimal conditions to about 600 ms in conditions comparable to night-time driving [2]. Alferdinck has tested detection of targets in a driving simulator under different luminance levels, colours (of target and background: white, yellow, red, blue) and eccentricities of targets [56]. All three variables had a significant effect on reaction time and number of missed targets, where reaction time increased with decreasing luminance and increasing eccentricity. For low luminance levels (0.01-0.1 cd/m^2) the longest reaction times and highest percentage of missed targets were found in a red driving environment. In Alferdinck's experiment, target and background had the same colour, which is not realistic for the driving situation. When it comes to discrimination of colours, a dark environment can actually be advantageous, as demonstrated in an experiment by Sivak et al. [57]. Identification of red and yellow lights at different viewing angles, from 0 to 30 degrees, was investigated. For light intensities corresponding to turn signal lamps, it was found that, at night-time, colour was correctly identified irrespective of viewing angle, while during daylight, the proportion of correctly identified colours decreased to 80% at 10 degrees for both colours. For the red light, the performance deteriorated further at 20 and 30 degrees (50% and 43%, respectively). A similar pattern was found at night when low intensity lamps were used (0.5–1% of the intensity of the turn signal lamps). Thus, there is a perceptual shift of red towards yellow at the visual periphery, which is more pronounced during daylight conditions than in darkness.

Glare is frequently experienced while driving at night. There are two types of glare: *Disability* glare causes reduced contrast sensitivity and arises when bright light is scattered within the eye. *Discomfort* glare is the subjective sensation of glare, which can be present also in the absence of any deterioration in visual performance. Theeuwes et al. have investigated the relationship between driving behaviour and glare within the range that causes discomfort but not disability [58]. The study showed that drivers slow down, particularly on dark and winding roads, when exposed to discomfort glare. The detection distance of simulated pedestrians decreased when the drivers were exposed to glare (with illuminances of 0.55–1.1 lx, corresponding to vehicle headlamps). It was concluded that although discomfort glare does not directly affect vision, it may, for example, lead to drivers looking away from the glare source and thus lead to worse detection performance.

Stray light effects can also be caused or enhanced by rain, dirty windshields and poor eyeglass prescriptions. In a study by Rosenhahn, visual performance at night-time driving during rain was measured [59]. A wet road appears darker because light from the own vehicle is reflected forward. At the same time, light from oncoming vehicles' headlights may cause glare illumination on the road surface. Rosenhahn's result showed that contrast sensitivity decreases if glare illumination is present on the road. The readaptation time after being exposed to glare was found to increase with increased exposure (illuminance). Readaptation time after being exposed to glare from a wet road was typically 1–4 s.

Ranney and colleagues have studied the effects on driving performance when truck drivers are exposed to glare from the rear-view mirrors, both for ordinary mirrors and for glare-reducing mirrors [60]. It was found that glare was associated with worse vehicle control in terms of increased lane position variability, reduced speed in curves and increased steering variability. Glare also lead to shorter detection distances of pedestrians. The use of glare reducing mirrors only lead to minor improvements in pedestrian detection, while no improvements were seen in vehicle control. However, drivers preferred the glare reducing mirrors.

It is reasonable to assume that people would drive slower in night-time conditions, when visibility is limited. On the other hand, the low traffic densities present at night might tempt people to drive faster. Research within this area supports both hypotheses. Owens describes an experiment on a closed road circuit, where speed was found to decrease with less than 10% while driving at night with high-beam headlights, compared to daylight conditions [6]. In another study by the same author, the driving behaviour of drivers of different ages under four different headlight conditions was investigated [45]. Test subjects drove on a closed road circuit without a speedometer and it was found that the speed was significantly lower at night than in daylight, but the reduction was relatively small and thus, it did not compensate for the decrease in visual performance at night. The results also showed that line crossings increased at night. In a literature review by Sagberg, some studies indicated that the average speed is reduced in some environments at night [61], while Olson and Farber claim that people usually not drive slower at night [12]. Olson and Farber point out that drivers usually “overdrive” their headlamps at night, i.e., the speed is too high compared to the visibility distance. However, in order not to overdrive, speed limits would have to be lowered to about 30 km/h, which is obviously not realistic.

When drivers overdrive their headlights, they violate the assured clear distance ahead (ACDA) rule. The ACDA rule, which implies that the driver is responsible to maintain a speed low enough to avoid collision with objects that might appear in the vehicle’s path, is discussed in an article by Leibowitz et al. [62]. According to Leibowitz, drivers are not aware that their vision is degraded when driving at night and thus, they do not necessarily disregard public safety intentionally when they violate the ACDA rule. Another reason why drivers usually overdrive the headlamps is that they adjust their speed to the posted speed limit. As mentioned by Olson and Farber above, also Leibowitz brings up the complicating fact that drivers complying with the ACDA rule will impede the traffic flow which, in turn, might increase the risk of having an accident. In order to overcome the discrepancies regarding the ACDA rule, Leibowitz has some recommendations:

- Different speed limits in daylight and at night.
- Public information about the hazards related to night time driving.
- Encourage the use of high-beams where possible.
- Restriction of pedestrians’ exposure to vehicles in low light conditions.
- Reflectorization of potential hazards.

6.1.2 Detecting Pedestrians and Other Objects

A frequently reported problem in literature on night-time traffic is drivers’ limited ability to detect low contrast objects, such as pedestrians, on or in the proximity of the roadway. The ability to see an object and understand what it is is often described by the terms visibility, conspicuity and identifiability. Visibility is used to describe whether an object is possible to see or not or, according to a definition by Janoff: Visibility is the quality or state of being perceivable and the visibility of an object is directly affected by its contrast and by a number of other factors [63]. Conspicuity is described by Olson and Farber as the characteristics of an object that determine the likelihood that it will come to the attention of an observer who does not expect it to be there [12]. When an observer can see and understand what an object is, the object is identifiable. An object that is visible may not be conspicuous, and an object that is conspicuous may not be identifiable. However, there is no clear dividing line between these terms.

Olson and Farber discusses the theory behind visibility and night-time driving [12]: Contrast describes how readily an object will appear distinct from its background. In a well-illuminated environment differences in luminance, colour, pattern, shading and texture can provide contrast. In the low light conditions present when driving at night, objects are mainly detectable by luminance contrast. When the target is brighter than the background, it is seen in positive contrast, which is usually the case when a pedestrian is illuminated by a vehicle’s headlights. Luminance contrast arises when:

- The target and the background receive different levels of illumination.
- The background is far from the target.
- When the background contains lighting sources.
- When the target and the background differ in reflectivity.

In situations where the vehicle's headlights are the sole light source, the background – usually the road – and the target will be relatively close since the headlight beam is directed downwards. This will result in a low contrast and consequently, poor visibility of targets. Moreover, targets and background usually have about the same reflectivity in the driving environment, which will further impair the ability to detect targets. Higher headlight beams provide greater contrast, but will also increase the glare effects experienced by oncoming drivers. Olson and Farber mean that the best way of developing good contrast under night driving conditions is to create a difference in reflectivity of the target and the background. Other attributes that are beneficial for the conspicuity of objects are brightness, flashers, cyclic motion, colour and colour contrast, uniqueness, size and location.

The seeing distance to a target is strongly related to the reflectivity of the target and its background, but it also depends on the size of the target, whether the vehicle is on high or low beam, the amount of headlamp misaim, the presence or absence of glare, the location of the glare, the location of the target, roadway geometry, ambient luminance and the driver's age and contrast sensitivity [12]. Since low-beam headlights are directed away from oncoming traffic, there will be a great difference in seeing distance to targets to the right and to the left. An example is provided in a study by Olsen and Sivak, where the detection distance to targets to the right was found to be 1.5–2 times longer than that to targets to the left, due to headlight beam asymmetry [64], cited by [12].

The limited visibility of targets in night-time driving conditions is reinforced by the fact that drivers seem unaware that their vision is impaired when driving at night, see also Section 6.1.1. Leibowitz explains this unawareness by the fact that the ability to detect obstacles is infrequently needed and that there are few opportunities to learn about it, in contrast to for example the steering ability, which is continuously used and – in the presence of road illumination, other vehicles, reflective signs and road marker posts – rarely difficult [62].

Drivers usually overestimate the visibility provided by headlights [12]. Cohen means that drivers may be deceived by far-away objects with high luminance to believe that the distance to those objects equals the seeing distance, and thus not realize that the detection distance to low-luminance objects will be much shorter [65], cited by [61].

Under most night time conditions, the visibility distance for pedestrians is shorter than the total stopping distance. Even at a speed of 32 km/h, the driver may fail to detect a dark-dressed pedestrian in time to stop [62]. In a study by Olson and Sivak, the results showed that when driving in 70 km/h, about 90% of the subjects were not able to stop in time for dark-dressed pedestrians located on the right side of the road [64], cited by [12]. It has been reported that among drivers who have struck a pedestrian at night, the majority claimed they had difficulty seeing the person and every four drivers were aware of striking the pedestrian only after they heard the impact [66], cited by [67]. In a study by Sullivan and Flannagan, it was found that almost 70% of pedestrian crashes at night-time occurred when the vehicle was going straight ahead (compared to about 50%

in daylight), which may be related to the limited forward preview in darkness, in combination with the higher speeds on straight roads than in intersections [68].

The visibility of pedestrians under different conditions has been investigated in several studies. The probability that a pedestrian will be detected at night is influenced by the reflectivity of the pedestrian's clothing, their position on the road, weather conditions, road characteristics, road illumination, vehicle headlamps, other ambient lighting, the driving environment and the performance of the driver [69]. Furthermore, retroreflective markings have a considerable effect on visibility, as shown by the studies reviewed below.

Balk and colleagues have investigated pedestrian conspicuity using four different configurations of retroreflective markings, with and without natural pedestrian motion (i.e., walking) [70]. The four configurations of retroreflective markings were:

- Rectangular area on the chest.
- Stripes around the ankles.
- Stripes around the ankles and the wrists.
- Stripes around the ankles, knees, waist, shoulders, elbows and wrists (biomotion).

The total area of the markings was the same in all configurations. There was also one test pedestrian without any retroreflective markings at all (black). The detection distance was significantly greater when the pedestrian was walking than when the pedestrian was standing still (on average 70.2 m vs. 38.0 m). Overall, the biomotion configuration resulted in significantly longer detection distances than the other configurations. When the pedestrian was walking, the biomotion, only ankles and ankles + wrists configurations resulted in significantly longer detection distances than the chest marking and the black condition. On average, the biomotion configuration resulted in the longest detection distance (mean = 113.5 m, which can be compared to the shortest distance, 25.0 m for the chest configuration). When the pedestrian was standing still the biomotion configuration resulted in significantly longer detection distances than the chest, ankles and black configurations. However, the use of biomotion markings may be impractical. See also Section 6.2.

Balk's findings differ somewhat from those obtained in a study by Luoma and Penttinen [71]. In the latter study, significant differences in detection distance were found, with the longest detection distance for pedestrians with retroreflectors on the limbs (224 m, 2.6 cm wide stripes on wrists and ankles), followed by retroreflectors on major joints (210 m, eleven 1 cm wide stripes on the hips, knees, ankles, wrists, elbows and shoulders), torso (147 m, 1.3 cm wide stripes on the shoulders and one 2.6 cm wide stripe at midtorso) and no retroreflectors at all (21 m). Pedestrians that were crossing the road were detected on a longer distance than those who were approaching the vehicle (174 m vs. 127 m). The authors have conducted a similar study in the US and the results were about the same, even though the US drivers – in contrast to the Finnish drivers – had limited experience of pedestrian retroreflectors.

Drivers' ability to detect pedestrians with different clothing under different light conditions (low-beam versus high-beam headlights, and absence/presence of glare) has been studied by Wood et al. [72]. The pedestrians were either dressed in white, black, black with a retroreflective panel on the torso or black with retroreflective stripes on the wrists, elbows, shoulders, waist, knees and ankles (biomotion configuration). The ability of drivers to recognize pedestrians varied from 5% (black clothing, low-beam and glare) to 100% (biomotion, low- or high-beam and no glare). Interestingly, white dressed pedestrians were better recognized than those wearing black with a retroreflective panel on the torso, which might be explained by the downward direction of the headlight beam.

Two types of biomotion configuration have been investigated in a study on conspicuity of emergency response personnel garments conducted by Cassidy et al. [73]. The first garment had a conventional trim pattern, with stripes on arms, legs and torso and the second garment had retroreflective material distributed across the entire surface (area-reflective). The two garments were made such that they reflected the same total amount of light. Three different levels of the reflected light were investigated and it was found that the conventional patterned garment was both detected and recognized as a human on a significantly longer distance than the area-reflective garment.

Results from visibility tests – when, for example, driving at a closed circuit, pressing a button when a pedestrian becomes visible – cannot be directly applied to real driving [12]. Subjects in such tests know what to look for and they expect to see pedestrians and consequently, the results will be more favourable than they would in the real setting. In addition, real driving situations are usually more complex than those on closed circuit roads. Moberly and Langham have conducted a study on pedestrian conspicuity in visually cluttered environments at night [74]. Two different retroreflective markings were used: A vest with two retroreflective stripes around the torso and a biomotion configuration with stripes on the ankles, knees, wrists and elbows. The pedestrians were either walking or standing still. The scenario was filmed and showed to the subjects on a screen. The moving pedestrians were detected at significantly greater distances than the stationary pedestrian, for both marking configurations. However, there was no significant difference in detection distance between the vest and the biomotion configuration, for the moving pedestrian, which disagrees with several other studies. The authors explain the findings by referring to a study by Owens et al. where no benefit was found for biomotion in environments illuminated by street lights [75]. The authors also point out that a video-based experiment differs from real world.

Sayer and Mefford have examined the conspicuity of pedestrians with safety garments with retroreflective markings on the torso and in some conditions also on the arms, in a naturalistic driving environment [76]. Only older drivers participated in the study. Pedestrians were detected significantly farther away in a low complexity environment (no/little street lights, low traffic density) than in a medium complexity environment (street lights, higher traffic density, traffic control devices and lights from business areas). Pedestrians perpendicular to the traffic were detected at significantly longer distances if their arms were in motion than if they were stationary. If the pedestrian faced the traffic, however, there was no difference in detection distance between stationary pedestrians and pedestrians with moving arms. Furthermore, arm motion significantly increased detection distances when the pedestrian was in a low complexity environment, but it had no effect on detection distance in medium complexity environments. The authors did not find any difference in detection distance for garment with and without retroreflective markings on the arms; however, arm motion was associated with improved detection distances.

Colours that differ from the background are beneficial for conspicuity. Coloured retroreflective markings may thus be a way to increase visibility of pedestrians. Sayer and colleagues have assessed the effect of retroreflective markings of four photometrically matched colours: red, yellow, green and white [77]. A pedestrian with a 3.5 cm x 2.3 cm retroreflective marking on one leg was walking along a road, either towards a stationary car or away from it. The subjects, who were sitting in the car, were asked to respond when the pedestrian was either visible or no longer visible. The road was dark and there was no other traffic. Red, yellow and green were detected on a significantly farther distance than white. On average, red was detected at the farthest distance, followed by green and yellow (no significant differences). The difference in visibility between white and the three other colours were 7–10%. Sayer concludes that night-time detection of coloured retroreflective markings cannot be predicted from photometric measurements alone.

A similar study has been conducted by Muttart, who has investigated the conspicuity of retroreflective silver-white, yellowish-green and red-orange [78]. Silver-white was chosen because it is the most luminous colour; yellowish-green is the colour which the human eye is most sensitive to and red-orange yields the shortest reaction times. Subjects were told to look for pedestrians with one of the three coloured retroreflective markings. The pedestrians were standing still and were wearing a yellow t-shirt with two vertical and one horizontal 2 inch wide retroreflective stripes on the torso. Red-orange was detected significantly earlier than yellowish-green and silver-white (time to impact was on average 6.2, 4.7 and 3.5 s, respectively). The difference was the greatest during the early evening hours, when there was a larger influence from visual noise and glare (the traffic density at the test route decreased from moderate to negligible during the night). Muttart means that a colour that contrasts significantly to white would be more easily recognized since there are many white signs, streetlights, road-markings and headlights present in the night-time driving environment.

In contrast to the results obtained by Sayer et al. and Muttart, in a study by Sayer and Mefford it was found that red retroreflective markings on safety garments were less conspicuous than blaze orange and silver-white [79]. The experiment was performed in a simulated work zone that provided some visual cluttering. The detection distance for any of the safety garments was on average about three times as long as for a dark dressed pedestrian. When the intensity of the reflected light was decreased by applying a density film on the retroreflective trim material (resulting in a coefficient of retroreflection of about 16% of the original value), the conspicuity did not decrease significantly. The results also supported the hypothesis that biomotion configuration of the retroreflective trims increases conspicuity.

Interesting progress in technology for enhanced visibility under night-time conditions – although beyond the scope of this literature review, but worth mentioning – is night vision systems and adaptive headlights.

Night vision systems are based on infrared cameras installed in the vehicle for improved detectability of pedestrians, animals and other objects [80]. An image of the scene in front of the vehicle is shown on a display above or in the dashboard. Some night vision systems also automatically detect and warn drivers of obstacles in the roadway [81].

Adaptive headlighting is automotive lighting that is adapted to certain driving situation such as curves, corners and motorways, in order to improve visibility [82, 83]. Curve lighting directs light to follow horizontal curves, corner lighting illuminates the side of the roadway during turning manoeuvres and motorway lighting provide more lighting further down the road.

6.1.3 Interaction with Road Equipment and Environment

This section concerns driver interaction with road equipment such as street lighting, road markings, and traffic lights and signs in night-time conditions. Also some newly developed technology for improved visibility in night-time is described.

Street Lighting

In general, street lighting has beneficial effects on traffic safety [63]. In *Vägar och Gators Utformning*, the number of accidents is estimated to decrease by 15–30% at roadways and by 20–40% at intersections when street lighting is installed [26]. An American study of nine intersections conducted by Green et al. showed that the installation of street lighting decreased the number of accidents by 45% [5]. Also in Japan, where more than 20% of all fatalities occur in intersections at night, street lighting has been found to be beneficial for safety [3, 16]. Oya et al. have analysed the number of accidents in 18 intersections and it was found that the night-time accident rate was reduced by 40% after installation of street lighting [3]. However, the accident rate was related to the illuminance level. An average road surface illuminance of 30 lux or more was found to significantly reduce the number of accidents, while an illuminance of 20 lux had no effect on the number of accidents.

In a literature review by Sagberg, it is concluded that when street lighting is provided, the safety margins in terms of speed, lateral position and overtaking are usually reduced, but that there is still a favourable effect on accident rate [61].

Other light sources than street lighting may have a disadvantageous influence on the driving environment. Murray et al. point out that increasing light levels do not necessarily provide a better and safer driving environment, since for example glare and light pollution may reduce the visibility of targets [50].

Visual performance under street lighting conditions is influenced by several factors such as road surface luminance, lamp colour, glare and driver age. Human colour vision is best under white light; however, most street lighting does not provide white light. There are four types of lamps that are regularly used for street lighting: Mercury vapour (MV), low pressure sodium (LPS), high pressure sodium (HPS) and metal halide (MH) [5, 63]. HPS, which has a pinkish-orange light, is the most widely used lamp type in street lighting systems, because of its efficacy (lumens per watt), long life and relatively good colour rendering, Figure 6. LPS lamps have a high efficacy but they have a monochromatic yellow light and, accordingly, their colour rendering is poor. MV and MH lamps have a bluish-white light and objects seen under these sources thus appear normally coloured. White light appears more uniform than sodium light to the human eye [24]. However, the efficacy of MV and MH lamps are lower than that of sodium lamps.

The high efficacy of sodium lamps is due to the eye’s high sensitivity to yellow light. White light sources, such as MH lights, consist of all wavelengths and thus, they have lower lumens per watt. Despite their higher efficacy, sodium lights do not necessarily provide better visibility. The spectral sensitivity at mesopic conditions is a combination of the two luminous efficiency functions shown in Figure 4 and varies with the light level. Luminance meters only have correction filters for pure photopic or scotopic conditions, and thus yield incorrect results in the mesopic range. In a review on recent research about white versus sodium lights, Lewin reports that two different research groups using different methods have come to the same result regarding a spectral correction factor for determining the effectiveness of a particular light source at a given luminance, in the mesopic range [24]. Lewin also refers to other studies that have shown other results regarding spectral correction factors.

Figure 6 The pinkish-orange high pressure sodium lamps (HPS) is the most widely used lamp type in street lighting.

The European Commission project MOVE, which was carried out 2002–2004, aimed at establishing mesopic luminous efficiency functions and to develop a new standard on performance-based mesopic photometry [84], see also Chapter 3. Thus, it is likely that in the future, there will be methods available that will result in better adaptation and evaluation of light sources for night-time traffic.

Another, less complicated way of describing light, taking both photopic and scotopic conditions into account, is the S/P ratio, which is the ratio of scotopic lumens to photopic lumens.

It could be expected that no mesopic spectral effects would be found in the fovea, since it only consists of cones. Research indicates that this is not the case. Lewin refers to research that has shown that scenes with low spatial frequencies, i.e., blurred and not well-defined objects, are mainly seen by the rods [24]. At night-time most objects consist of low spatial frequencies, which means that the rods are highly involved even though observers direct their eyes toward the object. Consequently, the spectral efficiency of the eye is not pure photopic in the centre of the visual field in mesopic conditions.

Lewin means that historically, research has focused too much on luminance contrast, i.e. monochromatic light, but not on colour contrast, which is more convenient for real world situations. Thus, if colour is present in a scene, it can be assumed that white light will result in better visibility through colour contrast than sodium light. Under sodium lighting yellow and red show up well while blue and green appears muddy [24].

The influence of spectral power distribution, i.e., colour, on visual performance at mesopic levels similar to those present while driving at night is discussed in a review by

Bullough and Rea [19]. Based on results from several studies – both laboratory, simulator and field studies – it was concluded that for low luminance levels (< 1 cd/m^2) the reaction time for detecting targets in the periphery is shorter in MH light than in HPS light, while there is no difference for targets in the centre of the visual field. Lamps that are effective for peripheral vision under mesopic conditions are e.g. MH, xenon and sulphur lamps.

In the UK, as in Sweden, street lighting is based on the EN-13201 standard and divided into six classes – the S-series – where each class has a minimum average illuminance. What class to use in what environment is given by a document that takes e.g. traffic flow and crime rate into account. When using white light instead of the most common yellow sodium lights a reduction in illuminance of one S-class is permitted. Fotios and Cheal have compared HPS lamps with MH lamps of one S-class lower [85]. It was found that observers ranked HPS and white light as equally bright, when the white light had an illuminance of one S-class below that of the HPS. However, Fotios and Cheal refer to another study ([86]) where the colour of the light (HPS and MH) did not affect the appeared brightness, when the illuminance was kept constant. In the latter study the subjects were allowed to adapt to the light while in Fotios and Cheal's study, the subjects gave their ratings immediately after the exposure. Fotios and Cheal thus limit their result to be valid only for immediate exposure.

In an extensive report, Lewin et al. have reviewed literature on three different light sources – HPS, LPS and MH – with respect to visibility, lamp performance and accidents [87]. Regarding spectral distribution, it is concluded that in situations where vision is achieved mainly by the fovea, the type of light source does not affect visual performance, while where peripheral vision is involved, MH lamps are beneficial (see also Bullough and Rea above [19]). Furthermore, the authors have not found any studies that indicate that visibility is lower with MH lights than with sodium lights, for equal lighting level. However, Lewin and colleagues mean that there is a lack of knowledge about the relationship between foveal and peripheral vision and accident causes and prevention. They also think that research on lighting level versus visibility and safety is inconclusive, and that further studies are needed within both these areas.

Lewin et al. have also analysed the cost for the three light sources and concludes that the overall operating and owning costs over a 30 year period were highest for LPS, and slightly higher for MH than LPS [87]. The authors point out that MH lamps have shorter life than sodium lamps, but also that MH technology is rapidly evolving regarding lumen output, maintenance and life.

In a study by Morante, the use of light sources that are tuned to mesopic vision was investigated [88]. HPS lamps (with an S/P ratio of 0.63) were compared to induction lamps and MH lamps with high S/P ratios (2.88 and 1.6, respectively) and tuned to optimize human vision under low light levels. The optimized lamps used 30–50% less energy, but were still perceived by test subjects as providing higher levels of visibility, safety, security, brightness and colour rendering. From an economical point of view, the induction lamp, but not the MH lamp, was found to be a cost effective alternative to HPS lamps.

A large number of studies considering street lighting and its consequences for visibility, safety, accident rate and driver behaviour are summarized in a comprehensive review from 2006 by Nygårdhs (in Swedish) [89].

Crosswalks

Several studies on visibility at crosswalks have been reported in the recent years. Edwards and Gibbons have studied the visibility of pedestrians with different clothing at crosswalks under different lighting conditions [90]. Two lamp types, HPS and MH, with the vertical illuminance levels 6, 10, 20 and 30 lux were used. The detection distance was the greatest at 30 lux for the HPS and at 20 lux for the MH, i.e., the detection distance did not necessarily increase with increasing luminance. With all conditions taken into consideration, an illuminance level of 20 lux was found to be the best compromise, which was also in agreement with American recommendations for crosswalks in commercial areas.

Hasson et al. describe an initial field test of a Swiss method for improved visibility of pedestrians at crosswalks [91]. The Swiss method recommends lighting poles to be placed on the approach sides of the crosswalk, producing 40 lux vertically. The pedestrian will thus be seen in positive contrast. The field test included two crosswalks and significant improvements when using the Swiss method compared to ordinary lighting were seen at one of the two crosswalks.

Another approach for increased conspicuity at pedestrian crossings where vehicles are turning and thus are coming from the left or the right is suggested by Sakai and Shimamura [92]. The authors describe a system where extra illumination is provided at pedestrian crossings and where the illumination is switched on in the presence of pedestrians and vehicles and coupled to the colour of the traffic lights. No results are presented.

The detection of pedestrians at crosswalks depends not only on the light level but also on the design of the crosswalk, as demonstrated in experiments by Lundkvist et al. [93, 94]. Lane narrowing at the crosswalk had a beneficial effect on the recognition of pedestrians, while intense illumination in the absence of lane narrowing deteriorated the detection of pedestrians that cross the street behind the crosswalk. When intense illumination was combined with lane narrowing, the visibility of pedestrians was improved, both for pedestrians at and behind the crosswalk.

Lewin and O’Farrell presents a system of lights embedded in the roadway in front of crosswalks, in order to increase the visibility of the crosswalk and thus improve pedestrian safety [95]. Pulsed light is suggested since it is more conspicuous and is less likely to be confused with other lights sources. The system has been evaluated at several test crossings and a positive response was found. It was found that the system was most effective in night-time and under foggy and rainy conditions. The system was less effective on roads with high traffic densities or high speeds.

A less costly alternative to Lewin and O’Farrell’s system is suggested by Lindenmann et al. [96]. Small retroreflectors are attached on the roadway in front of the stripes of the pedestrian crossing in order to increase the conspicuity of the crossing. A study of the effects of the retroreflectors on isolated pedestrian crossings not situated in intersections or roundabouts has been conducted. Speed tended to decrease and the readiness of drivers to stop was greater with the retroreflectors than without. Lindenmann claims that the retroreflectors are suitable for roads with and without lighting, but not for brightly lit urban roads.

Traffic Signs

Traffic signs may be less visible at night due to the low light levels. On the other hand, many roadways appear less visually cluttered at night-time conditions, which may improve the conspicuity of traffic signs. Studies on this topic show ambiguous results.

Owens reports in a review that recognition of signs and speed bumps is significantly better in daylight than at night conditions (closed road circuit) [6].

Ho and colleagues have investigated visual search behaviour for traffic signs in images showing different traffic environments [97]. Search efficiency decreased with age and with increased clutter. There was no significant difference between night and daylight conditions, but search efficiency tended to decrease for the night images. The authors however point out that the results might not apply to real night-time conditions.

Driver's eye scanning behaviour for symbolic warning signs has been studied by Zwahlen and Schnell [98]. No major difference in scanning behaviour was found between daylight and night-time conditions, but look durations were slightly longer during daylight conditions than at night. Drivers usually looked twice at each sign. The road look duration, i.e., the time spent looking at the road between the two glances at the sign, was longer in daylight conditions. Subsequently, the minimum distance at which a symbolic sign must be legible is somewhat shorter at night. Based on the results, the authors developed a model that determines the minimum distance at which a symbolic warning sign must be legible.

Finley et al. have found that the legibility distance of signs at night-time is longer when driving a commercial vehicle than a private car, which might be explained by the higher headlamp illuminance of the commercial vehicle [99].

The influence of colour on the conspicuity of traffic signs has been investigated by Neale et al. [100]. Four different unique colour combinations (i.e., other colours than those present on ordinary traffic signs) were used on signs for incident-management trail-blazing: black on fluorescent coral, fluorescent yellow on fluorescent purple, black on fluorescent yellow-green and nonfluorescent yellow on nonfluorescent purple. Driving performance and subjective ratings were studied both during daytime and night-time conditions. No significant difference in driving performance was found between the four signs, but subjective ratings indicated that black on fluorescent yellow-green was the most preferred colour combination. The second best colour combination was black on fluorescent coral but, at night-time, the results indicated that fluorescent yellow on fluorescent purple was preferred over fluorescent coral.

Road Markings

In a comprehensive report from 1998, Rumar and Marsh claim that drivers consider road guidance to be their main difficulty in night-time driving and that a majority of drivers are not satisfied with the lane markings [101]. The authors are of the opinion that drivers need a preview time of at least 5 s, which corresponds to 70 m at a speed of 50 km/h. The visibility distance of lane markings is about 25–90 m depending on the conditions (new/old markings, glare/no glare, wet/dry road), i.e., the visibility distance of the lane markings is usually longer than the visibility distance of the road, which is about 30 m with low-beam headlights. Rumar and Marsh mean that drivers need both short-range (< 3 s) and long-range (> 5 s) guidance, and that road markings only fulfil the need for short-range guidance. Side-post delineators can be used in order to improve long-range guidance. However, there is a risk that improved long-range guidance leads to increased speed and accident rate, but the authors believe that improving guidance is more beneficial than not doing it. They also emphasize the need for more research.

In agreement with Rumar and Marsh, Sagberg concludes in a review that more research is needed on visibility of road markings [61]. He also points out that increased visibility of road markings may result in higher speeds and may thus have an unfavourable effect on traffic safety.

COST 331 was a European project with the purpose to establish a scientific method, based on drivers' visual needs, for optimum road marking design in all weather and light conditions. Nygårdhs has written a summary of the COST 331 project, which involves several studies [102]. A simulator study showed that the visibility distance of road markings should be at least 45 m at 90 km/h (preview time = 1.8 s), when only the steering task is considered. Distance/time for looking in mirrors, unexpected events, comfort, etc, should be added. It was also found that drivers compensate for poor visibility by choosing a lower speed. Field studies indicated that improved visibility of road markings partially leads to higher speeds, but mainly increases the preview time, which has a beneficial effect on safety. A preview time of 2.2 s was found to be too short for comfortable driving. Nygårdhs comments that out of the three road marking types – 10 or 30 cm continuous or 15 cm intermittent – that are used in Sweden (specified by VGU), only the continuous 30 cm marking will fulfil the requirements of a preview time of 2.2 s, in dry conditions. Based on the results from the subprojects, COST 331 resulted in a model for prediction of visibility of road markings, where not only road geometry and lighting properties of markings and road are taken into account, but also driver's age, vehicle type, speed and glare.

Schnell and Zwahlen suggest that the preview time of road markings should be at least 3.65 s [103]. In a small study (n = 6), they collected driver eye scanning data for road markings with different visibilities, in order to investigate whether drivers make use of the longer visibility distance provided by brighter markings. Large variability was found between subjects, but in general, the subjects appeared to adjust their scanning behaviour to the visibility of the markings.

Schnell and colleagues have investigated eye scanning behaviour and visibility of three different road marking types and compared detection distances to visibility determined from objective measurement methods under dry, wet and rainy conditions. The dry weather condition resulted in longer detection distances than the wet and the rainy conditions, and generally, the wet condition resulted in longer detection distances than the rainy condition. Eye scanning recordings indicated that the visual search comfort was higher for highly visible markings (more concentrated, less scattered search). A positive correlation was found between measured retroreflectivity and detection distance; however, the results also show that an increase in retroreflectivity does not always lead to increased detection distance. The study also emphasizes the importance of using a retroreflectivity measurement method that is adapted to the present weather condition (i.e., ASTM E-1710, ASTM E-2177 and ASTM E-2176 for dry, wet and rainy conditions, respectively).

Schnell's results regarding detection distances in relation to weather conditions and measured retroreflectivity are supported by a study by Gibbons et al., where night-time conspicuity of six different road markings (including one type of road stud) during dry and wet conditions was investigated [104]. Retroreflective road studs performed the best in both dry and wet conditions, and for this marking type, there was no significant decrease in visibility distance in the wet condition compared to the dry condition. All other marking types performed worse in the wet condition than in the dry condition. One aim was to determine what level of retroreflectivity drivers need under rainy conditions; however it was found that the reflectivity of markings at the threshold visibility distance was different for different material type. The visibility distance correlated most highly with the road marking luminance and moderately with the measured retroreflectivity. The visibility distance (measured as the number of skip marks that was seen by the subject) was on average longer when the driver was sitting in a truck than in a sedan, despite the retroreflectivity being lower for the greater observation angle obtained when sitting in a truck.

Also Rumar et al. have found that retroreflective road markings have a significantly longer detection distance for truck drivers than for passenger car drivers [105]. The authors mean that the difference is related to the height of the headlights and not to the eye height of the driver.

The influence of vehicle headlights on the visibility of road markings has been demonstrated in a study by Zwahlen and Schnell [106]. The use of high-beam headlights was found to have a beneficial effect on the visibility for young drivers (7–11% longer visibility distances). Road surface retroreflectivity also had an influence on visibility.

A complement to retroreflective road markings is in-road lighting systems, i.e. road studs that emit light (also known as intelligent road studs). This is an interesting technique that provides enhanced delineation and extends the preview time compared to traditional road markings [107]. Light emitting road studs can be used not only to improve road guidance but also to increase the visibility of intersections, railroad crossings and pedestrian crosswalks.

Traffic Lights

Traffic lights may appear more conspicuous at night than during daylight conditions, because of their brightness and colour contrast. On the other hand, at night drivers are adapted to low luminance levels and the relatively bright traffic lights can thus cause discomfort. Bullough and colleagues have examined the visual discomfort from simulated traffic lights in night-time conditions [108]. Yellow signals were rated as less uncomfortable than red and green signals of the same luminance. For traffic lights with luminances according to the recommendations set by the American association Institute of Transportation Engineers (ITE), it was found that about 42% of the drivers rated the yellow light (23 100 cd/m^2) as uncomfortable, 36% of the drivers rated the green light (10 000 cd/m^2) as uncomfortable while 0% of the drivers thought the red light (5 000 cd/m^2) was uncomfortable at a viewing distance of 20 m. The luminances at which 50% of the drivers experienced the signals as uncomfortable was 17 700 cd/m^2 for red light, 28 900 cd/m^2 for yellow and 14 200 cd/m^2 for green. The subjects were relatively young (< 50 years) and older people are usually more sensitive to glare.

Sayed et al. have found that treatments for improving conspicuity of traffic lights (larger signal lens size, new backboards, adding reflective tape to existing backboards and additional signal heads) significantly decrease the number of collisions, both at daytime and night-time [109].

Road Surfaces

No literature on road users' needs, problems and experiences in relation to road surfaces was found.

Summary, drivers

- Drivers might not be aware that their vision is impaired during night-time driving.
- There are no unequivocal results indicating that driving behaviour at night differs from that during daytime conditions.
- At night, both speed and posted speed limit are usually too high compared to visibility distance.
- The ability to detect pedestrians (without retroreflective markings) is severely impaired in low light conditions.
- In low complexity environments, detection distances significantly increase if pedestrians have retroreflective markings.
- Not much literature about the potential benefits of using retroreflective markings in urban, high complexity environments was found.
- Studies indicate that new types of street lighting both can improve visibility and reduce energy consumption.
- Methods for measuring light are not adapted to the mesopic luminous efficiency function of the eye. Thus, measured light characteristics do not always correlate with human-perceived light characteristics.
- The visibility distance of road markings do not meet drivers' needs.

Authors' comments and proposals for further research

Drivers' difficulties detecting pedestrians give rise to a number of research questions. First of all, the conspicuity of pedestrians in visually complex urban areas is not well documented in literature, and more knowledge within this area is therefore needed. A natural continuation of such a study would be to investigate how the conspicuity of pedestrians could be improved in complex environments. This could involve investigation on different configurations of retroreflective tags (colours, patterns, location) but also alternative designs of road equipment, such as crosswalks. In order to obtain realistic results from conspicuity studies it is important to find new measurement methods that are based on eye scanning behaviour rather than telling the participants to e.g. press a button when they see a pedestrian.

An important question for the future is to find ways of reducing the energy consumed by street lighting, in order to fulfil the climate goals. Since street lighting usually decreases the accident rate, the climate goals might be hard to reconcile with traffic safety. Research within this area is thus of great importance, in order to find new solutions that are beneficial both for the environment and for the traffic safety.

Several of the references in this chapter show that humans and measurement instruments do not "see" the same thing. It is thus important to involve humans when evaluating conspicuity, and not only rely on instruments.

6.2 Pedestrians

Pedestrians are at an increased risk of having an accident during night-time conditions, see also Chapter 2. Sullivan and Flannagan have analysed more than 1 200 American crashes involving pedestrians and it was found that most night-time crashes occurred when the pedestrian attempted to cross the road, either away from an intersection (31%) or at an intersection (27%) [68]. This differed somewhat from daylight conditions, where crashes at intersections were most frequent (36%), followed by crashes away from intersections (24%). The proportion of crashes involving pedestrians walking in the roadway was higher in darkness than in daylight, both for pedestrians walking with traffic (10% versus 5%) and against traffic (4% versus 2%). In rain, pedestrian crashes were proportionally much higher in darkness than in daylight (18% versus 5%).

Drivers' difficulties in detecting pedestrians at night are frequently mentioned in literature, see also Section 6.1.2. Low contrast, limited illumination and drivers overdriving their headlights create potentially risky situations for pedestrians. In addition, pedestrians usually overestimate the distance at which they can be seen, which may be explained by the fact that, in general, the pedestrian is aware of the vehicle before the driver is aware of the pedestrian [67]. Furthermore, in dark environments, pedestrians are usually adapted to a lower light level than drivers and thus, they are better primed to detect targets than drivers, which may contribute to pedestrians' overestimation of their own conspicuity [110], cited by [111].

The use of retroreflective markings has since long been known to enhance recognition of pedestrians [67], see also Section 6.1.2. Reflective markings displaying biological motion are usually more effective than markings on the torso [6, 67]. In a review of about 25 studies about interventions for increasing pedestrian and bicyclist visibility, it is stated that, in addition to biomotion, also lamps, flashing lights and red and yellow retroreflective markings improve the recognition [112, 113]. However, the effect of retroreflective markings and other visibility aids on accident rate is not well documented in literature. In the review mentioned above, one of the objectives was to quantify the effect of visibility aids on pedestrian and cyclist-motor vehicle collisions and injuries, but no such trials were found [113].

In general, the use of retroreflective markings is low. In Sweden 1995–1997, reflective tags were used in 16% of all pedestrian journeys at night in urban areas [14]. Expressed in kilometres walked, this figure is 21%, which means that the average walking distance for those who used a reflective tag was longer than for those who didn't use a reflective tag. In other countries, such as the US and Australia, reflective tags are not regularly used [71, 114].

The low use of retroreflective markings may be explained by e.g., a lack of knowledge or that pedestrians find them impractical to use. In a study by Balk et al., it was found that retroreflective markings in a biomotion configuration provided the best conspicuity, but it was suggested that – since pedestrians may find the use of biomotion markings impractical – the use of retroreflective marking on only the wrists and ankles could be a good compromise between conspicuity and practicality [70]. Another reason why pedestrians do not use reflective tags may be the fact that they usually overestimate their conspicuity. In Sweden, about 90% of pedestrian night-time journeys in urban areas are undertaken on roads with lighting [14], where pedestrians may believe they are sufficiently conspicuous.

Pedestrians not only overestimate their conspicuity, but also underestimate the benefits of retroreflective markings, which has been demonstrated by Tyrrell and colleagues in a series of experiments on pedestrians' estimates of the own conspicuity [115, 116]. In the first study, pedestrians (i.e., the subjects) were dressed in four different clothing conditions: black, white, retroreflective vest and retroreflective stripes in biomotion configuration [115]. The subjects estimated their conspicuity when wearing black clothes as significantly lower than with the other three clothing conditions (measured as detection distance). They also believed that their conspicuity was significantly lower with low beams than with high beams. Overall the subjects overestimated their conspicuity with a factor of 1.8. The overestimation was the greatest in the worst condition, i.e. with black clothes, where the factor was 7.0. However, when wearing biomotion retroreflective clothing, the subjects actually underestimated their conspicuity.

In another study, Tyrrell et al. have examined pedestrians' estimates of their own conspicuity (under three different clothing conditions: black, white and biomotion), after being educated about it [116]. A group of students who had heard a lecture about visual perception and night-time driving 7 weeks prior to the test (without being told about the connection between the lecture and the test), estimated their detection distance to be 10% shorter on average, than a control group. Overall, the subjects underestimated the benefits from retroreflective clothing and high beams. The authors mean that the former may be explained by the fact that when viewed from a pedestrian's perspective, retroreflective material does not appear to increase conspicuity. In a following experiment a group of subjects heard a more focused lecture about the limitations of vision at night, with several images and video clips. Without being aware of the connection, the subjects then participated in a test similar to the one described above. It was found that the lecture group estimated their detection distance to be 56% of that of a control group. Based on the results, Tyrrell et al. recommend that education about night-time traffic for the general public should focus on basic concepts, such as contrast, retroreflectivity and biomotion, rather than just saying that people should be careful.

Pedestrians' visual performance and visual needs are not well documented in the literature reviewed. Street lighting in general improves visual performance and – of importance for pedestrians – lighting also makes people feel safer and reduces the fear of crime [63]. Fotios and Cheal have compared high-pressure sodium (HPS) lamps with metal halide (MH) lamps (white light) of one S-class lower [85], see also Section 6.1.3. Regarding abilities that are of importance for pedestrians, the authors claim that achromatic visual acuity and contrast detection threshold are reduced under the lower class MH lighting and maybe also the ability to detect obstacles, while visual orientation and facial recognition are not affected.

Summary, pedestrians

- Pedestrians are at an increased risk of having an accident at night.
- Pedestrians tend to overestimate their own conspicuity.
- The use of reflective tags is low.

Authors' comments and proposals for further research

In order to decrease the number of accidents involving pedestrians, more knowledge on pedestrian behaviours and attitudes is needed. Some important and relevant questions are:

- How can pedestrians become aware of their poor conspicuity?
- Do pedestrians experience any difficulties in low light conditions that might explain their increased risk of having an accident (for example problems with distance estimation or glare)?
- Do pedestrians change their behaviour at night (for example, are they more or less willing to wait at a red light)?
- How can the use of retroreflective tags or other visibility aids be increased?

6.3 Bicyclists

Information about bicyclists in night-time traffic was very limited in the literature reviewed.

Thulin and Kronberg report that in Sweden 1995–1997, bicycle lighting was used in about half of all bicycle journeys at night in urban areas [14]. The journeys where the lighting was used were on average longer than those without lighting. About 90% of bicycle night time journeys in urban areas were undertaken on roads with lighting.

In a study by Lindahl and Stenbäck, it was found that about 30% of bicyclists in urban areas in Sweden are fully conspicuous, i.e., the bicycle has light at the front and at the rear and reflector tags on the sides [117]. About half of the bicyclists have neither lights nor reflective tags.

Summary, bicyclists

- The use of bicycle lighting and reflector tags is low.
- Not much literature on bicyclists was found.

Authors' comments and proposals for further research

Since very limited information on bicyclists was found in literature, all kinds of research within this area would be of interest. Further research should comprise both the problems and needs experienced by the bicyclists themselves and the potential problems related to the low use of lights and reflector tags that may affect other road users.

6.4 Older Road Users

Several studies report about the problems encountered by older road users during night-time conditions. Older people often have degraded night vision (see also Section 5.2), which leads to poor visual performance and discomfort while driving at night. In a study of 900 older drivers, about 20% reported difficulties with driving at night [118].

Many older drivers avoid driving at night. In a study by Okonkwo et al., about 1 500 older drivers were asked about their driving habits [119]. The second most avoided situation was driving at night (after driving in bad weather). The drivers' risk of having a crash was estimated from a UFOV[1] test and in general, high-risk drivers were found to avoid driving more than low-risk drivers. However, with regard to night-time driving, both groups reported a similar level of avoidance. Okonkwo's results are supported by a study by Charlton and colleagues who have examined driving habits among a sample of older drivers in Tasmania [120]. Night driving was found to be the most avoided driving situation. A third of the drivers said that they always avoided driving at night and more than 20% stated that they usually or sometimes avoid driving at night. However, no relationship was found between this self-regulatory behaviour (i.e., avoid driving at night) and the functional abilities of the drivers (determined from a test measuring cognitive, perceptual, attention and motor functions).

Owens and Tyrrell claim – based on the results from a simulator study – that the reluctance of older drivers to drive at night might be explained by age-related impairments in guidance vision [51]. The study showed that steering performance of older drivers was worse than that of younger drivers in all luminance conditions and that the steering performance of all drivers decreased with decreasing luminance, but the decrease was the largest for older drivers. The authors mean that the study supports the selective degradation hypothesis, i.e., that there are two modes of vision: one serving focal functions and one responsible for guidance vision. At night, focal vision is severely impaired but guidance vision is preserved – at least among younger drivers – and thus, steering a car at night is usually not experienced as a particular difficult task (see also Section 6.1.1). However, if guidance vision is impaired, driving at night will be experienced as troublesome.

The sensitivity to glare increases with age and the recovery time after being exposed to glare is longer for older drivers [43]. Lockhart and colleagues have studied discomfort glare from the side-mirrors [121]. Older drivers reported greater level of glare than younger drivers, when exposed to the same level of illuminance. It was also found that a certain type of mirrors – nonplanar mirrors – reduced the feeling of glare for both older and younger drivers, compared to planar mirrors.

Older drivers, vehicle lighting and related problems, such as glare and the need for sufficient illumination, are discussed in a report by Rumar [44]. Rumar claims that older drivers would benefit from greater illumination from the headlamps even though that would increase the problems with glare. Moreover, it is suggested that the light beam should be wider for better road guidance. Concerning vehicle signalling and marking lights, the author suggests that a lower intensity level should be used at night than during daytime in order to reduce discomfort glare. Rumar also thinks that different light levels should be used inside the car during day and at night. Many older drivers

[1] Useful Field of View, a test of visual attention

complain about difficulties seeing instruments and controls inside the car at night, and therefore improved interior lighting would be beneficial for the comfort.

Age-related changes in vision lead to impaired detection of pedestrians and other objects in the driving environment. Owens reports that in a closed road circuit experiment, the recognition of signs and speed bumps decreased as a function of both age and illumination [6]. Zwahlen and Schnell have investigated the visibility of road markings and found that older drivers had a significantly shorter detection distance than younger drivers [106]. For old drivers, the influence of illumination (high versus low beam) was rather small and the authors mean that the visibility of road markings in the elderly is affected more by the visual angle than the brightness of the markings.

Luoma and Penttinen have examined the detection distance to pedestrians with different retroreflective markings [71]. Older drivers (mean age 66) had a significantly shorter detection distance than younger drivers (mean age 24) (126 m vs. 174 m). Similar results have been found by Sayer et al., although with a smaller difference between young and old drivers [77]. The younger subjects (mean age 21.6) detected the pedestrian at a significantly longer distance than the older subjects (mean age 68.9), and the average difference was 16.5%.

Wood et al. have conducted a study about the ability of younger and older drivers to recognize pedestrians with different clothing at night, both with low beam and high beam headlights, and with and without glare [72] (see also Section 6.1.2). The ability of the older drivers to recognize pedestrians was consistently worse than that of the younger drivers. The older drivers recognized 53% of the pedestrians while the young drivers recognized 84%. The older drivers also recognized the pedestrians at significantly shorter distances than the young drivers. On average, the older drivers had a recognition distance of 58% of that of the young drivers.

Owens and colleagues have studied visual performance and driving behaviour of drivers of different ages at night-time under four different headlight conditions [45]. It was found that average speed and recognition of road signs decreased with increasing age and decreasing illumination. Middle-aged and older drivers' ability to recognize pedestrians was severely degraded compared to younger drivers. However, if the pedestrian had biomotion markings, the middle-aged drivers' recognition ability was similar to that of younger drivers, while the older drivers significantly improved their recognition ability but not to the level of younger drivers. It was concluded that older drivers drive more cautiously than middle-aged and younger drivers, at night.

Summary, older road users

- Many older drivers avoid driving at night.
- In general, the visual performance of older road users at night is poor, compared to younger road users.
- The sensitivity to glare increases with age.
- No literature on the needs and experiences of older pedestrians and bicyclists was found.

Authors' comments and proposals for further research

A frequently mentioned problem experienced by older drivers is glare. Thus, glare and how to avoid glare should be taken into consideration when designing roads, road equipment and vehicles.

From literature it is known that many older drivers avoid driving at night. However, the reasons why they avoid driving are less known. With more knowledge on older drivers and their needs, it might be possible to design road equipment, vehicles and new technical solutions in a way that can support older drivers.

An important question for older drivers is to decide when to stop driving. Such discussions should include night-time driving aspects, since this is one of the most avoided and problematic driving situations for older drivers.

6.5 Visually Impaired

Visual impairments include a wide range of diseases and conditions – from relatively mild conditions such as myopia, which can be corrected for by glasses or contact lenses, to severe diseases that eventually lead to blindness. Accordingly, the needs and problems experienced by this group of road users can be expected to vary a lot within the group.

A workshop held in 2004 within the European project IMMORTAL summarized current research on problems related to visual and perceptual deficiencies among drivers [122]. Some reviewed studies indicated that drivers with reduced night vision, sensitivity to glare or reduced visual acuity are at a higher risk of having an accident. Regarding visual field defects, not many studies were found and they were not unambiguous, but most of the referred studies indicated that drivers with visual field defects at least partially compensate (for example by reduced speed and increased eye movements) for their visual deficiencies and that they are not at an increased risk of having an accident. There were also very few studies found about colour vision defects. It was stated that severe colour vision defects can cause problems with detecting traffic lights, but results regarding accident risk were ambiguous. Corrective laser surgery for treatment of refractive conditions (myopia, hyperopia) was reported to cause increased glare sensitivity in some patients. The workshop concluded that more research is needed in order to obtain knowledge about problems related to visual impairments among drivers.

Impaired visual acuity caused by refractive conditions, such as myopia, is very common in the population. Usually a normal visual acuity can be achieved by the use of glasses or contact lenses. However, glasses and contact lenses can cause or enhance stray light effects. Moreover, Meyer et al. have found that the acceptability of non-optimal luminous conditions varies a lot according to the presence of refractive conditions [123].

Many older drivers have visual impairments, but continue to drive. Chaparro and colleagues have asked approximately 160 older drivers about their driving habits [124]. About half of the drivers were considered as having low vision, caused by cataracts, glaucoma, retinitis pigmentosa, macular degeneration or diabetic retinopathy. It was found that more than 80% of the normal vision drivers continue to drive, while about 50% of the visually impaired continue to drive. Drivers with and without visual impairments drove approximately the same number of kilometres a year. However, the visually impaired were significantly less likely to drive at night than the elderly drivers with normal vision. Drivers with low vision also reported greater difficulties with glare caused by headlights and problems seeing the instrument panel clearly at night.

In a later similar study by the same research group, 195 older women and men (mean age 78.5) with and without visual impairments (such as glaucoma, retinitis pigmentosa, macular degeneration or corrected visual acuity worse than 20/40) were asked about their driving habits [125]. The results were similar to those in the first study: More than half of the visually impaired drivers continued to drive and low vision drivers spent a significantly less percentage of their total driving time at night, than normal vision drivers. Both impaired and no impaired drivers reported problems related to contrast sensitivity, acuity, illumination and peripheral vision. Regarding driving at night, both groups reported difficulties related to near acuity and glare. Other driving-related difficulties were peripheral vision, motion perception and distance acuity. Low-vision drivers reported greater difficulties keeping the instrument panel in focus at night, than the nonimpaired drivers. The authors suggest that low vision drivers should have the options of purchasing an instrument panel that magnifies the instrument readings.

Adler et al. have investigated the driving habits of older men with and without glaucoma [126]. Those with glaucoma were significantly more likely to have changed their driving habits with regard to driving at night. In contrast to the three studies summarized above, Ball and colleagues have found that older drivers with and without visual impairments limit their driving at night to the same extent [127]. The authors mean that this can be explained by the fact that most older drivers have impaired vision in low light conditions.

Cataract is one of the most frequent visual impairment among older people. It causes blurred vision and accordingly, it can potentially have an unfavourable influence on driving performance. Cataract can be removed surgically, often with very good results, as shown in a study by Mönestam and Wachtmeister [128]. They have assessed the outcome of cataract surgery on the patients' self estimation of visual performance while driving. About 200 patients with driving license answered a questionnaire before and after the surgery. Out of the patients who were actually driving before the surgery (56%), about 70% reported difficulties with driving in darkness and in twilight, before surgery. Other difficulties reported were problems with distance estimation and glare. In total, 82% of the drivers reported some visual functional problem while driving before surgery. After surgery, this figure had declined to 5% and then the most reported problem was glare sensitivity. There was no correlation between visual acuity and the degree of subjective visual functional problems before surgery and thus, the authors recommend that visual functional problems while driving should be considered as an indication for cataract surgery.

Summary, visually impaired

- Visually impaired road users are a heterogeneous group with different problems and needs.
- Studies indicate that about 50% of older drivers with visual impairments continue to drive.
- Driving performance and accident risk of visually impaired are not well documented.
- No literature on the needs and experiences of visually impaired pedestrians was found.

Authors' comments and proposals for further research

Some eye diseases such as cataract and glaucoma are quite common and since research shows that many visually impaired people continue to drive, it would be interesting to get some more information on these drivers, their needs and their risk of being involved in accidents.

It would also be of interest to study the needs of visually impaired pedestrians, particularly those who have diseases that mainly affect night vision.

7 Discussion

In this report, recent literature on road users' problems, needs and experiences in relation to night-time traffic has been reviewed. The main focus has been on urban environments. However, there is no clear dividing line between urban and non-urban areas and some facts in this report thus refers to traffic in general and not specifically to urban conditions.

Among the most discussed and studied problems in literature are drivers' difficulties detecting pedestrians. Drivers' unawareness of their impaired vision in night-time conditions in combination with pedestrians' overestimation of their own conspicuity result in pedestrians being exposed to an increased risk at night. Interesting progress in technology for improved visibility are new lamp types that are better adapted to human vision. In addition, the current development of photometric instruments for mesopic conditions is important for a better evaluation of existing and new street lighting.

The literature review covers a wide range of research related to human aspects of night-time traffic. However, some areas are not well documented in literature. Only a few references were found on traffic signs and traffic lights, while no references at all were found on road surfaces.

Road user groups that are only sparsely represented in literature are bicyclists and visually impaired. A few studies indicate that bicyclists may be at an increased risk in darkness, but very little literature on bicyclists' experiences and behaviour in night-time traffic was found. Visually impaired are a heterogeneous group with different needs and experiences, and the limited information about problems related to this group may be explained by the fact that many of the subgroups are relatively small and/or not active road users. There are, however, some eye diseases that affect a large part of the population – mainly the older – and literature shows that many of those affected continue to drive. Research about these road user groups is thus important. Also older road users are an important group to include in research about night-time traffic. This is a relatively large group of road users and the needs and problems experienced by this group differ from those who are young and healthy.

Based on the results of this literature review, some research areas, which are interesting for further studies are suggested (see also the summaries in each chapter):

- Visibility and detection of pedestrians. This includes behavioural aspects, for example eye scanning behaviour of drivers, and technical solutions, such as improved street lighting and road surfaces. Both passenger car and heavy vehicle drivers should be considered because of the different geometries.
- Older road users – both drivers and pedestrians – and their needs and problems in night-time traffic. This could also include development of novel technical solutions in order to facilitate safe driving and increase driving comfort for older drivers with minor problems.
- Bicyclists in night-time traffic. This comprises both the problems and needs experienced by the bicyclists themselves and the potential problems related to the low use of lights and reflector tags that may affect other road users.
- Visually impaired in night-time traffic. The problems and needs experienced by active drivers with common eye diseases, such as cataract and glaucoma, should be further studied. Also visually impaired who are not active drivers, but still use the roads as pedestrians, are an interesting group for further research.

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