VTI rapport 882A
Published 2015
www.vti.se/en/publications

Revision of criteria for selection of road lighting class

A pre-study

Carina Fors
Annelie Carlson

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Diarienummer: 2013/0297-26
Omslagsbild: Thinkstock och Katja Kircher, VTI
Tryck: LiU-Tryck, Linköping 2015

Abstract

The aim of this project is to investigate the potential in decreasing the energy use of road lighting by a revision of the guidelines regarding the selection of lighting level. The starting point of this work has been the method for selection of lighting classes suggested in the recently published technical report CEN/TR 13201-1, which considers road lighting for drivers and for vulnerable road users. In order to investigate whether CEN/TR 13201-1 is applicable in Sweden, a literature review on guidelines and criteria for selection of road lighting classes was carried out, with the aim of identifying criteria that are scientifically grounded. The literature review was supplemented by a workshop where road lighting criteria were discussed by invited road lighting experts from the Nordic countries. The results from the study show that there is some support that the parameters traffic volume, traffic composition, separation of carriageways, ambient luminosity and navigational task are relevant for the selection of road lighting class, but also that there is a lack of knowledge of road users' needs and experiences of road lighting. The report gives recommendations for further work on a revision of the guidelines for road lighting, and suggestions for further research studies.

Title: Revision of criteria for selection of road lighting class. A pre-study

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Publisher: Swedish National Road and Transport Research Institute (VTI)
www.vti.se

Publication No.: VTI rapport 882A

Published: 2015

Reg. No., VTI: 2013/0297-26

ISSN: 0347-6030

Project: National application of the CEN standard for road lighting classes

Commissioned by: Swedish Energy Agency

Keywords: Road lighting, energy use, traffic safety, guidelines, road users

Language: English

No. of pages: 94

Referat

Ökade krav på energieffektivitet inom transportsektorn har gjort vägbelysningens energianvändning till en aktuell fråga. Syftet med projektet är att undersöka möjligheterna att minska vägbelysningens energianvändning genom en revidering av rekommendationerna för val av belysningsnivå. Utgångspunkten för detta arbete har varit en metod för val av vägbelysningsklass föreslagen i den nyligen publicerade tekniska rapporten CEN/TR 13201-1, som omfattar belysning för både vägar och gator för motorfordon och för gång- och cykelvägar. För att undersöka möjligheterna att införa CEN/TR 13201-1 i Sverige gjordes en litteraturstudie om riktlinjer och kriterier för vägbelysning, med syfte att identifiera kriterier som har ett vetenskapligt stöd. Litteraturgenomgången kompletterades med en workshop där kriterier för vägbelysning diskuterades av inbjudna experter från de nordiska länderna. Resultaten från studien visar att det finns ett visst stöd för att parametrarna trafikflöde, trafiksammansättning, separering av körbanor, omgivningsljus och komplexitet är relevanta för valet av vägbelysningsklass, men också att det till stor del saknas kunskap om trafikanternas behov och upplevelser av vägbelysning. Rapporten ger rekommendationer för fortsatt arbete med en revidering av riktlinjer för vägbelysning, samt förslag på fortsatta forskningsstudier.

Titel:	Revidering av kriterier för val av vägbelysningsklass. En förstudie
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Utgivare:	VTI, Statens väg och transportforskningsinstitut, www.vti.se
Serie och nr:	VTI rapport 882A
Utgivningsår:	2015
VTI:s diarienr:	2013/0297-26
ISSN:	0347-6030
Projektnamn:	Nationell tillämpning av CEN-standard för vägbelysningsklasser
Uppdragsgivare:	Energimyndigheten
Nyckelord:	Vägbelysning, energianvändning, trafiksäkerhet, riktlinjer, trafikanter
Språk:	Engelska
Antal sidor:	94

Preface

This report constitutes the first two parts of a three-stage project that aims at reviewing guidelines and criteria for selection of road lighting levels, with the goal of having scientifically grounded and energy efficient recommendations. The starting point of this work was the method for selection of lighting classes suggested in the technical report CEN/TR 13201-1, which was published recently.

The first stage of the project was a literature review, where the scientific basis of the suggested method and the application of lighting guidelines in different countries was investigated. The report also includes an overview of methods and metrics for the evaluation of road lighting.

The second stage of the project was a workshop with invited experts from the Nordic countries, which aimed at discussing the proposed method.

In stage three, some methods for evaluating road lighting will be investigated in a field test, based on the results of stage one and two.

The report was written by Annelie Carlson and Carina Fors at VTI.

The authors would like to thank:

- The Swedish Energy Agency for funding the study
- Petter Hafdell, Trafikverket, for help in organizing the workshop
- The workshop participants for fruitful discussions.

Linköping, November 2015

Carina Fors
Project manager

Quality review

Internal peer review was performed on 3 December 2015 by Björn Lidestam. Carina Fors has made alterations to the final manuscript of the report. The research director Jan Andersson examined and approved the report for publication on 14 December 2015. The conclusions and recommendations expressed are the author's/authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Intern peer review har genomförts 3 december 2015 av Björn Lidestam. Carina Fors har genomfört justeringar av slutligt rapportmanus. Forskningschef Jan Andersson har därefter granskat och godkänt publikationen för publicering 14 december 2015. De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

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Summary

Revision of criteria for selection of road lighting class - A pre-study

by Carina Fors (VTI) and Annelie Carlson (VTI)

For increased energy efficiency within the road sector, some attention has been given to road lighting. Reductions in energy use for road lighting can primarily be achieved by replacing old road lighting installations by modern ones and by reducing lighting levels by revising current road lighting recommendations. Less attention has so far been paid to current practice and standards. However, there are reasons to believe there is a realistic potential in changing recommendations for road lighting so they promote a less energy consuming lighting regime without decreasing the benefits. Several researchers have during the past decade, pointed out that there is a weak empirical basis of the current standards and recommendations for road lighting. There is a lack of knowledge of the relationship between road users' needs and visual condition, which gives reasons to believe road lighting may be over-dimensioned in many situations. The need for energy savings together with the fact that the current guidelines for road lighting are not well-founded from a road user perspective implies the need for a review of the current recommendations and standards.

The starting point of this work has been the method for selection of lighting classes suggested in the recently published technical report CEN/TR 13201-1, which considers road lighting for drivers and for vulnerable road users. In order to investigate whether CEN/TR 13201-1 is applicable in Sweden, a literature review on guidelines and criteria for selection of road lighting classes was carried out, with the aim of identifying criteria that are scientifically grounded. The literature review was supplemented by a workshop where road lighting criteria were discussed by invited road lighting experts from the Nordic countries. The literature review and the workshop constitute the first and the second part of a three-stage project that aims at forming a basis for further discussions and work on a possible revision of current guidelines, with the long-term goal of having more scientifically grounded and energy efficient recommendations for road lighting design in the future.

Our review shows that there is no strong link between the selection criteria in CEN/TR 13201-1 and the scientific literature, which is in line with previous studies on guidelines for road lighting. We recommend that new guidelines should have a stronger base in scientific results and they should also be easy to understand and to apply. There should be limited possibilities for interpretations and their application should be equal regardless of who is using them. In developing new guidelines, the suggestion is that the factors to be considered should be road users' needs, energy and costs. The road users' needs must be defined in future studies, but may include for example, detectability of vulnerable road users and visual comfort. Regarding energy, guidelines for dimming and adaptation needs to be developed. Costs is a relevant factor but the traditional cost-benefit calculations should be avoided due to the weak scientific basis the estimations are based on. Also, other factors such as mobility, accessibility and light pollutions may be relevant to consider in guidelines for lighting and lighting level. Three potential ways of evaluating lighting are suggested; Visibility and detectability of pedestrians; Glare, visual discomfort and visual experience and Subjective experience. These methods relate to the parameters in CEN/TR 13201-1 that are assumed to be relevant for the selection of lighting class, namely traffic volume, traffic composition, separation of carriageways, ambient luminosity and navigational task.

Sammanfattning

Revidering av kriterier för val av vägbelysningsklass – En förstudie

av Carina Fors (VTI) och Annelie Carlson (VTI)

Ökade krav på energieffektivitet inom transportsektorn har gjort vägbelysningen till en aktuell fråga, där olika möjligheter till minskad energianvändning undersöks. En viktig del i detta är införandet av nya energieffektiva ljuskällor som kan ge en väsentligt minskad energianvändning när gamla ineffektiva ljuskällor byts ut. En annan mindre uppmärksammad möjlighet är att sänka nivåerna för belysningen, vilket kräver en revidering av gällande riktlinjer. Kunskapsläget talar för att det finns en realistisk möjlighet att ändra gällande rekommendationer för vägbelysning så att den blir mer energieffektiv utan att det får negativa effekter. Flera forskare har under det senaste decenniet påpekat att det vetenskapliga underlaget för gällande riktlinjer och rekommendationer för vägbelysning är svagt. Det saknas till stor del kunskap om sambanden mellan trafikanters behov och de visuella förhållandena, vilket talar för att vägbelysningen många gånger kan vara överdimensionerad. Kraven på ökad energieffektivitet och det faktum att nuvarande riktlinjer för vägbelysning inte är väl underbyggda ur ett trafikantperspektiv utgör skäl för att se över de gällande rekommendationerna och standarderna för vägbelysning.

Utgångspunkten för detta arbete har varit en metod för val av vägbelysningsklass föreslagen i den nyligen publicerade tekniska rapporten CEN/TR 13201-1, som omfattar belysning för både vägar och gator för motorfordon och för gång- och cykelvägar. För att undersöka möjligheterna att införa CEN/TR 13201-1 i Sverige gjordes en litteraturstudie om riktlinjer och kriterier för vägbelysning, med syfte att identifiera kriterier som har ett vetenskapligt stöd. Litteraturgenomgången kompletterades med en workshop där kriterier för vägbelysning diskuterades av inbjudna experter från de nordiska länderna. Litteraturstudien och workshopen utgör första och andra delen i ett trestegsprojekt som syftar till att ta fram ett underlag för en möjlig revidering av gällande riktlinjer, med det långsiktiga målet att det i framtiden ska finnas mer vetenskapliga och energieffektiva rekommendationer för vägbelysning.

Litteraturgenomgången visar att det inte finns någon tydlig koppling mellan kriterierna i CEN/TR 13201-1 och den vetenskapliga litteraturen, vilket är i linje med tidigare studier om riktlinjer för vägbelysning. Vår rekommendation är att nya riktlinjer ska ha en tydligare förankring i vetenskapliga studier och att de ska vara enkla att förstå och använda. De ska vara tydligt formulerade och inte ge utrymme för tolkningar. Faktorer som bör vägas in vid framtagande av nya riktlinjer är trafikanternas behov, energiåtgång och kostnader. Trafikanternas behov behöver identifieras i forskningsstudier, men det kan till exempel handla om upptäckbarhet av fotgängare och visuell komfort. Gällande energiåtgång behöver man ta fram riktlinjer för dimring och adaptiv belysning. Kostnader är en relevant faktor, men traditionella samhällsekonomiska analyser bör undvikas eftersom de baseras på osäkra uppgifter om vägbelysningens effekter på olyckor. Andra faktorer, såsom mobilitet, tillgänglighet och ljusföroreningar kan vara viktiga att ta hänsyn till i riktlinjer för belysning och belysningsnivå. Tre möjliga metoder för utvärdering av vägbelysning föreslås: Synbarhet och upptäckbarhet av fotgängare, Bländning, visuellt obehag och visuell upplevelse och Subjektiv upplevelse. Dessa metoder relaterar till de parametrar i CEN/TR 13201-1 som antas vara relevanta för valet av vägbelysningsklass, nämligen trafikflöde, trafiksammansättning, separering av körbanor, omgivningsljus och komplexitet.

1. Introduction

In the global challenge of decreasing CO_2 emissions, reducing the energy use of road lighting has come in focus for road authorities. Reductions in energy use can primarily be achieved in two ways: by replacing old road lighting installations by modern ones and by reducing lighting levels which needs a revision of the current road lighting recommendations. While a lot of effort has been spent on developing and (successfully) introducing new energy efficient light sources and lighting controls, less attention has been paid to current practice and standards.

In Sweden, guidelines for road lighting are given by *Vägar och gators utformning*, VGU (Trafikverket 2015a, Trafikverket 2015b). For roads and streets, there are six luminance classes which are defined by a set of photometric requirements such as average road surface luminance and luminance uniformity. For conflict zones, such as crossings and roundabouts, and for bicycle and pedestrian paths the requirements are based on illuminance. The lighting classes are defined by the European standard *EN 13201-2* (CEN 2003a). This standard is intended to make it easier to develop, use and compare lighting products and services and, although the photometric parameters included in the standard have been selected with the road users' needs in mind, there is no actual link between a certain lighting class and what the road users need in terms of visual conditions and traffic safety. In other words, the standard does not give guidelines on how to select a feasible lighting class for a certain road – it merely defines a number of classes. Thus, guidelines for how to apply the standard are developed by national road authorities and as a consequence, how they are applied varies between countries.

In Sweden, the criteria for selection of lighting class are road type, complexity and annual average daily traffic. These criteria are based on experience and practice, and they probably provide sufficient visual conditions for an average driver under normal conditions, in most cases. That is, there is no indication that the current practice is poor from a safety perspective, but the lack of knowledge of the relationship between road users' needs and visual conditions gives reasons to believe that road lighting may be over-dimensioned in many situations.

The weak empirical basis of the current standards and recommendations for road lighting has been pointed out by several researchers during the past decade. Raynham (2004) questioned the principles of road lighting design and emphasized the need for more research on road users' visual needs. Brémond (2007) explained the many criteria proposed, and their change over time, as a lack of consensus among experts, about what is the best compromise between quantitative criteria that engineers need when designing or evaluating a lighting installation, and the highly subjective underlying concepts of visibility, visual task, etc. Mayeur et al. (2008) gave the example of a shortcoming of consensus with the wide range of recommended threshold values for the visibility index (VL) proposed by different researchers, ranging from 4 to 30. Goodman (2009) discussed shortcomings of the current measurement systems for light and lighting, and argued for a broadening of the current measurement scales and instrumentation in order to take into account various aspects of human visual responses, such as visual task performance, physiological effects and ageing. Fotios and Goodman (2012) reviewed the British guidelines for selection of illuminance level for residential streets and the visual tasks relevant for pedestrians, and concluded that there is little evidence to support these guidelines.

Traditionally, road lighting has been assumed to reduce the number of accidents by about 30% (CIE 1992). This was more or less supported by meta-analysis from 1995, where it was estimated that road lighting leads to a 65% reduction of fatal accidents, a 30% reduction in injury accidents and a 15% reduction in property damage accidents (Elvik 1995). However, in more recent literature it is argued that it is very difficult to estimate the safety effects of road lighting, that many studies suffer from methodological weaknesses and flaws, and that the effects probably are much smaller than what has been previously assumed (Boyce 2009; Crabb, Crinson et al. 2009; Beyer & Ker 2010; Sasidharan & Donnell 2013).

The need for energy savings together with the fact that the current guidelines for road lighting are not well-founded from a road user perspective and that the safety effects of road lighting probably are relatively small in many cases, urge the need for a review of the current recommendations and standards.

The European Committee for Standardization (CEN) has recently published a technical report[1]: *CEN/TR 13201-1:2014 Road lighting – Part 1: Guidelines on selection of lighting classes* (CEN 2014), in this report referred to as C*EN/TR 13201-1*. The report lists a number of selection parameters, including design speed, traffic volume, traffic composition, overall layout of the road and environmental conditions, and describes a procedure on how to weight these parameters in order to determine an appropriate lighting class. It is emphasized in CEN/TR 13201-1 that the proposed method should be seen as a starting point for normal road lighting, i.e. it is not intended to cover all different road cases. It is also stressed that the levels of the selection parameters and the weighting values should be seen as examples and that they should be adapted to national conditions and possibly supplemented with national code of practice.

The present report constitutes the first and the second parts of a three-stage project that aims at investigating how CEN/TR 13201-1 can be adapted and applied in Sweden, with the goal of having more scientifically grounded and energy efficient recommendations for road lighting design in the future. Stage one is a literature review on criteria for selection of road lighting classes, while stage two is a workshop with invited experts from the Nordic countries. In stage three, criteria for road lighting is investigated in a field experiment.

In this report, the term "road lighting" is used as a generic term for all types of street- and road lighting. Relevant photometric terms and definitions can be found in Appendix A.

1.1. Aim

The overall aim of this study is to investigate whether CEN/TR 13201-1 is applicable in Sweden, by compiling available information about various aspects of road lighting. More specifically, the aims are to:

- investigate and compare how the lighting class standards are applied in different countries
- benchmark electricity price against road lighting in different countries
- examine the effects of road lighting in terms of road safety
- assess the scientific basis of the method suggested in CEN/TR 13201-1
- compile an overview of methods for evaluating road lighting
- conduct a workshop with road lighting experts in the Nordic countries
- give recommendations for further work.

The report considers road lighting for drivers and for vulnerable road users. Tunnel lighting is not included.

[1] Initially, CEN/TR 13201-1 was suggested to be a standard but it was finally approved as a technical document. This implies that CEN/TR 13201-1 will not be compulsory to use. The Swedish Standards Institute (SIS) decided to publish it as a technical report in December 2014: SIS-CEN/TR 13201-1:2014.

The literature review is presented in Chapters 2–5. A table of methods for evaluation of road lighting is given in Chapter 6. The workshop is summarized in Appendix B. Discussion, recommendations and conclusions from the literature review and from the workshop can be found in Chapter 7.

2. Method

Literature was searched using the search tool *Summon*, which is provided by the VTI Library and Information Centre. *Summon* includes the VTI library catalogue and all records in the database *Web of Science*.

Search words were:

- road lighting
- street lighting
- roadway lighting
- lighting visibility pedestrian
- lighting visibility target
- lighting driving behaviour.

The search, which was limited to publications published 1983–2014, resulted in approximately 2400 references. From this, references related to effects of road lighting, road user needs, or methods for evaluating lighting were selected for the literature review. References with a technical focus were excluded. In total, 61 journal papers, 5 conference papers and 27 reports from research institutes and similar, were included.

Approximately another 20 references, such as standards, manuals, books and other references, were included in the material that was used when writing this report.

References that seemed to have no or very little relevance for Swedish road and traffic conditions were not included in the literature review.

3. Lighting classes

Lighting classes for motorized traffic, for conflict areas and for pedestrians and pedal cyclists are given by the standard EN 13201-2 (CEN 2003a). The lighting classes are defined by a set of photometric requirements that are regarded as relevant for the roads users of the different types of roads.

The purpose of standardized lighting classes is to make it easier to develop and use road lighting products. The lighting class standard does not state how the classes should be used. The application of the classes, i.e. what classes to use in what traffic environment and how to select an appropriate class, thus differs between countries.

The lighting class criteria are either based on *luminance* or on *illuminance*. The luminance concept is applied on roads for motorized vehicles, where the aim is to provide a bright road surface against which objects can be seen. The luminance is dependent on the amount of light from the light source, the road surface characteristics and the observer's position, and it is thus somewhat complicated to calculate. The illuminance concept is used when the luminance concept cannot be applied or defined, e.g. in intersections where there are several possible observer positions, or in roundabouts where the road surface cannot serve as a background for objects because of the geometry.

The M classes are intended for drivers of motorized vehicles on traffic routes of medium to high driving speed, Table 1. The photometric requirements for the M classes include:

- **Average road surface luminance** ($\bar{L}$): A measure of the brightness of the road surface.
- **Overall uniformity of road surface luminance** (U_o): A measure of the luminance variation.
- **Longitudinal uniformity of road surface luminance** (U_l): A measure of the conspicuity of the repeated pattern of bright and dark patches on the road.
- **Threshold increment** (*TI*): A measure of disability glare from luminaires.
- **Edge illuminance ratio** (*EIR*): A measure of the amount of light that falls on an area just outside the edge of a carriageway.

For definitions of the parameters, see *EN 13201-3 Road lighting – Part 3: Calculation of performance* (CEN 2003b).

Table 1. M lighting classes.

	Luminance of the road surface				Disability glare	Lighting of surroundings
Class	Dry			Wet		
	$\bar{L}$ [min]	U_o [min]	U_l [min]	U_o [min]	*TI* [max]	*EIR* [max]
M1	2.00	0.40	0.70	0.15	10	0.35
M2	1.50	0.40	0.70	0.15	10	0.35
M3	1.00	0.40	0.60	0.15	15	0.30
M4	0.75	0.40	0.60	0.15	15	0.30
M5	0.50	0.35	0.40	0.15	15	0.30
M6	0.30	0.35	0.40	0.15	20	0.30

The C classes are intended for drivers of motorized vehicles, and other road users, on conflict areas such as road intersections, roundabouts, and shopping streets, Table 2. The photometric requirements for the C classes include:

- **Average illuminance** ($\bar{E}$): A measure of the amount of light that falls on the road.
- **Overall uniformity of the illuminance** (U_o): A measure of the illuminance variation.

Table 2. C lighting classes.

	Horizontal illuminance	
Class	$\bar{E}$ [min]	U_o [min]
C0	50	0.4
C1	30	0.4
C2	20	0.4
C3	15	0.4
C4	10	0.4
C5	7,5	0.4

The P classes are intended for pedestrians and pedal cyclists on footways, cycle tracks and other road areas lying separately or along the carriageway of a traffic route, Table 3. The photometric requirements for the C classes include:

- **Average illuminance** ($\bar{E}$): A measure of the amount of light that falls on the road.
- **Minimum illuminance** (E_{min}): A measure of the lowest illuminance on the road area.

Table 3. P lighting classes.

	Horizontal illuminance	
Class	$\bar{E}$ [min]	E_{min} [min]
P1	15.0	3.0
P2	10.0	2.0
P3	7.5	1.5
P4	5.0	1.0
P5	3.0	0.6
P6	2.0	0.4
P7	*Performance not determined*	*Performance not determined*

3.1. Application in Sweden

The lighting classes used in Sweden are basically identical to those given by the standard EN 13201-2 (Table 1–Table 3), with a few exceptions (Trafikverket 2015a). For the M classes, there are some minor deviations in U_l (for M1 and M2: 0.60 instead of 0.70, for M3 and M4: 0.40 instead of 0.60, for M6: 0.35 instead of 0.40). The C and P classes are identical to Table 2 and Table 3, with the addition that the Swedish C classes also include requirements of threshold increment (*TI*). Guidelines for how to use and apply the lighting classes are given by *Krav för vägars och gators utformning* (Trafikverket 2015a), *Råd för vägars och gators utformning* (Trafikverket 2015b) and *Vägbelysningshandboken* (Fors 2014).

The guidelines are mandatory for roads governed by the Swedish Transport Administration (rural roads and motorways) and advisory for roads governed by municipalities (urban roads and streets).

3.1.1. Rural roads and motorways

Rural roads are normally not illuminated, but in some cases road lighting is either required or recommended. In roundabouts and in traffic-light controlled junctions, road lighting is required. Road lighting may also be used on roads where any of the following criteria are fulfilled: high traffic flow, presence of vulnerable road users, disturbing or misleading ambient light, high accident rate or short distances between illuminated sections. If lighting is to be used on a rural road, the recommended M class is given by a two-step procedure by which 1) classification of the difficulty of the road is made, and 2) the M class is selected, based on difficulty and road type.

The difficulty is *high* if:

- there are many vulnerable road users on the road
- there is disturbing or misleading ambient light
- there are narrow lanes, shoulders or central reserve, or short distances between interchanges
- the speed limit is 80 km/h or higher (does not apply to motorways)
- the road is a rural road with AADT (annual average daily traffic) > 15000.

If the difficulty is not classified as high, the difficulty is *normal* if:

- The road is a motorway with AADT ≥ 15000
- the road has separate lanes or more than two lanes (e.g. 2 + 1 road) and has AADT ≥ 5000
- the road is a rural road with AADT 5000–15000.

The difficulty is *low* if it is not classified as high or normal. The lighting class is then selected from Table 4.

Table 4. Lighting classes for rural roads, based on the difficulty level of the road.

Road type	Difficulty		
	High	Normal	Low
Motorway, AADT ≥ 70000	M1	-	-
Motorway, AADT < 70000	-	M3	-
Roads with separated lanes, no vulnerable road users	M3	M4	-
Roads with separated lanes, vulnerable road users present	M2	M3	-
Two-lane rural roads, no vulnerable road users	M3	M4	-
Two-lane rural roads, vulnerable road users present	M3	M4	-

In junctions and interchanges, the same lighting classes as for the primary road should be used. In junctions where the connecting roads are not illuminated, the C classes C3 (≥ 70 km/h) or C4 (≤ 60 km/h) are recommended. In roundabouts where the connecting roads are not illuminated, class C3 should be used.

3.1.2. Urban roads

Basically, all urban roads are illuminated. Similar to rural roads, the recommended lighting class for a certain road is given by the difficulty of the road and by the road type.

The difficulty is *high* if:

- there are many vulnerable road users on the road
- there is disturbing or misleading ambient light
- there are narrow lanes, shoulders or central reserve, or short distances between interchanges
- the speed limit is 80 km/h or higher (does not apply to motorways)
- trackbound traffic is present
- the road has two lanes and the number of vehicles during the dimensioning hour (Dh) is ≥ 1500
- the road has more than two lanes and the number of vehicles during the Dh is ≥ 3500.

If the difficulty is not classified as high, the difficulty is *normal* if:

- the road has two lanes and the number of vehicles during the Dh is 300–1500.
- the road has more than two lanes and the number of vehicles during the Dh is 1000–3500.

The difficulty is *low* if it is not classified as high or normal. The lighting class is then selected from Table 5.

Table 5. Lighting classes for urban roads, based on the difficulty level of the road.

Road type	Difficulty		
	High	Normal	Low
Motorway, AADT ≥ 70000	M1	-	-
Motorway, AADT < 70000	M3	M4	M5
Arterial roads	M2	M3	M4
Primary streets	M3	M4	M5
Collector roads and local streets 40 or 50 km/h	M3	M4	M5
Collector roads and local streets 30 or 40 km/h	M4	M5	M6
Streets nearby schools 30 km/h	M3	M4	M5
Low speed streets	C3	C4	C5
Living streets	C4	C4	C4

*) Decided by the road authority

In intersections and in roundabouts, the lighting class should correspond to the highest of the lighting classes of the connecting roads. At pedestrian crossings, the lighting level should be one class higher than that of the ordinary street lighting.

3.1.3. Paths for pedestrians and cyclists

Paths for pedestrians and cyclists in urban areas shall be illuminated. Recommended classes are P2–P3, where the higher class is recommended for paths with a high traffic flow, or with high ambient luminance.

3.2. Application in other countries

3.2.1. Denmark

The guidelines for road lighting in Denmark are defined in *Vejregler for vejbelysning* (Vejdirektoratet 1999). According to the guidelines, road lighting should be of a sufficient quality to ensure adequate vision conditions and is there to maintain accessibility, traffic safety and security at night. Furthermore, the energy use should be kept as low as possible, the visual effect lighting will have on road environment during both night and day should be considered, the light pollution should be limited, and the lighting should have a high architectural quality.

There are three main lighting classes called L, LE and E. L-classes are based on luminance and are used for roads where lighting is mainly for the benefit of the motorized drivers. The LE-classes are based on illuminance and are also used for improving the road environment for motorized drivers. However, LE-classes are used in areas where luminance is not practical, such as in intersections and roundabouts. The E-classes are for areas where the lighting is for the pedestrians or cyclists, or both categories in combination. The L-classes are described in Table 6.

Table 6. Lighting classes for traffic routes in Denmark (Vejdirektoratet 1999, Nørgaard Andersen 2013).

Lighting class	Luminance of the road surface				Disability glare	Lighting of surroundings
	Dry			Wet		
	$\bar{L}$ [min]	U_o [min]	U_l [min]	U_o [min]	*TI* [%]	Strip of 3,5 m adjacent to carriageway [lx]
L1	2.00	0.40	0.60	0.15	6.1	5.0
L2	2.00	0.40	0.30	0.15	6.1	5.0
L3	1.50	0.40	0.60	0.15	6.5	5.0
L4	1.50	0.40	0.30	0.15	6.5	5.0
L5	1.00	0.40	0.60	0.15	6.8	2.5
L6	1.00	0.40	0.30	0.15	6.8	2.5
L7a	0.75	0.40	0.30	0.15	7.0	2.5
L7b	0.50	0.40	0.30	0.15	7.0	2.5

The road network is divided into urban roads and roads in an open landscape (rural), respectively. Roads in rural areas do in general not have lighting. But if a stretch of road or a conflict area (intersection) has had relatively many traffic accidents during night time, this section can be equipped with road lighting. For roads in urban areas, the basic rule is that they should be equipped with road lighting. For these, the lighting classes are chosen according to the characteristics of the area based on if it is:

- motorway
- traffic road
- local road
- intersection
- roundabout.

Urban motorways and expressways are illuminated if they, foremost, are used by local road users, or if light from the surrounding urban area is disturbing. Normally the lighting class L5 is used, but L1 and L3 can also be chosen. Urban traffic roads should be illuminated (L2, L4, L6 and L7). The basic lighting classes that are recommended are L6, L7a and L7b.

The choice is dependent on the speed limits; High (60–70 km/h); Middle (50 km/h) and Low (30–40 km/h) and on the complexity of the road environment, i.e. if cyclists and pedestrians are present, see Table 8. Also, it can be considered to not illuminate roads classified as "Middle" if there are separate lanes for pedestrians and cyclists.

Table 7 shows the lighting classes for local roads, paths, etc. (E) and pedestrian crossings (F). For adjacent parts of the sidewalk, bike path, etc. to the pedestrian crossings, the horizontal illuminance levels should be at least 30 lx (operating value) and at least about 10 lx (operating value), respectively, for classes Fl and F2.

Table 7. Lighting classes for local roads, paths, parking lots etc. (E) and pedestrian crossing (F) in Denmark (Vejdirektoratet 1999).

Lighting class	$\bar{E}$ [min]	U_o [min]
E1	5.00	0.15
E2	2.50	0.15
E3	1.00	0.15
E4	-	-
	Operational value [lx]	
F1	100	
F2	30	

Table 8. Lighting recommendations for dry traffic routes in Denmark (Kjaersgaard 2011).

Road	Complexity				Lighting class		
Motorway					L5		
Traffic road	Speed class	Pedestrians on the road	Cyclists on the road	Glare from oncoming traffic	2–3 lanes	4 lanes	6 lanes
	High	No	No	Yes	L7a	L6	L6
		No	No	No	L7b	L7a	L6
	Middle	No	No	Yes/No	L7b	L7a	L6
		No	Yes	Yes/No	L7a	L7a	-
		Yes	Yes/No	Yes/No	L6	L6	-
	Low	Yes	Yes	Yes/No	LE4	-	-
Local road	Dense and high buildings.				E1		
	Low buildings or low density of buildings.				E2		

Lighting in intersections that are regulated by signals should always be illuminated, and the lowest quality lighting class to use is LE5. For areas with intersections and connecting roads it is recommended to choose the highest lighting class used on the roads involved. In intersections with high complexity the recommended LE-class is dependent on the lighting classes of the adjacent roads in the intersection. The higher the luminance is on adjacent roads, the higher the recommended illuminance class is:

- LE2 if L2 on the adjacent road
- LE3 if L4
- LE4 if L6
- LE4 if L7a
- LE5 if L7b.

Roundabouts should always be illuminated including the entrance and exit roads, as well as cycle lanes if present. If no cyclists or pedestrians are present, the lighting should be as it is for intersections. When cyclists or pedestrians are present, the minimum lighting class is LE4. Speed bumps and other installations that are intended to lower speed should always be illuminated.

In rural areas the lighting class LE5 is used for conflict areas, such as intersections that are regulated with signals, roundabouts and for places where there are speed bumps in the road.

Vejdirektoratet in Denmark has updated the criteria for when there should be road lighting on rural roads (Kjaersgaard 2011). The criteria are:

- high traffic volume
- passability problems
- complexity

- Poor visual conditions
- proximity to urban area
- accident frequency.

As a basis, it is stated that road lighting should be considered on all roads where the actual or expected AADT is > 50 000. If any, or several, of the other criteria is also present, it is recommended that road lighting should be established. Road stretches that are close to, or have reached the capacity level, should be illuminated, as should longer stretches that are difficult to overlook for the drivers. This also applies to areas that have a high accident frequency. If the road, such as a ring road or similar, is close to a larger urban area, it should be equipped with lighting.

There are also recommendations for luminance of wet surface that should be 0.15 for all L-classes. In addition, there are four E-classes (E1–E4) that apply to areas close to carriageways, local roads, paths, parking lots etc., see Table 7. The E-class are similar to the A-class in EN 13201-2:2003.

For these roads, it is possible to use a lighting class with lower quality taking into consideration the character of the road stretch. However, L7b is the lowest useful lighting class. On access and exit roads to highways, L7b is enough in both urban areas and open landscapes.

Lighting class L5, or L3 in particularly difficult situations, is used in junctions, and access and exit lanes. In times with lower traffic volumes it is possible to turn the lighting off.

The level of lighting is increased with one class for areas where there are many lanes and where the number of lanes change.

In ramp intersections, road lighting should be established if:

- at least one of the roads has road lighting
- the intersection has road signals
- the intersection is a roundabout
- there are complex conditions on the secondary road with blocked surfaces, turning lanes, etc.
- there are specific problems with ghost drivers (i.e. drivers heading in the wrong direction)

For motorways, lighting classes L1, L3 and L5 apply. The recommendation is to use lighting classes L5 or L3 on motorways in urban areas. If the motorway situated in an open landscape is equipped with road lighting there should be lighting class L5. In these areas, the lighting should be possible to be reduced or even turned off during limited periods when this is considered appropriate.

3.2.2. Norway

In Norway the recommendations for road lighting is described in *Teknisk planlegging av veg-, gate- og tunnelbelysning* (Statens vegvesen 2013). In the report it is stated that the main objective for road lighting is to improve traffic safety by helping the drivers to handle different tasks, such as:

- position, correct placement on the road
- navigation, have the correct course and/or the right placement sideways on the road
- situations that happens unexpectedly.

Road and street lighting should be installed when its benefit in terms of reduced accidents overweigh the cost of installation and operation. Lighting for other reasons such as public security and comfort are not prioritised and therefore no general criteria are defined.

Table 9 shows if and when there are requirements for lighting for new roads owned by Staten Vegvesen, and based on road class. As can be seen, the two road categories with a speed limit of 100 km/h are the only ones with a '*shall*' requirement, whereas the other road classes have a '*should*' requirement as basis. Many existing roads also need to be illuminated due to presence of unprotected road users and the risk for accidents. The risk for accidents shall be a base for deciding whether the roads should be illuminated or not. The following recommendations for illuminating existing roads are:

- roads ≤ 60 km/h and AADT ≥ 1 500
- roads ≥ 70 km/h and AADT ≥ 8 000
- roads with vulnerable road users but with no separate lanes

Table 9. Requirements of road lighting for new roads (Statens vegvesen 2014).

Road class[1]	AADT	Speed limit (km/h)	Road width (m)	Lanes	Required lighting
H1	0–12 000	60	7.5 / 8.5	2	Should if AADT > 1 500
H2	0–4 000	80	8.5	2	No
H3	0–4 000	90	8.5	2	No
H4	4 000–6 000	80	10	2	No
H5	6 000–12 000	90	12.5	2	Should
H6	> 12 000	60	16	4	Should
H7	> 12 000	80	20	4	Should
H8	12 000–20 000	100	20	4	Yes
H9	> 20 000	100	23	4	Yes
Hø1	0–1 500	80	6.5	2	No
Hø2	1 500–4 000	80	7.5	2	No
Sa1	< 1 500	50	6	2	Should
Sa2	> 1 500	50	6	2	Should
Sa3	< 1 500	80	6.5	2	No
A1		30	3.5 / 5	2	Should
A2		50	7	2	No
A3		50	4	1	No

1) H1–H9 are national main roads and/or other main roads, Hø1 and Hø2 are other main roads, S are collector roads and A are access roads.

To avoid accidents, the following areas should also have lighting; lanes for pedestrians, intersections with pedestrians and cyclists, junctions on a main road, roundabouts, established crossings for wild life such as at openings in wild life fences, stretches shorter than 500 meters between sections of lighting.

Other places that should be illuminated are roads with parallel pedestrian and cycle lanes, intersections that are grade separated, or marked and divided in lanes with a high complexity, road stretches with a high number of wild life crossing, and bridges longer than 100 meters with no separation of pedestrians and cyclists.

Furthermore, with respect to pedestrians and cyclists, roads and streets in a built-up area should normally have lighting. Lighting should also be present in residential areas with low volume traffic due to social aspects and general safety.

Three separate lighting classes are used; MEW, CE and S. MEW are used for roads with a minimum speed limit of 40 km/h. CE applies to roads with a speed limit of 30 km/h and areas with short sight distance, such as intersections, or if other characteristics makes it not possible to use MEW. Class S is used for lanes used by pedestrians or cyclists. For the MEW-classes there are requirements for average luminance, overall luminance uniformity (dry and wet road surface, respectively), longitudinal luminance uniformity, glare and the illumination of the surrounding environment. Table 10 presents these requirements. For residential roads, pavements and cycle tracks in Norway there are requirements for average and maintained illuminance, see Table 11.

Table 10. Lighting classes for traffic routes in Norway (Statens vegvesen 2014).

Lighting class	Luminance of the road surface				Disability glare	Lighting of surroundings
	Dry			Wet		
	$\bar{L}$ [min]	U_o [min]	U_l [min]	*Uov* [min]	*TI* [max]	*SR* [min]
MEW1	2.00	0.40	0.60	0.15	10	0.50
MEW2	1.50	0.40	0.60	0.15	10	0.50
MEW3	1.00	0.40	0.60	0.15	15	0.50
MEW4	0.75	0.40	0.60	0.15	15	0.50
MEW5	0.50	0.35	0.40	0.15	15	0.50

Table 11. Lighting classes for residential roads, pavements and cycle tracks in Norway (Statens vegvesen 2014).

Lighting class	Average illuminance [min lx]	Illuminance maintained [min lx]
S1	15.0	5.0
S2	10.0	3.0
S3	7.5	1.5
S4	5.0	1.0
S5	3.0	0.6
S6	2.0	0.6

The basic recommendations for the lighting class to choose are based on AADT, speed limit and if the lanes are separated or not, see Table 12.

Table 12. Lighting recommendations for traffic routes in Norway (Statens vegvesen 2014).

Road	AADT	Lighting class
Separated with railing or a middle section	1 500–4 000	MEW3
	> 4 000	MEW3
Not separated, speed limit > 40 km/h	< 1 500	MEW4
	1 500–4 000	MEW3
	> 4 000	MEW2
Speed limit 30 km/h	< 1 500	CE4
	1 500–4 000	CE3
	> 4 000	CE2

Motorways and other roads where the lanes are separated normally have a simpler traffic environment than roads with lanes that are not separated by railings or a mid-section. Thereby the lighting class is also lower for these type of roads. However, it is also recommended not to choose a lighting class that is of too low quality on lane-separated roads where the traffic load is high and the mid-section is narrow. This is due to the risk of glare from oncoming traffic. The lighting class should be high enough to allow drivers to use low beam to lower the risk for glare. As also can be seen in Table 12, the lighting class is higher, the larger the traffic volume is.

Other recommendations are that one lighting class higher should be chosen for road areas that are complex, such as the presence of lanes for pedestrians or complex intersections, for road stretches with difficult traffic conditions, and on routes with many vulnerable road users or distracting ambient light. The possibility to reduce the lighting, either stepwise or by dimming, during certain times should be evaluated. An example of such an occasion is late at night when the traffic volume can be considered low as well as the presence of pedestrians and cyclists. Reducing the light levels are especially interesting when the luminance levels are higher than 1.00 cd/m^2. The following criteria should, however, be fulfilled:

- MEW5 for roads separated with railings or midsections
- MEW4 for roads not separated
- CE for residential streets with a speed limit of 30 km/h.

In Norway there are also areas where there are several road tunnels and for those areas the luminance of the roads at night should be adapted to the luminance in the tunnels.

Intersections should have the same lighting level as the main road and should be illuminated at a distance corresponding to the stop distance. However, for complex or important intersections one lighting class higher should be chosen. If the roads leading into the intersections are not illuminated the intersection should be transition zones where the luminance level in the crossing is over 1.00 cd/m^2.

3.2.3. Finland

In Finland, the decision as to whether a rural road should be illuminated is defined according to that the economic benefit should outweigh the cost. The basis for calculating the benefits of road lighting installations is the reduction in night-time accidents due to road lighting, which reduces personal injury and fatality. Time and vehicle cost savings are not considered. The cost comprises of construction, energy use and maintenance, and the time-period considered is generally 30 years.

Finnish guidelines for road lighting is given by *Maantie- ja rautatiealueiden valaistuksen suunnittelu* (Hautala et al. 2014)[2]. In order for a road to be illuminated, the traffic volumes need to exceed a limit value of the AADT. This value depends on the accident rate and also on an estimation of how much road lighting could reduce accidents. Therefore, the limit value differs depending on different road types, such as motorway, two-lane roads, number of connections per km, etc. However, road lighting could also be installed on roads for specific reasons, for instance if they are poorly lined, levelled, if the road section is narrowing, if the environment is bright, etc. In these cases, the traffic volume should be at least 60% of the limit value of the AADT for the specific road. For urban roads consideration should also be taken to narrowness, presence of pedestrian crossings, parked vehicles, closeness to a school or kindergarten, as well as the comfort aspect. The used traffic volumes should be the predicted values 10 years from the current traffic volume.

Besides the profitability aspect of lighting, motorway areas that should be illuminated are those with high complexity such as roundabouts, road interchange ramps, grade-separated junctions, and crossings. In urban areas, the areas that should be illuminated regardless of traffic volume are for example tunnels and other enclosed section of the road with a length of more than 25 m, open bridges, roads and urban structure in the built-up area of the highways and main roads, if there are less than 500 m in length between illuminated units or illuminated connections, high traffic on main roads with ramp connections and other important connections such as a hospital and a school.

For pedestrian and cycle lanes the road lighting can be used to illuminate both road and lanes in case they are close to each other. Separated lighting should be used when the road lighting is not sufficient. If there are parallel lighting it should not interfere with the main road in the optical and visual guidance. Therefore, a separate pedestrian and bicycle path lighting will rarely be present if the main route is not illuminated.

The cost-benefit aspect only depicts if a road should be illuminated and it does not state what lighting class to use. This depends on the road and traffic characteristics. In Table 13, the typical lighting class per road type is described. The technical characteristics for the lighting classes are presented in Table 14. The criteria for what lighting class to choose are that the lighting must be of such a level that the road user is detected in time, and that they should also get a correct view of their own position, as well as own motion and speed, compared to other road users. The requirements also include the need for drivers to detect pedestrians and cyclists. Since the demand varies between different traffic conditions, so does the required level of illumination.

[2] A revised version of the Finnish guidelines was published in 2015

Table 13. Road type and lighting class (Hautala et al. 2014).

Road class	Lighting class
Dual carriageway main roads	
Urban	M2
Rural	M3a
Road with an overtaking lane, guardrail	
Rural	M3b
Regional four lane road	
With intersection - Urban	M1
With intersection - Rural	M2
Interchange – Urban	M2
Interchange –Rural	M3a
Two lane road with guardrail	
Urban	M3b
Single carriageway roads	
Highways and main roads	M3b
Regional and connecting roads	M4

Table 14. Lighting classes for traffic routes in Finland (Hautala et al. 2014).

Lighting class	Luminance of the road surface				Disability glare	Lighting of surroundings
	Dry			Wet		
	$\bar{L}$ [min]	U_o [min]	U_l [min]	U_o [min]	*TI* [max]	*SR* [min]
M1	2.00	0.40	0.60	0.15	10	0.40
M2	1.50	0.40	0.60	0.15	10	0.40
M3a	1.00	0.40	0.60	0.15	15	0.40
M3b	1.00	0.40	0.40	0.15	15	0.40
M4	0.75	0.40	0.40	0.15	15	0.40
M5	0.50	0.40	0.40	0.15	15	0.40
M6	0.30	0.35	0.40	0.15	15	0.40

The P-classes, which are identical to those presented in Table 3, are for residential roads, parking lots, pedestrian and cyclists lanes and for other areas next to a road.

All new street lighting and all the street lighting which is renewed should be possible to dim and there are also recommendations of dimming schedules, see Table 15. Table 15 describes an intermittent reduction of lighting classes using a two-step method, recommended for LED (light emitting diode) lights, or a one-step dimming strategy used for other lights, such as HPS (high pressure sodium) lights, where the intermediate steps in brackets are not used. The quality of the lighting class is reduced by not more than two steps and can occur during dark periods when the traffic volume is low. At the one-step dimming is implemented when the traffic per hour less than 2% of the daily average traffic

(AADT). For the two-step strategy the lighting class is reduced by one when the traffic per hour is below 3% of AADT, and one more when traffic per hour is below 1% of AADT. The option of switching of road lighting is a possibility but dimming should be used when possible.

There is also a recommendation to dim the lighting during periods when the road or the road side is covered in snow and the road surface is dry, since snow increases the luminance. However, this shall only be done if the snowy period is expected to be carried over sufficiently long periods of time. One rule of thumb is that dimming can begin when the snow is assumed to be left on the ground for at least a week. Dimming will not stop for one or two days of thaw but will be terminated in case the lanes are wet for several days due to an increase in temperature or to salting.

Table 15. Variable lighting schemes (Hautala et al. 2014).

Lighting class	Variabel lighting	The average luminance %
M1	M1 – (M2) – M3 – (M2) – M1	100 – (75) – 50 – (75) – 100
M2	M2 – (M3) – M4 – (M3) – M2	100 – (70) – 50 – (70) – 100
M3a	M3 – (M4) – M5 – (M4) – M3	100 – (75) – 50 – (75) – 100
M3b	M3 – (M4) – M5 – (M4) – M3	100 – (75) – 50 – (75) – 100
M4	M4 – (M5) – M6 – (M5) – M4	100 – (70) – 40 – (70) – 100
M5	M5 – (M6) – P5 – (M6) – M5	100 – (60) – 40 – (60) – 100
M6	M6 – P6 – M6	100 – 50 – 100

3.2.4. Austria

In Austria the guidelines for lighting classes are based on the road lighting standards defined in CIE 115:2010 (CIE 2010). Four different light categories are used for roads and areas close to roads; ME for motorized drivers for use on traffic routes, see Table 16; C for drivers of motorized vehicles in conflict areas; P and HS for pedestrians and cyclist for use on areas such as footways and cycle tracks.

Table 16. Lighting classes for dry traffic routes in Austria.

Lighting class	Luminance of the road surface			Disability glare	Lighting of surroundings
	Dry				
	$\bar{L}$ [min]	U_o [min]	U_l [min]	*TI* [max]	*SR* [min]
ME1	2.00	0.40	0.70	10	0.5
ME2	1.50	0.40	0.70	10	0.5
ME3a	1.00	0.40	0.70	15	0.5
ME3b	1.00	0.40	0.60	15	0.5
ME3c	1.00	0.40	0.50	15	0.5
ME4a	0.75	0.40	0.60	15	0.5
ME4b	0.75	0.40	0.50	15	0.5
ME5	0.50	0.35	0.40	15	0.5
ME6	0.30	0.35	0.40	15	-

In Table 17 there is a description of the different road classes. To decide upon which lighting class to apply, this table is used together with

Table 18. For instance, for a road class type A2, with an AADT of more than 7000, less than 3 crossings per km and that is a conflict area the lighting class is ME3a. The ‘o’ in Table 18 represents a standard value. If it is decided that the lighting could be of lower quality or if there is a need for a higher quality, the lighting classes in the column marked ‘<’ and ‘>’ respectively, should be used.

Table 17. Road classes in Austria.

Road class	Speed (km/h)	Main road user	Other road users	Forbidden road users	Use
A1	> 60	Motorized drivers		Slow vehicles, Cyclists, Pedestrians	Motorway and motor vehicle road
A2			Slow vehicles	Cyclists, Pedestrians	Upgraded rural road with separate lanes for cyclist and pedestrian
A3			Slow vehicles, Cyclists, Pedestrians		Minor rural road
B1	30–60	Motorized drivers, Slow vehicles	Cyclists, Pedestrians		Main road, connecting road, collective road
B2		Motorized drivers, Slow vehicles, Cyclists	Pedestrians		
C1	5–30	Cyclists	Pedestrians	Motorized drivers, Slow vehicles	Cycle lanes, cycle/pedestrian lanes
D1	5–30	Motorized drivers, Pedestrians		Slow vehicles, Cyclists	Motorway rest area
D2			Slow vehicles, Cyclists		Station square, bus stop, parking space
D3		Motorized drivers, Pedestrians	Slow vehicles, Cyclists, Pedestrians		Residential streets, 30 km/h zone usually with walk way
D4		Motorized drivers, Slow vehicles, Cyclists, Pedestrians			Residential streets, 30 km/h zone usually without walk way

Table 18. Example of road class and the corresponding lighting class, Road class A2.

Crossing per km	AADT					
	< 7000			≥ 7000		
	<	o	>	<	o	>
< 3	ME5	ME5	ME4a	ME4a	ME3a	ME3a
≥ 3	ME5	ME4a	ME3a	ME4a	ME3a	ME2

A2 Complimentary table					
Conflict area	Visual complexity	Difficulties to drive	Surrounding luminance		
			low	middle	high
no	normal	normal	<	<	o
		higher	o	o	>
yes			>		

3.2.5. United Kingdom (UK)

British guidelines for road lighting design are given by *Code of practice for the design of road lighting* (BSI 2013). There is no statutory requirement to provide road lighting or to install a particular road lighting class, but there are statutes that empower highway authorities to light roads. Thus, authorities such as city councils may have their own lighting requirements. The guidelines presented below (BSI 2013) are advisory.

For traffic routes, there are recommendations for average luminance, overall uniformity of luminance, longitudinal uniformity of luminance, threshold increment and surround ratio or edge illuminance ratio, either for the ME, CE and P classes defined in BS EN 13201-2:2003 or for the M, C and S classes defined in CIE115:2010. The ME classes can be found in Table 19, while the M classes are shown in Table 1.

Table 19. Lighting classes for dry traffic routes in the UK (BS EN13201:2003).

Lighting class	Luminance of the road surface			Disability glare	Lighting of surroundings
	Dry				
	$\bar{L}$ [min]	U_o [min]	U_l [min]	*TI* [max]	*EIR* [max]
ME1	2.0	0.40	0.70	10	0.50
ME2	1.5	0.40	0.70	10	0.50
ME3a	1.0	0.40	0.70	15	0.50
ME3b	1.0	0.40	0.60	15	0.50
ME3c	1.0	0.40	0.50	15	0.50
ME4a	0.75	0.40	0.60	15	0.50
ME4b	0.75	0.40	0.50	15	0.50
ME5	0.5	0.35	0.40	15	0.50
ME6	0.3	0.35	0.40	15	-

The selection of lighting classes for traffic routes is based on the parameters design speed, traffic flow, single/dual carriageway, and junction density. The recommendations for the most common road types are shown in Table 20. The highest lighting class, ME2, is recommended for high speed roads with high traffic flow. For most traffic routes, the recommended luminance is 0.75–1.0 cd/m^2. The selection process prescribes that a risk assessment is carried out to identify specific lighting needs, which may lead to an adjustment of the lighting class recommended by Table 20. Risk parameters are traffic composition, parked vehicles, bus stops, pedestrian crossings, ambient luminance and poor visual guidance.

The CE and C classes are intended for conflict areas. The lighting level in the conflict area is determined by the highest lighting class (M/ME) of the connecting traffic routes. A conversion table is used to convert the M/ME classes to C/CE classes.

Table 20. Lighting recommendations for traffic routes in the UK (BSI 2013).

Design speed	Traffic flow	Carriageway	Junction density	Lighting class
> 40 mph	High to very high, ADT > 40 000	Dual	High	ME2
			Low	ME3b
		Single	-	ME2
	Low to moderate, ADT ≤ 40 000	Dual	High	ME3b
			Low	ME4a
		Single	-	ME3b
≤ 40 mph	High to very high, ADT > 40 000	Dual	High	ME3b
			Low	ME4a
		Single	-	ME3b
	Low to moderate, ADT ≤ 40 000	Dual	High	ME4a
			Low	ME5
		Single	-	ME4a

For subsidiary roads including pedestrian areas, footpaths and cycle tracks, either the S classes (Table 21) or the P classes (P1–P6 in Table 3) are used. The selection parameters include traffic flow and ambient luminance. For subsidiary roads where the typical speed is ≤ 30 mph, the recommended lighting class increases with traffic flow and ambient luminance, while for roads with mainly slow-moving vehicles, cyclists and pedestrians, the determining parameter is traffic flow. Similar to the selection process for traffic routes, a risk assessment is recommended which includes the parameters traffic composition, complexity of task, risk of crime and need for facial recognition. Presence, or absence, of risk factors suggests that the lighting class is adjusted by one class. In a third step, adjustment for the light source can be made. If the light source has a high S/P ratio (cool white light), the requirement on illuminance is lower than for traditional light sources.

The British guidelines list four measures to minimize electrical energy use: variable lighting (e.g. reducing light between certain hours), trimming (adjustment of switch on/off times), part-night (lighting is turned off between certain hours) and switch off (lighting is removed). Selection of lighting classes for variable lighting is suggested to be done according to the same principles as for static lighting. Some of the parameters, such as traffic density or ambient luminance, can change throughout the night, which gives the possibility to vary the lighting level.

Table 21. Lighting classes for residential roads, pavements and cycle tracks in the UK (BS EN13201:2003).

	Horizontal illuminance	
Class	$\bar{E}$ [min]	E_{min} [min]
S1	15.0	5.0
S2	10.0	3.0
S3	7.5	1.5
S4	5.0	1.0
S5	3.0	0.6
S6	2.0	0.6

3.2.6. USA

In US, there are variations of the standards used in different states. According to Boyce (2009) many states are using the recommended practice described in IESNA (2005). Roads are classified into five major classes, namely Freeway; Expressway; Major; Collector; and Local. A sub division of these classes, except freeways, is made according to pedestrian area conflict. These are defined as low (< 10 pedestrians), medium (10–100) and high (> 100) and describes the number of pedestrians walking on both sides over a 200-meter section of a road during the first hour after dark. Also, the people crossing the road anywhere besides at an intersection is included. In addition to the six main road classes there is also a class for isolated traffic conflict areas, for instance intersections on otherwise unlit roads.

There are three different metrics recommended for road lighting. All are minimum criteria that shall be maintained over the installation lifetime. The metrics are illuminance of the road, luminance of the road as seen by the driver and small target visibility for the driver. In Table 22, the luminance criteria for the different road classes is presented. In general, the luminance recommendations increase as the pedestrian conflict class goes from low to high. The highest luminance level is recommended for major road where the pedestrian conflict is high. Also, the more the roads become defined as residential, the luminance uniformity is relaxed.

Table 22. Luminance criteria classes for road classes used in parts of the USA (IESNA 2005).

		Luminance of the road surface		
Road class	Pedestrian conflict class	$\bar{L}$ [min]	U_o [min]	U_l [min]
Freeway A)	-	0.6	0.29	0.17
Freeway B)	-	0.4	0.29	0.17
Expressway	High	1.0	0.33	0.20
	Medium	0.8	0.33	0.20
	Low	0.6	0.29	0.17
Major	High	1.2	0.33	0.20
	Medium	0.9	0.33	0.20
	Low	0.6	0.29	0.17
Collector	High	0.8	0.33	0.20
	Medium	0.6	0.29	0.17
	Low	0.4	0.25	0.13
Local	High	0.6	0.17	0.10
	Medium	0.5	0.17	0.10
	Low	0.3	0.17	0.10
Isolated traffic conflict area	-	0.6	0.29	0.17

A) Divided major road with full control of access. High visual complexity, high traffic volumes.

B) Divided major road with full control of access.

For intersections between any combination of major, collector and local roads there are illuminance recommendations. The reason why there are none for freeways and expressways is that there either are no intersections or they are controlled by traffic signals. The recommendations follow the same reasoning as for illuminance and luminance for continuously lit roads. The higher the level of conflict area, the higher the illuminance. The principle is that the average illuminance should be equal to the sum of the recommended values for the intersecting roads (assuming R2 or R3 road surface)[3].

3.2.7. Canada

In the state of Alberta, it is stated in the guide for highway lighting that the primary objective of roadway lighting is to enhance vehicle safety by providing drivers with improved night-time visibility of roadway conditions and potential hazards (Alberta Transportation 2003). This is done by improving the night-time visibility of roadway conditions and potential hazards. However, it is also recognized that road lighting may create conditions where the driver's vision must adjust back to darkness when leaving the lighted area. Therefore, the decision to provide roadway lighting must be based on a documented need and the application of appropriate criteria.

In the guide for highway lighting, the roads are divided into five main road classes: Freeways, Expressways, Arterials, Collectors and Locals (Alberta Transportation 2003). These road classes are

[3] R-values for road surfaces describes the roadway's reflective characteristics, defined by its physical surface properties.

divided into area classes: Urban, Suburban or Rural[4]. Luminance criteria should be the primary method of report lighting levels. However, illuminance may be used for situations with roadway curves and high mast lighting.

In Table 23 the design lighting levels that apply to different roadways and area classes are described. These apply to the main roadway sections but may require adjustments for special situations such as cross walks and other pedestrian areas, and tunnels.

For instance, if rural and suburban highways are passing through high pedestrian situations the lighting designer should use the next higher area class to account for these situations.

Table 23. Design lighting levels, Alberta, Canada.

Roadway class	Area class	$\bar{L}$ [min]	Max Luminance uniformity ratio [Ave/Min]	Max Luminance uniformity ratio [Max/Min]
Freeways	Urban	0.6	3.5:1	6:1
	Suburban/Rural	0.4	3.5:1	6:1
Expressways	Urban	1.0	3:1	5:1
	Suburban	0.8	3:1	5:1
	Rural	0.6	3.5:1	6:1
Arterials	Urban	1.2	3:1	5:1
	Suburban	0.9	3:1	5:1
	Rural	0.6	3.5:1	6:1
Collectors	Urban	0.8	3:1	5:1
	Suburban	0.6	3.5:1	6:1
	Rural	0.4	3.5:1	6:1
Locals	Urban	0.6	3:1	6:1
	Suburban	0.5	6:1	10:1
	Rural	0.3	6:1	10:1

In an area where lighting is installed and has a significant wildlife concern, lighting the areas past the roadway edge should also be considered. This will assist in detecting wildlife entering the roadway and help in avoiding a collision.

3.3. Discussion about differences between countries

The similarities between the lighting classes in the different countries and their criteria for choice are that the recommended illumination increases with the complexity of the road traffic situation. The level of light depends on the type of road, number of lanes, speed, traffic composition, intersection type, etc. In urban areas the main recommendation is that all roads should be illuminated.

For rural roads, the main rule is no road lighting. There are, however, exceptions such as at signal-controlled intersections, at roundabouts and at other major intersections. One area where the recommendations for illuminating roads differ substantially between countries is regarding motorways. While motorways in Norway are always illuminated, this is not the case for the other

[4] The exception is freeways that is divided into Urban or Suburban/Rural.

countries. In Sweden and Denmark, the recommendations are that they should not be equipped with road lighting. Also, the recommended luminance levels when the motorway is illuminated (including motorways in urban areas) differs. In Sweden it is 1.0–2.0 cd/m^2, in UK 0.75–1.5 cd/m^2 while it in the US is 0.4–1.0 cd/m^2 and in Norway 1.0 cd/m^2.

In Nørgaard Andersen (2013), a compilation is presented of the regulations for road lighting on small and medium traffic roads in the Nordic countries (i.e., Sweden, Norway, Denmark and Finland). In general, the MEW-classes listed in EN 13201-2:2003 have been implemented. However, there are differences between the countries. Type of road, traffic volume, type of traffic, speed limit, geometry of the road and presence of vulnerable road users are all bases for selecting lighting class. The differences can be found in the use of longitudinal uniformity, in the requirements for areas close to carriageways and in the restrictions for glare. Denmark differs from the EN-13201-2 in that restrictions are tighter regarding disability glare, where the recommended figures are lower in all lighting classes. Also, the luminance of dry roads and lighting of surroundings varies; and Denmark has its own recommendations for lighting the surrounding areas of a road. Finland has deviating values of luminance for the lighting classes with lower quality, whereas both Sweden and Norway for the main part follow the EN standard, with a few exceptions.

Energy conservation is mentioned in several of the guidelines for road lighting. In Denmark and Norway, the possibility to reduce lighting during some parts of the dark period should be evaluated and executed in case it is deemed possible, and new lighting instalments should have the possibility to be dimmed. In Finland, all new road lighting should be equipped with the possibility to dim and there is a recommendation of how and when the dimming should occur. In Alberta, Canada the recommendations are that the least amount of lighting infrastructure should be used for efficiency reasons. The minimum lighting requirements of this guide should be met and they should not be exceeded by more than 10% whenever possible, i.e. where there are no conflict areas.

In the UK and in the code of practice for the design of road lighting, the energy efficiency is an aspect when choosing light source. According to this, considerations should be given, not only to the efficacy in lm/W, but also to the efficiency of the complete lighting installation, where the effectiveness of the lamp and luminaire combination should be accounted for in the possibility to provide the selected class for lighting and the desired degree of colour rendering. Furthermore, for energy saving, dimming should be considered when the demands of lighting are low. This is also valid the other way, that whenever the demand for lighting is high it should be possible to increase the lighting, i.e., for safety reasons. The optimal solution for lighting should normally take into account operating cost, capital cost, energy use as well as environmental-technical and aesthetic issues in meeting the performance requirements and should be selected to minimise whole life-cost and energy use.

In Austria the guidelines state that from an energy-efficiency and environmental perspective, a lighting installation should have a lighting level that matches the minimum required value of the relevant lighting class, as well as meeting all other relevant requirements. In case a road section is equipped with significantly higher lighting level than those required or specified, corrective actions should be taken to minimise any over-lighting with respect to the energy efficiency and environment. Furthermore, variable lighting control is useful to optimise the energy use when considering the depreciation of the installation over time.

One hypothesis is that a possible reason to why the recommendations for lighting differs between the countries is the variation in the electricity price, i.e. a low cost for the electricity per kWh would mean more illumination of the roads. Figure 1 shows the cost of electricity in €/kWh (including and excluding taxes and levies) for the second semester in 2013 in the European countries included in the present report. The cost is adjusted according to the purchasing power standard (PPS), which means that it reflects the same purchasing power in the EU25. The presented electricity prices are those representative for industry with an annual use of 500 to 2,000 MWh electricity. As can be seen, the variations of the electricity price is quite high. When looking at prices including taxes and levies, Denmark stands out, with a more than 2.5 times higher cost than Sweden, Finland and Norway.

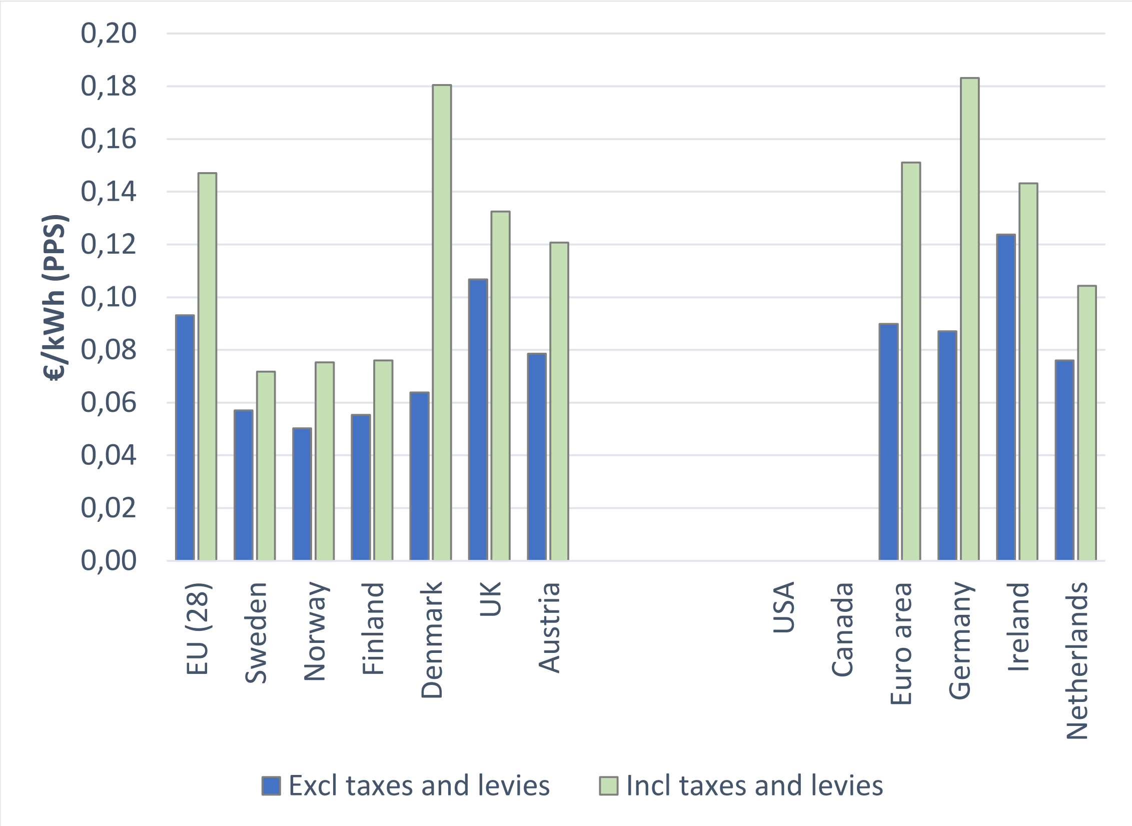

Figure 1. Electricity prices 2013:2, Industry 500-2000 MWh, Purchasing Power Standard.

The electricity prices in US and Canada are relatively low compared to several of the European countries. A study, where the purchasing power parity was used, showed that the relative price of electricity was 0.08 and 0.12 USD/kWh in Canada and US respectively in 2011[5]. This was considerable lower than the price in Denmark, 0.28 USD/kWh, and UK, 0.20 USD/kWh the same year.

To evaluate if there is a dependency between electricity price and road lighting the price is related to electricity use per km road for road lighting. A brief description of the road network for some countries are presented below as well as estimated electricity use for illuminating the roads. In Figure 2 the electricity prices [€/kWh PPS] is benchmarked with respect to total road length and annual electricity use for road lighting [MWh/km]. As can be seen in Figure 2, the use of road lighting in MWh/km and year looks like it can be dependent on the level of electricity price. The countries with the lowest electricity price also have the highest use of road lighting, and vice versa. However, the data that is used as a basis for the figure is uncertain, especially regarding the amount of electricity that is used for road and street lighting in each country since this data have not been subject to be specifically collected and reported. However, the result indicate that it could be of interest to further investigate this matter.

[5] http://theenergycollective.com/lindsay-wilson/279126/average-electricity-prices-around-world-kwh (2014-07-21)

Sweden has in total 140,100 km roads and streets. 41,600 km are owned by the municipalities and 98,500 km roads are governed by the Swedish Transport Administration. Of the national governed roads are:

- 2330 km motorways or highway
- 200 km 4 lane roads
- 95,930 km two-lane roads.

Approximately 2 million lights are installed, of which 200,000 is owned by the transport administration and 75,000 is municipal lights by public roads. The rest is municipally owned light along municipal roads (Swedish Transport Administration).

In Finland, the estimated annual energy use of outdoor lighting is 800 GWh, (1% of the country's total electricity use). The estimated number of outdoor luminaires is 1.3 million of which 51% are HPM (high pressure mercury) lamp luminaires and 45% are HPS. The rest are LPS (low pressure sodium), MH (metal halide) and induction lamp luminaires. Total length of roads in Finland is 104,000 km excluding private roads and forest roads. Municipalities are responsible for 26,000 km and the Transport Administration have 78,000 km of roads, 700 km of which is motorways, 12,300 is primary roads and the remainder is regional and connection roads.

In Denmark the electricity use for street and road lighting amounted to 382 GWh in 2009, which is app. 1.2% of the total electricity use (Dansk Energi 2010). The road network in Denmark 2014 consists of 3797 km that Vejdirektoratet have authority over[6]. Adding to those are 41 km handled by public companies and 70,569 km that municipalities are governing. The length of numbered roads is:

- Europe roads 943 km
- primary roads 3220 km
- secondary roads 5947.

The Norwegian public road network was 93,815 km in 2013 and consists of:

- national roads 10,446 km of which 750 km is motorway
- county roads 44,333 km
- municipal roads 39,036 km.

Road lighting equipment in Norway is made up by approximately 1.2 million units that in total is estimated to use 2 TWh per year. Of these, road lighting is using 760 GWh plus 140 GWh for tunnels (Lio 2012).

In the UK in 2007, app 2.5 TWh electricity was used by road lighting and traffic signals (Boyce et al. 2009). According to other studies, about 70% of the electricity consumption by road side equipment is due to road lighting (Stockbridge 2010). This leads to an estimation of 1.75 TWh electricity use for illumination roads and streets. The length of roads in the UK amount to about 302,100 km (Department for Transport statistics, Table RDL0201) divided into:

- major roads 35,343 km

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[6] http://www.vejdirektoratet.dk/da/viden_og_data/statistik/vejeneital/l%C3%A6ngdeoffentligeveje/sider/default.aspx (2014-07-23)

- motorway 3043 km
- major roads rural 22,643 km
- major roads urban 9657 km

- minor roads 266,750 km
  - rural 153,624 km
  - urban 113,126 km

- minor roads 266,750 km
  - rural 153,624 km
  - urban 113,126 km

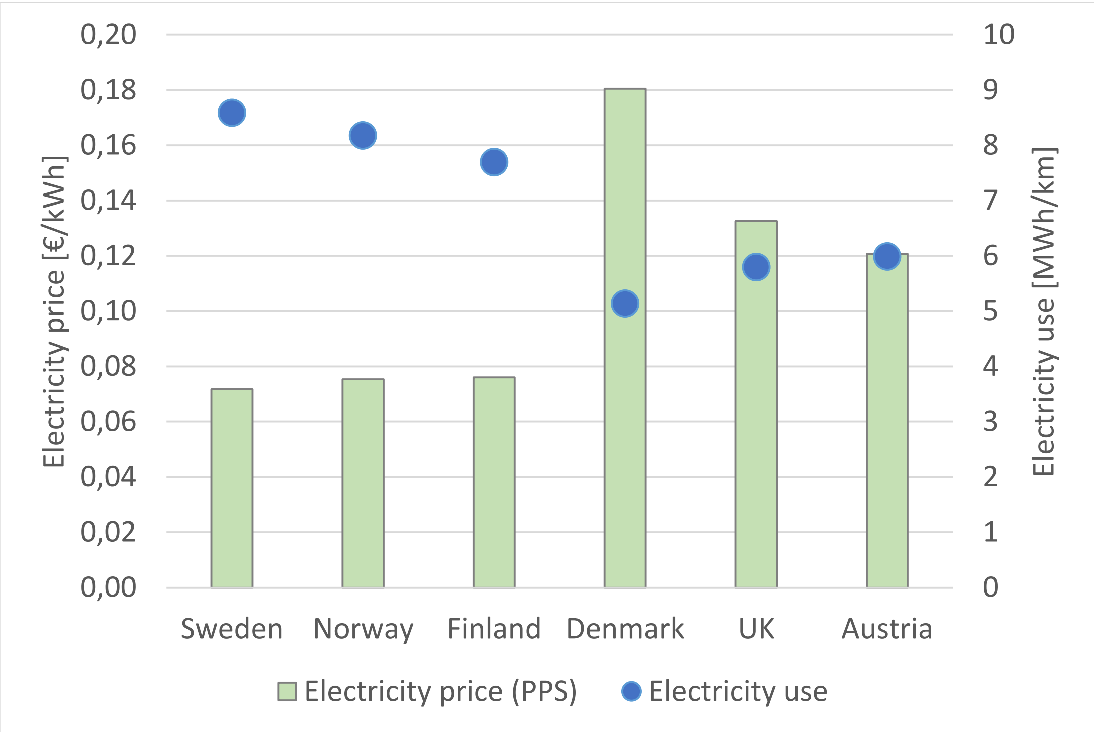

Figure 2. Benchmarking electricity prices [€/kWh PPS] with respect to road length and annual electricity use for road lighting [MWh/km].

4. New CEN technical report for selection of lighting classes

The technical report CEN/TR 13201-1:2014 *Guidelines on selection of lighting classes* (CEN 2014) suggests a method for selection of lighting classes for the M, C and P classes, based on a number of parameters related to the road characteristics and the traffic. The method originates in a method described in the CIE report 115:2010 *Lighting of roads for motor and pedestrian traffic* (CIE 2010).

It is emphasized in CEN/TR 13201-1 that the suggested selection method should be seen as a starting point and that other factors should perhaps be taken into account. It is also recommended that the method should be adapted to a national level, for example by incorporating the national classification system of roads. Further, the values stated in the report should be seen as examples and they may thus be modified in order suit the needs in a specific country.

4.1. M and C classes

For the M classes, the road is classified according to eight parameters, shown in Table 24. The appropriate weighting values V_w for each of the eight parameters are selected and added to a sum V_{ws}. The number of the lighting class M is then calculated as:

$$\textit{Number of lighting class } M = 6 - V_{ws}$$

If the sum V_{ws} is < 0, the value 0 should be applied. If the resulting class number is ≤ 0, the lighting class M1 should be applied.

Table 24. Parameters for the selection of lighting class M.

Parameter	Options	Description*		Weighting value V_w
Design speed or speed limit	Very high	$v \geq 100$ km/h		2
	High	$70 < v < 100$ km/h		1
	Moderate	$40 < v \leq 70$ km/h		−1
	Low	$v \leq 40$ km/h		−2
Traffic volume		Motorways	Two lane routes	
	High	> 65% of max**	> 45% of max	1
	Moderate	35–65% of max	15–45% of max	0
	Low	< 35% of max	< 15% of max	−1
Traffic composition	Mixed with high percentage of non-motorized			2
	Mixed			1
	Motorized only			0
Separation of carriageway	No			1
	Yes			0
Junction density		Intersection/km	Interchanges, distance between bridges, km	
	High	> 3	< 3	1
	Moderate	≤ 3	≥ 3	0
Parked vehicles	Present			1
	Not present			0
Ambient luminosity	High	Shopping windows, advertisement expressions, sport fields, station areas, storage areas		1
	Moderate	Normal situation		0
	Low			−1
Navigational task	Very difficult			2
	Difficult			1
	Easy			0

*) The values stated in the column should be seen as examples. Any adaptation of the method or more appropriate weighting values can be used instead, on the national level

**) Percentage of maximum capacity

For conflict areas for motorized traffic, i.e. intersections, roundabouts or changes in road geometry (reduced number of lanes etc.), where the road layout does not allow calculation of road surface luminance, the lighting classes C are applied. CEN/TR 13201-1 provides a conversion table where M classes selected from Table 24 can be converted to a corresponding C class, taking the brightness of the road surface into account. It is advised that the conflict area should have a lighting level no lower than that of the highest lighting class of the connecting roads. As a recommendation, the lighting used for a conflict area should normally be of one class higher than the lighting with the highest lighting class of the connecting roads.

For certain conflict areas such as city centres and for conflicts areas where there is no lighting on the connecting roads, CEN/TR 13201-1 provides a table similar to that for the M classes (Table 24). The differences are that in the C class selection method, speed has a somewhat higher weight and the parameter “Junction density” has been excluded.

4.2. P classes

For pedestrian and low speed areas, the lighting classes P are applied. The suggested selection method for the P classes is shown in Table 25. The number of the lighting class P is calculated as:

$$\textit{Number of lighting class } P = 6 - V_{ws},$$

where V_{ws} is the sum of the weighting values V_w. If the sum of the weighting values V_{ws} is < 0, the value 0 should be applied. If the result P is 0 the lighting class P1 should be applied.

Table 25. Parameters for the selection of lighting class P.

Parameter	Options	Description*	Weighting value V_w
Travel speed	Low	v ≤ 40 km/h	1
	Very low	Walking speed	0
Use intensity	Busy		1
	Normal		0
	Quiet		−1
Traffic composition	Pedestrians, cyclists and motorized traffic		2
	Pedestrians and motorized traffic		1
	Pedestrians and cyclists only		1
	Pedestrians only		0
	Cyclists only		0
Parked vehicles	Present		1
	Not present		0
Ambient luminosity	High	Shopping windows, advertisement expressions, sport fields, station areas, storage areas	1
	Moderate	Normal situation	0
	Low		−1
Facial recognition	Necessary		-**
	Not necessary		-**

*) The values stated in the column should be seen as examples. Any adaptation of the method or more appropriate weighting values can be used instead, on the national level

**) Specific guidelines on the use of facial recognition parameter are defined at national level for each country

5. Parameters and criteria for road lighting – A literature review

5.1. The purposes and effects of road lighting

5.1.1. The effectiveness of road lighting

The traditional assumption that road lighting reduces the number of accidents by about 30% (CIE 1992) has been examined and reviewed in some newer studies. In a Norwegian thesis on the effects of road lighting, it was concluded that this estimate still holds and that road lighting is an effective safety measure (Wanvik 2009b). Wanvik (2009b) also concluded that the effect of road lighting tends to be somewhat different for different road types, that the effect is larger for pedestrian accidents than for other accidents and that road lighting is less effective in adverse weather than in fine weather.

In 2010, the Cochrane Collaboration published a systematic review on the effects of road lighting on injuries caused by road traffic crashes (Beyer & Ker 2010). The review included 17 controlled before-after studies, 12 of which investigated the effects of newly installed lighting, four investigated the effects of improved lighting and one investigated both new and improved lighting. Out of the 17 studies, 15 were included in meta-analyses of crash rate ratio[7]. In studies with an area control, the pooled rate ratio was 0.45 for total crashes ($n = 3$) and 0.78 for total injury crashes ($n = 2$). In studies with a day-time control, the pooled rate ratio was 0.68 for total crashes ($n = 11$), 0.68 for total injury crashes ($n = 6$), and 0.34 for fatal crashes. It was concluded that the results suggest that street lighting *may* prevent road traffic crashes, injuries and fatalities. The authors however raised a number of concerns regarding the interpretation of the results. First of all, it is pointed out that the methodological quality of the trials generally was poor. Methodological issues raised were inappropriate selection of control area, risk of regression-to-the-mean effects and lack of randomization. Further limitations are that the 15 included studies were conducted in only four countries (USA, UK, Germany and Australia) and that the majority of the studies were published before 1990. To what extent the results are generalizable to other countries or to today's traffic conditions is not known. Moreover, the authors discussed the risk of publication bias, i.e. that only studies with "positive" results are published and available for meta-analysis. Because of the uncertainties in the interpretation of the results, the authors emphasized the need for well-designed studies in order to determine the effectiveness of road lighting (Beyer & Ker 2010).

A similar meta-analysis of the effectiveness of road lighting – although not limited to controlled before-after studies – was carried out by Elvik, Høye et al. (2013). 50 studies (37 of which were published before 1994) on the effects of installing road lighting on previously unlit roads were categorized with respect to crash type, road type, injury type, and road/weather condition. The authors assumed the data material to be influenced by publication bias and hence, categories with a sufficient amount of data have been adjusted for publication bias (marked with an [a] below). The analysis showed a reduction of fatal crashes of about 60% and a reduction of injury crashes of 14%[a]. The effect on pedestrian crashes were larger than the effect on other crash types. For fatal crashes (all crash types), the effect was larger on non-urban roads (87%) than on urban roads (40%[a]), while the opposite was found for injury crashes, i.e. the effect was larger on urban roads (27%[a]) than on non-urban roads (13%[a], n.s.). For crashes involving motorized vehicles (all injury types), the effect was the largest on rear-end collisions, followed by head-on collisions and single-vehicle collisions. The effect on injury crashes in intersections were larger than for other crash types, both on urban (40% vs. 27% [a]) and on rural roads (22% vs. 13% [a]). The effects of road lighting on motorways were in general small. Significant reductions in crashes were only found for intersection collisions (41%) and for rear-end

[7] The rate ratio gives the reduction in the event rate in the intervention area compared to that in the control area. A rate ratio of 0.8 corresponds to a 20% reduction in events.

collisions (20%), while there was no significant reduction in the total number of crashes. The effects of road lighting in relation to road/weather condition were inconsistent. (Elvik, Høye et al. 2013).

The meta-analyses by Beyer and Ker (2010) and by Elvik, Høye et al. (2013) were scientifically well-grounded and they show similar results (they were partly based on the same studies). However, in both publications, methodological issues and the risk of bias in the included studies were discussed. Methodological weaknesses and flaws in studies aiming at estimating the effectiveness of road lighting were further discussed in Sasidharan and Donnell (2013). Therein, a method for estimating countermeasure effects from non-randomized observational data was presented, which showed that roadway lighting reduces intersection crashes by approximately 6%. Without considering confounding variables, the crash reduction would have been 40%. In previous studies (Donnell, Porter et al. 2010; Gross & Donnell 2011), which used different methods but the same database, the reduction in crashes was found to be 11–12%. Unlike many other studies on lighting and safety, the model used in these studies do not assume a linear relationship between accident rate and traffic volume, and they control for confounding variables. The results can be compared to the reduction presented by Elvik, Høye et al. (2013), which was 25% for all crash types in intersections, while individual studies have reported crash reductions of up to 40–50% (Sasidharan & Donnell 2013). A further step towards more reliable models of the safety effects of road lighting was taken in Bullough, Donnell et al. (2013). In their study, the statistical approaches presented in Donnell, Porter et al. (2010) were compared to a model of visual performance, and the results suggest that the visual performance improvements from road lighting could serve as input for predicting improvement in accident rates.

In the book *Lighting for driving: Roads, vehicles, signs and signals* (Boyce 2009), various methods for evaluating the effects of road lighting were discussed and reviewed. It was concluded that it is difficult to examine effectiveness, because it is obvious from available data that accidents have many influencing causes. This conclusion origins from the fact that even high quality studies may have come to inconsistent conclusions, or may only have found weak relationships between road lighting and accident rates. Although it is difficult to obtain a clear relationship between road lighting and accidents, Boyce pointed out that research indicate that some types of accident are more sensitive to reduced visibility. This includes accidents involving unlighted and/or unexpected objects, such as pedestrians and animals, and accidents where the road suddenly changes direction (Boyce 2009).

The difficulties in interpreting and using available data on the effects of road lighting were also discussed in Crabb, Crinson et al. (2009). The aim of the study was to identify improved models of the effect of road lighting on accidents, which could be used in cost-benefit analyses. The study included a literature review and analysis of British accident data. However, despite a thorough and comprehensive approach, the authors were unable to identify such effect models, because other unidentified variables were found to have a significant influence, resulting in large uncertainties in the models. The study demonstrated complex interactions between variables and a lack of independence between presence of road lighting and potential accident rate (roads that can benefit from lighting already has it installed). The analyses that were carried out could not demonstrate any reduction in accidents due to lighting (Crabb, Crinson et al. 2009).

In a report by the *Conference of European Directors of Roads* (CEDR), European research on road lighting and safety was summarized (Breyer, Chambon et al. 2010). It was stated that the research in France and the UK indicates that the benefits of road lighting on rural motorways and on dual carriageways is limited, with the exception of slip road merges and diverges where a significant reduction of personal injury accidents have been observed. In UK, the standard for lighting appraisal was updated in 2007 (TA 49/07). For economic appraisal purposes, road lighting has been assumed to reduce accidents by 30% but in the 2007 update, this figure was changed to 10–12.5% (for motorways and carriageways), based on an extensive and critical review of the old standard (Breyer, Chambon et al. 2010).

In a relatively new observational study, the effect of road lighting on motorways was investigated (Wanvik 2009a). The estimated effect of road lighting on injury crashes was 49% in the Netherlands, while the effect was significantly smaller in Sweden and in Great Britain. These results are not in agreement with the results of the meta-analysis in Elvik, Høye et al. (2013), where only small effects of road lighting on motorways were found. Whether this discrepancy is caused by e.g. a real difference over time or e.g. by some methodological differences is not known. Secondly, and perhaps more importantly, the results raises concern about the generalizability of results between countries. Differences between countries were further discussed in Wanvik's doctoral thesis (Wanvik 2009b), where it was suggested that the quality of the road lighting and the presence of snow may explain the differences in accident rates.

Accidents in darkness, both on lit and unlit roads, constitute a large amount of the total number of accidents among young drivers, but "Time of day" analyses presented in Clarke, Ward et al. (2006) however suggest that the darkness accidents are not a matter of poor visibility, but a rather a matter of how young drivers use the roads at night.

The vast majority of effect studies investigated accident rates in relation to road lighting versus no road lighting. The relationship between lighting level and accident rates has been studied less (Wanvik 2009b; CIE 2010). In the meta-analysis presented in Elvik, Høye et al. (2013), the effects of improving and reducing existing road lighting were investigated. Twenty-five studies, all of which were published before 1994, were included in the analysis. Doubling the lighting level gave no significant reduction in injury crashes or vehicle damage crashes. Increasing the lighting level to 2–5 times the original lighting level reduced injury crashes by 13% and vehicle damage crashes by 9%. Increasing the lighting level to more than five times the original lighting significantly reduced injury crashes by 32% and a non-significant reduction of fatal crashes by 50%. The analysis of the effects of reducing existing road lighting included nine studies, eight of which were published before 1994. Reducing the lighting level by 50% was found to increase the number of injury crashes by 17% and the number of vehicle damage crashes by 27%. It should however be emphasized that the reductions in lighting level in these studies primarily was done by switching off every second lamp, which gives a highly varying road surface luminance. In a relatively recent study, the effects of reducing motorway illumination for energy conservation was investigated (Monsere and Fischer 2008). When lighting was reduced from full to either no lighting or to one direction lighting (on motorway sections), the total night-time crashes increased by 29% and 39%, respectively. At interchanges, where the lighting was reduced (but not switched off), the results were less clear with respect to the effects on crash rates.

The night-to-day-crash-rate-ratio was compared to the road lighting conditions, for a relatively large dataset of approximately 90,000 crashes (Gibbons, Guo et al. 2014a). The results indicated that the night-to-day-crash-rate-ratio decreased with increasing horizontal illuminance and with increasing vertical illuminance, while there were no significant trends in the relationship to vertical-to-horizontal illuminance ratio, uniformity or luminance. Gibbons, Guo et al. (2014a) however stated that there are limitations to the data collected for the analyses and that there was an imbalance in the dataset with respect to roadway criteria and characteristics.

In Mace (1996: as cited in Keck 2001), the relationship between accidents and the three different lighting design criteria used in the US – horizontal illumination, average pavement luminance and small target visibility (STV, see also Section 5.1.3) was investigated. No correlation (n = 56) between night/day accident rate and any of the three design criteria was found. The accident rate however correlated significantly with posted speed limit and the number of lanes.

In summary, the literature indicates that road lighting may reduce the number of crashes, but the size of the effect and the generalizability of the results are uncertain. Many factors contribute to crashes and the cause- and effect relationships are complex, which is reflected in the large spread in results over studies. One aspect of generalizability is whether the results from one country is applicable to another country. Several factors may interact with the effects of road lighting, such as road standard, road delineation (lane markings, road marker posts, cat's eyes), traffic density, climate, use of game fences, use of retroreflective tags and the rate of drunken driving. Most or all of these factors may vary a lot both within and between countries. It might thus not be reasonable to assume that the potential benefits of road lighting are similar in different countries. Older studies indicate relatively large effects of road lighting, with accident reductions in the range of 10–60%. These effects have been questioned in newer studies. First of all, many old (and new) studies have methodological issues, which may have led to overestimations of the effects. Furthermore, traffic safety improves continuously. Today's vehicles and roads are much safer than they were 20 years ago (WHO 2015) and road lighting might thus play a less important role in today's traffic. Some recent studies indicate that the effects of road lighting are substantially smaller than what has been reported previously, but it should be emphasized that there is a lack of high quality studies. The actual effects of road lighting on accident rates are thus to a large extent unknown. In particular, little is known about the effects regarding vulnerable road users, as most literature consider accidents involving motorized road users only.

When it comes to the effects of lighting level on accident rates, even less is known. There are some indications that higher lighting levels may be beneficial, but the results from different studies are not consistent. Besides, most studies were conducted more than 20 years ago. A further limitation is that in many studies, lighting level was manipulated by switching off lamps which results in a poor uniformity which is not desired.

5.1.2. Effects on driving behaviour

A potential effect of road lighting is increased speed. This notion is based on observations of risk compensation in human behaviour, where drivers will adjust their behaviour to a constant level of risk (Wilde 1982; Boyce 2009). This increase in speed tend to diminish the benefits of introducing lighting but not negate it (Elvik 1995).

Average speed was found to increase by 5% on a straight road section and by 1% in curves after the installation of road lighting in Jorgensen & Pedersen (2002). The observed concentration level, measured by lateral variability, decreased significantly while there was no difference in perceived concentration level. Similar results were observed in Assum, Bjornskau et al. (1999), where risk compensation in terms of average speed, concentration and travelled length in the case of road lighting was evaluated. The evaluation of data collected from a road before and after installation of lighting showed that drivers adjusted their behaviour when road lighting is present in that they increased the average driving speed and reduced the concentration level. However, Assum, Bjornskau et al. (1999) also recognized that there is most likely different composition of people driving during night and day respectively, and that different sub-groups of road users compensate in different ways.

In Rudin-Brown & Jamson (2013) two studies of driving behaviour and road lighting is described. One is a pilot study made on a motorway in the Netherlands where an evaluation of changes in speed with different luminance levels was performed for dry and wet road conditions, respectively, and compared with an unlit alternative of the same road section. It was found that the speed increased moderately with the introduction of lighting during both dry and wet road conditions, 1–2 km/h and 3 km/h, respectively, compared to an unlit road. The second study also looked at changes in speed due to presence of road lighting and higher workload. Lighting led to a decrease in workload and with that a higher speed and this effect was noticeable at favourable weather conditions. It was expected that the speed effect would be even stronger at road conditions that are less favourable such as rainy conditions (Rudin-Brown & Jamson 2013).

A Swedish study by Lundkvist & Ihlström (2014) on the relationship between speed and lighting level showed that there was a tendency towards higher speed with higher illuminance, but that the effect was small.

5.1.3. Effects on vision and visual perception

Lighting and vision

The road lighting standards are based either on luminance or on illuminance. The luminance describes the brightness of the road surface, while the illuminance is the luminous flux towards the road surface. Both these measures are weighted by the photopic (daylight) spectral sensitivity function, i.e. the amount of light that can be registered by the eye at different wavelengths. Luminance is more strongly related to visual perception than illuminance, since it describes the perceived brightness (both road surface characteristics and observer position are taken into account when calculating luminance) rather than "the amount of light".

Goodman (2009) discussed shortcomings of the current measurement systems for light and lighting. It was pointed out that appropriate measurements must take into account the visual responses of the eye, which include more than the photopic response function (with which physical measurements are weighted), such as age, changes in colour or intensity of a light source in different directions, preferences and task performance. In (Goodman 2009), four specific areas related to measurements of light and lighting are reviewed:

- *Lighting in the mesopic region:* The lack of an agreed method for measurements in the mesopic region is seen as one of the most serious shortcomings of the current measurement systems for road lighting. A new standard is however expected within a few years (CIE TC1-58).

- *Lighting for the aging population:* Lighting specifications and recommendations do not fully consider the requirements of the aging population. Older people need more light than young people, but they are also more sensitive to glare, why simply increasing lighting levels not necessarily improves visual performance.

- *Visual task performance:* Several models for predicting visual performance have been suggested in the literature, but they have not been widely adopted in practice which can be explained by the complexity of visual performance. Generic models for all visual tasks are not possible to develop and task performance may be influenced by e.g. cognitive and motoric performance, by external factors such as ambient noise or by psychological factors such as boredom.

- *Physiological effects of light and colour and influences on human health and well-being:* Although there is evidence that light influences human health, much still remains unknown regarding intensity, spectral characteristics and timing of light exposures, both when it comes to adverse health effects and to beneficial effects.

In Canada and the US, highway lighting practice has progressed from the illuminance method (i.e. physical quantities of light) to the luminance method (i.e. what the driver sees) and is now moving to a visibility based method called *Small Target Visibility* (STV) (Keck 2001; Khan & Kline 2011). STV is defined as the weighted average of the *Visibility Levels* (VL) of a number of flat, 18 cm square targets with a diffuse reflectance of 0.5, mounted vertically on the road surface, arranged in the form of a matrix (IESNA 2005; Boyce 2009). The target is located 83 m ahead of the observer and oriented normal to the observer-to-target sight line. The observer is assumed to be 60 years old and have normal vision. The VL is defined as the ratio of the actual luminance contrast of the target to the luminance contrast threshold of the target. The threshold contrast can be calculated using a quantitative model developed by Adrian (1989) and the actual luminance contrast can be obtained by calculating the luminance of the road surface and of the target, using any of several possible methods (IESNA 2005; Bremond, Dumont et al. 2011). Ising and Green (2009) used the Adrian threshold model to determine VL requirements for a large driver population. The average VL found in (Ising and Green 2009) was significantly higher than the VLs found in other studies using other data sets. It was concluded that the required VL likely depends on the exact viewing conditions, and that the Adrian model has limitation and requires modifications under some circumstances (Ising and Green 2009).

The STV and VL methods have been discussed also in several other publications. Boyce (2009) stated that although the STV method is closer to the ultimate purpose of road lighting, namely making objects visible, than conventional photometric measures, it is probably doomed to failure. The visual task of driving is multifaceted, but the STV only addresses one facet: detection of small targets on-axis. Lecocq (1999) pointed out that the shape of the target, a planar square, does not account for real objects and presented a method for calculating the VL of spherical objects instead.

Bremond, Dumont et al. (2011) investigated some metrological issues of the VL method. Since the luminance of the surroundings is varying in a driving situation and thus not easily defined, several methods for measuring background luminance and adaptation luminance were evaluated in a field experiment. The study showed that the method used strongly impacts the VL value. Regardless of the method used, it was concluded that the VL was not a good predictor of the detection distance to targets (observed in the field experiment). It was suggested that great caution is needed when using VL as an index of road visibility (Bremond, Dumont et al. 2011).

The feasibility of basing road lighting levels on the detection of small targets was further discussed in (Raynham 2004), where four critical questions were raised: 1) Is this the most relevant (visual) task for driving conditions? 2) Road lighting is based on detecting objects by luminance contrast – what is the impact of colour contrast? 3) What is the effects of vehicle headlights? 4) Is longitudinal uniformity the best parameter for improving driver comfort? Raynham (2004) claimed that more research is needed and suggested that the first step should be an analysis of what the driver needs to be able to see. In comments to the paper, additional questions were raised, related to peripheral vision, mesopic weighting of the light spectrum and age (Lewin 2004; Richards 2004).

The fact that the STV model does not include vehicle head lighting system was pointed out by Keck (2001), who suggested an alternative model that includes the ability to study the changing visibility of a small target as a vehicle approaches.

Safe driving involves both on- and off-axis vision, where off-axis is used for detection and on-axis for identification. Furthermore, there is literature showing that peripheral vision is responsible for avoiding accidents (Berthelon & Mestre 1993 and Crowell & Banks 1993; cited in Kostic & Djokic 2012). The contrast criterion is a key visual factor in target detection and relevant for assessment of road lighting. However, reference scenarios should be modified to take into account the main components of night driving like peripheral detection and task load (Mayeur, Bremond et al. 2008). More realistic driving situations should be addressed in order to improve road lighting specifications that are based on science, using for instance driving simulators and field experiments (Mayeur, Bremond et al. 2008). A field study demonstrated that it is more difficult for a driver to detect objects when driving compared to being a passenger and it was suggested that human factors components such as workload should be included for road lighting design (Mayeur, Bremond et al. 2010).

In the past decade, a great amount of road lighting research has been directed towards mesopic models and methods, since peripheral tasks at low luminances will not be properly characterized by conventional photopic methods (Bullough & Rea 2004). In short, white light will be more beneficial than yellow light in the mesopic region. However, since these effects are mainly observed at or below 0.1 cd/m^2, which is lower than the lowest lighting classes, mesopic models and its consequences will not be further discussed in this report. A summary of research on mesopic models can be found in Fors (2010).

Visibility of pedestrians and other targets

The visibility of targets is influenced by several factors, where visual size and luminance contrast are two of the most relevant ones (Boyce 2009). Also colour contrast has been found to have a high impact on target visibility if the road is illuminated by light sources with good colour renderings properties (Ekrias, Eloholma et al. 2009). The effect however decreases when the viewing distance increases or when the light source is dimmed. The importance of contrast was demonstrated by Edwards and Gibbons (2008), where the clothing colour (black, denim, white) of pedestrians was found to have an influence on visibility distance.

Another factor that has an influence on visibility is the reflecting properties of the road surface. It has been observed that the relative reflectance tends to be higher for the long wavelength region, which means that HPS lamps are more efficient than MH lamps in terms of light reflected from the pavement (Ekrias, Eloholma et al. 2009). Yet another factor that has an effect on visual performance is the optical properties of the vehicle windshield, which may change the spectrum of the transmitted light (Ekrias, Eloholma et al. 2009).

The possibilities to detect pedestrians or other targets do not depend solely on the visual conditions. The expectancy of the observer has been shown to play an important role, and so has object motion (Bhagavathula & Gibbons 2013).

Driving is a task involving visual, perceptual and cognitive complexity and conventional vision test do not reflect these aspects and, therefore, they are most likely to not being able to predict driving performance. To better describe the response of human visual system under mesopic conditions, Plainis and Murray (2002) suggested using a model (Plainis & Murray 2000) predicting simple reaction times linked to contrasts, spatial frequency and luminance. The reason is that reaction time has a direct relationship to the driving task as the speed of the response constitute an important part in the perceptual judgement. According to an experiment, an increase in processing time occurs as the luminance and contrast decreases with a resulting longer stopping distance. Reaction time increased also in the near-periphery, which is of critical importance when driving. (Plainis & Murray 2002).

Detection distances to pedestrians who are about to cross the street have been investigated in a Swedish study, where the factors roadway luminance level and luminance uniformity, pedestrian position and pedestrian clothing luminance were varied (Lundkvist & Nygårdhs 2012). It was concluded that the detection distance increased with increasing roadway luminance and that the detection distance was larger if the pedestrian had black clothing than if the clothing was light grey. There was no relationship between pedestrian luminance and detection distance, which implies that in this experiment the background luminance was of major relevance for the detection distance. Furthermore, the results demonstrated complex relationships between luminance uniformity, pedestrian clothing and pedestrian position in relation to the lighting luminaires (Lundkvist & Nygårdhs 2012).

In a field study, using moving pedestrians as detection objects, it was concluded that light levels has a strong effect on visibility of moving targets at mesopic luminance levels (Eloholma, Ketomäki et al. 2004). The result also show that the effect of light level is not linear in the different parts of the visual field. At luminance levels of 1.5 to 2.0 cd/m^2, the central visibility was better than the peripheral. When the light level decreased to 0.1 and 0.5 cd/m2, the differences in detection distances between peripheral and central vision disappeared and was also partly reversed. Another finding was that the light spectrum, in this case represented by HPS and MH lamps, did not have an effect of the visibility in central viewing at any light level. However, the light spectrum did have an effect on the peripheral vision and at low luminance levels, where the contrast threshold was better with MH than with HPS (Eloholma, Ketomäki et al. 2004).

The results by Eloholma, Ketomäki et al. (2004) regarding lamp type and visibility in the central field of view is supported by Gibbons and Hankey (2006), where pedestrian visibility in crosswalks with crosswalk lighting was investigated. Except in a few special cases, lamp type did not have a significant effect on visibility. Presence of glare worsened the ability to detect pedestrians, regardless of pedestrian clothing. The impact of glare was not necessarily mitigated by addition of overhead lighting (i.e. ordinary street lighting). It was also found that the use of specific crosswalk lighting in conjunction with overhead lighting can either improve or degrade the visibility of pedestrian, depending on the lighting levels, the lamp type (MH or HPS) and the pedestrian clothing (Gibbons and Hankey 2006).

In a study where visual performance under CMH and HPS lamps was investigated, it was found that the visibility of small targets and reaction times to peripheral objects were not significantly altered either by lamp type or by dimming from full to half the luminous output, corresponding to a reduction in road surface luminance from approximately 1 cd/m^2 to 0.5 cd/m^2 (Crabb, Beaumont et al. 2005). In a subsequent study an even lower lamp power was investigated, corresponding to 0.2–0.3 cd/m^2 which was compared to the level corresponding to 0.5 cd/m^2. No significant difference between the lamp types or between luminance levels were found, neither in the peripheral vision experiment nor in the visibility (central vision) experiment with the exception of two target positions (Crabb, Beaumont et al. 2005). The overall conclusion based on both these two studies were that it may be safe to dim to 0.5 cd/m^2, at least during the quieter part of the night (Crabb, Beaumont et al. 2005).

Different designs for pedestrian crossing illumination have been evaluated in several studies. High vertical illuminance is often beneficial because such a lighting will result in pedestrians being seen in positive contrast (Hasson & et al. 2002; Gibbons & Hankey 2006; Edwards & Gibbons 2008; Gibbons & et al. 2008; Bullough, Zhang et al. 2009).

Interaction between road lighting and vehicle lights

In an experiment by Bacelar (2004), the contribution of vehicle lights on visual performance was tested, with and without road lighting in an urban environment. The visibility level of a flat 0.2 m square target on the road in front of the vehicle was calculated for various lighting conditions. The results showed that road lighting (corresponding to class M1) alone or vehicles lights (dipped and full beam) alone in general gave a higher visibility level than when road lighting and vehicle lights were combined. It was also concluded that road lighting alone gave sufficient visibility of the target. In absence of road lighting, glare from oncoming vehicles' headlights was for drivers looking towards the oncoming vehicle with viewing distances < 30 m found to be large enough to prevent the driver from seeing the target. With road lighting, the visibility level was reduced by up to 50% depending on the level of glare, but the target was still visible (Bacelar 2004).

The finding that vehicle headlights in general do not contribute to the visibility of targets on the road was replicated in a later study (Ekrias, Eloholma et al. 2008). Ekrias, Eloholma et al. (2008) also concluded that the effects of vehicle headlights are highly dependent on the headlight type, the target reflection factor, and the positions of the target, the vehicle and the road lighting. It was however emphasized that it is very difficult to determine how the measured effects relate to safety (Ekrias, Eloholma et al. 2008).

The combination of headlights and road lighting leads to that both vertical surfaces and road surface are illuminated. In such cases where the object to be detected is seen as being darker than the road surface, the presence of headlight may actually reduce the visibility of the target and thereby have a negative effect on the road safety (Ekrias 2010).

Contrast sensitivity deteriorates in the presence of glare. Lens opacities, which usually arise with age, lead to more glare. High-beam glare has been estimated to reduce maximum contrast sensitivity by an order of magnitude in persons affected by mild lens opacities, taking into account the average luminance of objects lit by road lighting (Anderson & Holliday 1995).

Light colour

The most common light sources for road lighting today are high pressure sodium (HPS) lamps, metal halide (MH) lamps and light emitting diode (LED) lamps, which have somewhat different colour properties. HPS lamps emit a pinkish-orange light with relatively poor colour rendering, while MH lamps and LED lamps emit nominally white light.

In the UK, as in Sweden, street lighting is based on EN-13201-2 (see also Chapter 3) and divided into six classes – the S-series – where each class has a minimum average illuminance. 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 (2005) compared HPS lamps with MH lamps of one S-class lower. They 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 (2005) referred to another study (Boyce & Bruno 1999) where the colour of the light (HPS and MH) did not affect the appeared brightness, when the illuminance was kept constant. In Boyce and Bruno's 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 (2005) thus limited their result to be valid only for immediate exposure.

Lewin, Box et al. (2003) reviewed literature on three different light sources – HPS, LPS and MH lamps – with respect to visibility, lamp performance and accidents. 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. Furthermore, Lewin, Box et al. (2003) did not find any studies that indicate that visibility is lower with MH lights than with sodium lights, for equal lighting level. For further results on light colour and visibility, see the above section on *Visibility of pedestrians and other targets*.

In Morante (2008), HPS lamps were compared to induction lamps and MH lamps that were 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 (Morante 2008).

The photopic luminous sensitivity function is appropriate in characterizing a glare source in terms of disability glare, i.e. visual performance (Bullough, Van Derlofske et al. 2003), while discomfort glare has greater short-wavelength spectral sensitivity than implied by the function (Bullough 2009). The short-length sensitivity increases as eccentricity increases. This means that bluish light sources, such as some LED lamps, will appear more glaring, particularly peripherally, than what can be predicted by conventional lighting calculations.

Weather conditions

When the road surface is slightly snowy and the road surroundings are covered with snow, road surface luminance has been found to be about 50% higher than for a dry road (Ekrias, Eloholma et al. 2007). On roads that are covered by snow, the luminances can be multiple times higher. Also wet roads may have average luminances that are several times higher than dry roads, but the uniformity is usually very poor and there may be problems with specular reflections causing glare. Eloholma, Ketomäki et al. (2004) showed in a field experiment that the bright areas of a residential street with a wet surface were between 10 to 30 cd/m^2 whereas the darker areas had lower luminance compared to dry conditions. This leads to a very low luminance uniformity and consequently worse visibility conditions than at dry road conditions.

With the differences in luminance levels due to various weather conditions Ekrias, Guo et al. (2008) pointed at the possibility to use intelligent road lighting control that take weather situations into consideration. With this is would be possible to improve overall lighting conditions and to achieve energy savings.

5.1.4. Road users' needs

Drivers

In a Finnish questionnaire study, drivers' views on road lighting were investigated (Viikari, Puolakka et al. 2012). The participants were asked to rate the importance of various road lighting characteristics on a scale from –2 = not important to 2 = very important, and to rate the difficulty of various visual tasks on a scale from –2 = easy to 2 = difficult, for urban and motorway driving. The average ratings for all participants (old and young) are shown in Table 26 and Table 27.

Some additional results not shown in the tables were:

- older drivers valued road lighting more and considered visual tasks of dark-time driving more difficult than younger drivers
- the lighting of the road was considered as significantly more important when driving in urban areas as for driving on motorways, for both safety and comfort
- the participants were quite satisfied with the current road lighting practice
- half of the participants were willing to reduce the amount of light on motorways to save energy, but the majority of the drivers would not relinquish road lighting for energy savings in urban areas
- adaptive lighting was suggested in order to adapt the lighting level to various weather conditions.

A limitation of the study is however that it is not clear whether the ratings of the difficulty of visual tasks refer to lit or unlit roads.

Table 26. Importance of road lighting characteristics, ordered by the ratings for urban areas (Viikari, Puolakka et al. 2012).

Characteristic	Rating	
	Urban	Motorway
Improvement of traffic safety	1.69	1.51
The amount of light	1.44	0.50
Non-glaring light	1.35	1.21
Light also on the surroundings	1.14	0.84
Overall pleasantness of the lighting	0.95	0.76
Energy efficiency of the lighting	0.80	0.81
Uniformity of the light on the road	0.67	0.51
Colour discrimination of lit surfaces	0.56	-0.13
The colour of light	0.15	-0.07

Table 27. Difficulty of visual tasks in dark-time driving, ordered by the ratings for urban areas (Viikari, Puolakka et al. 2012).

Visual task	Rating	
	Urban	Motorway
Seeing under failed light columns	0.43	0.47
Seeing while the lights of the oncoming car are glaring	0.38	0.88
Seeing small targets	0.29	0.93
Seeing while the lights of the car driving behind are glaring	–0.05	0.34
Seeing pedestrians / large animals	–0.09	0.45
Assessment of the walking speeds of pedestrians	–0.14	-
Seeing the traffic signs and signboards	–0.63	–0.68
Seeing the driving lane and lane markings	–0.67	–0.64
Seeing pedestrian crossings	–0.41	-
Assessment of the driving speed of other vehicles	–0.50	–0.08
Seeing the structure of the road	–0.56	–0.37
Seeing parked cars	–0.59	-
Assessment of distances	–0.72	–0.11
Seeing crossroads	–0.77	–0.58
Seeing other cars	–0.96	–0.96

In a Swedish focus group study (Fors & Nygårdhs 2010), both cyclists, older pedestrians and older drivers thought that problems experienced in night-time traffic in urban areas mostly were related to vulnerable road users. Pedestrians and cyclists were seen as hard to detect, not only for driver but also for other pedestrians and cyclists. The group with older drivers wanted better lighting at pedestrian crossings (Fors & Nygårdhs 2010).

The visibility needs of older drivers were discussed in Khan et al. (2011), where a number of factors that require attention in order to improve road lighting design was listed:

- *Retinal illuminance*
  With increasing age, the pupil size declines and the opacity of the lens increases, thus preventing light from reaching the retina. At the age of 60 the retinal illuminance is about one third of its level at the age of 20. As a result, the ability to detect objects is deteriorated in low light conditions.

- *Glare and glare recovery*
  Older drivers are more sensitive to glare and they have a slower recovery from glare than young drivers. Glare may be produced not only by road lighting luminaires and vehicle lighting but also from headlamp reflections in the rear-view mirror.

- *Static acuity*
  Visual acuity declines with age. Acuity deficits are exaggerated by low contrast or luminance.

- *Contrast sensitivity*
  Contrast sensitivity declines with age, in particular for targets of intermediate and fine detail.

- *Dynamic acuity*
  Dynamic acuity is measured either as the smallest detail that can be resolved in a moving target or as the contrast needed to discriminate a moving grating.

- *Useful field of view*
  Useful field of view (UFOV) refers to the region of the visual field over which a person can detect, identify or discriminate visual stimuli without eye movements. In older drivers, the UFOV is reduced. UFOV has been found to be a robust predictor of crashes.

- *Serious visual disorders*
  Improved lighting design can benefit drivers with mild cataract, but it is assumed that it is probably not cost effective to alter lighting conditions to meet the needs of drivers with visual disorders where there is an irreversible loss of acuity and contrast sensitivity, such as diabetic retinopathy, glaucoma and macular degeneration.

- *Driver compensatory behaviour*
  Visual impairments may lead to self-imposed changes in driving behaviour and driving habits.

Kahn et al. (2011) concluded that the implication of these factors is that older drivers require carefully assessed lighting levels, object contrast and peripheral lighting of the roadway. It is also pointed out that there are other measures that may enhance visibility, such as road markings (Khan et al. 2011).

Pedestrians and bicyclists

Fotios and Goodman (2012) proposed new guidelines for lighting of residential roads in the UK, with focus on the needs of pedestrians. They stated stated that the primary requirements of lighting for pedestrians are to improve brightness (perceived safety), to aid the detection of pavement obstacles and to enable the intent and identity of other pedestrians and cyclists to be judged (Fotios and Goodman 2012). These statements were supported by Fors & Nygårdhs (2010), a Swedish focus group study on night-time traffic in urban areas, where cyclists said that they needed road lighting in order to see other road users and objects, and older pedestrians pointed out that lighting was important in order to see bumps and holes in the road, to avoid falling. Both cyclists and older pedestrians wanted better lighting in areas that feel unsafe, for example in parks and in tunnels. Moreover, older pedestrians thought it was important that the lighting does not cause glare (Fors & Nygårdhs 2010).

In a British questionnaire study of 237 patients attending an Accident and Emergency Department because of injuries from falling in public places, it was found that uneven surface or inadequate lighting were thought by over half of the patients to have contributed to the falls (Fothergill, Odriscoll et al. 1995).

Davoudian & Raynham (2012) investigated pedestrians' gaze behaviour during daytime and at night and found that about 40–50% of the time was spent looking at the pavement, both day and night.. The remaining time was mainly spent looking at houses, roads and trees, while relatively little time was spent looking at other people, signs and transient objects. However, although only a small fraction of time (3.5%) was spent looking at other people, it was clear from comments from the subjects that recognising people was regarded as very important. The results also showed that there was a significant difference in gaze distribution between the three routes included in the study, which seemed to be related to perceived insecurity. It was suggested that the time spent looking down is controlled by the amount of time left over after scanning the environment for potential threats (Davoudian & Raynham 2012).

In Niska (2007), a Swedish study of cyclists' opinions concerning the standard of cycle tracks, lighting was mentioned as important. The main reasons mentioned were to improve visibility for the cyclist to detect obstacles on the cycle track, like cracks and holes, and in order to avoid incidents by facilitating discovering other road users, such as children playing, pedestrians and other cyclists. During the dark hours of the day, the lamp on the bicycle was considered to not render enough light to fulfil these requirements (Niska 2007).

In a more recent study of bicycle accidents (Niska & Eriksson 2013), darkness was in some cases mentioned as a contributing reason to the accident where some comments were made saying the lighting of the cycle track was inferior.

In Johansson, Rosén et al. (2011), an urban footpath was assessed subjectively by visually impaired persons, elderly persons and young women. Visual accessibility, perceived danger, subjective lighting quality and environmental trust were measured by rating scales. The lighting level corresponded approximately to lighting class P4. Most of the elderly and the young women thought the visual accessibility was sufficient, while the visually impaired found it inadequate. The perceived accessibility was predicted by visual field, environmental trust and brightness. The perceived danger was predicted by the pleasantness of the lighting, gender, brightness and environmental trust. It was suggested that the influence of individual characteristics such as subjective judgments of brightness, pleasantness and trust should be considered when designing lighting for footpaths (Johansson, Rosén et al. 2011).

Boomsma & Steg (2014) studied the effects of entrapment, lighting level and gender on perceived safety and lighting policy acceptability. The participants (young students) perceived the lighting levels to be more acceptable when perceived social safety was not threatened. The participants felt safer in low entrapment areas, i.e. in settings offering opportunities to escape, and in settings with high lighting levels. However, reducing light levels did not automatically lead to a reduction of perceived safety; this depended on gender and the level of entrapment (women felt safer in low entrapment settings than in high entrapment settings, while men felt safe in both low and high entrapment settings). It was suggested that enhancing feelings of safety through street design can increase acceptability of reduced lighting levels (Boomsma & Steg 2014).

5.2. Criteria for lighting classes M and C

In this section, the suggested selection criteria for the M and C classes are discussed and where possible, linked to the scientific studies in section 5.1. An explanation of each parameter, as they are defined in CEN/TR 13201-1, is given in italics.

In each section, the relevance of the parameter as a selection criterion is estimated (yes/no/maybe). For the relevant parameters, research questions have been identified.

5.2.1. Design speed or speed limit

Design speed: *speed selected for purposes of design and correlation of the geometric features of a road and is a measure of the quality of design offered by the road. It is the highest continuous speed at which individual vehicles can travel with safety on a road when weather conditions are favourable and traffic density is so low that the safe speed is determined by the geometric features of the road.* (CEN/TR 13201-1).

Speed is relevant for stopping distance and it may be an indicator of the need for road lighting. This is because lighting can increase the sight distance and hence drivers will have longer time to react and brake in time to avoid accidents, which is important on roads where pedestrians and cyclists are present. From this perspective, the large weights suggested for this parameter, from –2 to 2, may be justified, but on the other hand, design speed co-varies with several factors regarding road characteristics. Factors that also decides the need for lighting. There can, for instance, be a lower speed limit for areas where there are unprotected road users present and conflict zones. Hence, using design speed as an indicator for road lighting may be redundant. Besides, the fact that most high speed roads are unlit is somewhat paradoxical to the recommendation that if a high speed road is to be illuminated, it should have a very high lighting class.

No literature that directly demonstrates evidence for why the lighting level should be increased with increasing design speed has been found.

Relevant: Maybe (in combination with other criteria)

Questions:

5.2.2. Traffic volume

Traffic volume: *the number of vehicles passing a given point in a stated time period in both directions.* (CEN/TR 13201-1).

One impact of traffic volume is glare that will be a more significant factor the more oncoming traffic there is, especially if the midsection of the road is narrow. Glare will worsen the ability to detect pedestrians and elderly are also more sensitive to it (Gibbons & Hankey 2006). In a Finnish questionnaire study by Viikari, Puolakka et al. (2012), seeing while the lights of the oncoming car are glaring was rated as somewhat difficult. Problems with glare can be reduced by increasing the adaptation level, i.e. by providing light. The amount of light needed to counteract glare from oncoming traffic is however not well documented in the literature.

Another aspect of traffic volume is that an increased amount of vehicles in the same direction and on the same time will lead to increased complexity in the sense that there will be less marginal and limited capacity for action. However, no literature that supports the hypothesis that road lighting will reduce the number of accidents in high traffic densities has been found.

Relevant: Yes

Questions:

- What is the relationship between experienced glare, level/amount of road lighting and amount of traffic? How is this related to for example comfort or the possibilities to detect pedestrians?

5.2.3. Traffic composition

Traffic composition: *the distribution of vehicle types in the traffic stream, directional distribution of traffic, lane use distribution of traffic, and type of driver population on a given facility. In this report simplified: mixed and motorized only.* (CEN/TR 13201-1).

There is some evidence that vulnerable road users are at increased risk of having an accident during the dark hours compared to daylight (see e.g. Johansson, Wanvik et al. 2009; Wanvik 2009c; Griswold, Fishbain et al. 2011; Gaca & Kiec 2013). The presence of vulnerable road users is thus probably a relevant parameter to consider when deciding upon road lighting levels, where the categories of children and elderly people can be extra relevant. In such areas there may be need for improved sight distance, which road lighting can provide (Eloholma, Ketomäki et al. 2004; Lundkvist & Nygårdhs 2012). This can be especially important in Nordic countries where it is dark until late in the mornings and early in the afternoons during wintertime.

It is however important to remember that the relationships between visibility/detectability and the lighting conditions are complex. The background of a pedestrian, which may vary a lot and which may be hard to influence by lighting, will have an effect on the possibilities to detect the pedestrian. So will other factors, such as the pedestrian’s position in relation to the lighting sources and the clothing of the pedestrian (Lundkvist & Nygårdhs 2012). Moreover, road lighting and vehicle lighting in combination is not always beneficial from a detectability point of view (Bacelar 2004; Ekrias 2010).

Another aspect of the parameter traffic composition is the needs of the vulnerable road users, i.e. when designing lighting for roads with a mixed traffic composition not only the needs of the drivers of motorized vehicles should be taken into account, but also those of cyclists and pedestrians.

Relevant: Yes

Questions:

- What methods should be used to evaluate the visibility and detectability of vulnerable road users in relation to road lighting?

5.2.4. Separation of carriageway

Separation of carriageway: *Central reserve and/or guardrail.* (CEN/TR 13201-1).

If the carriageways are separated or not can have an effect on the problem with glare. As mentioned in 5.2.2, the problem of glare is due to oncoming traffic and the problem gets worse the more traffic there is. This problem can be decreased if the carriageways are separated by a wide enough central reserve or if the headlights are blocked by a solid guardrail, such as concrete median barriers that are high enough.

Relevant: Yes

Questions: **-**

5.2.5. Junction density

Junction: *a place where several traffic routes meet, join, or cross each other, and a location here traffic can change between different routes.* (CEN/TR 13201-1).

Junction density may be a relevant criterion for road lighting for two reasons. Firstly, a high junction density increases the complexity and the difficulty of the driving task. High complexity is however closely related to the criteria “Navigational task” and this will thus be further discussed in section 5.2.8.

Secondly, if the junctions, but not the roads in between the junctions, are lit, there will be great variations in the luminance level. Consequently, the adaptation level will also vary, which may lead to poor visual performance and possibly discomfort. Adaptation from low luminance levels to high luminance levels is relatively fast (< 1 min), while dark adaptation is slower.

Relevant: Maybe.

Questions:

- On the basis of dark adaptation and potential annoyance, discomfort or problems detecting obstacles, what junction density (lit junctions) gives cause for using road lighting on the roads connecting the junctions?

5.2.6. Parked vehicles

Parked vehicles: -

Parked vehicles imply that there may be vulnerable road users present on or close to the roadway. This is however covered by the criteria “Traffic composition” which is further discussed in section 5.2.3.

In a Finnish questionnaire study by Viikari, Puolakka et al. (2012), seeing parked cars was rated as fairly easy.

Except for the potential presence of vulnerable road users, we cannot see any reason why parked vehicles should be a criterion for road lighting.

Relevant: No.

Questions: **-**

5.2.7. Ambient luminosity

Ambient luminosity: *Assessed luminance levels of the surroundings.* (CEN/TR 13201-1).

No literature that clearly points out ambient luminosity as a relevant criterion for road lighting has been found, but it is however known that ambient light may cause glare or increase the adaptation level. As a consequence, the road will appear dark and vulnerable road users may not be seen (see e.g. (Gibbons & Hankey 2006)). Ambient luminosity can thus be assumed to be a relevant parameter.

In CEN/TR 13201-1, "high" ambient luminosity has a weighting value of 1. This means that the lighting level will be higher than it would have if there were no ambient luminosity, but there is not really a connection to the actual luminosity level. Thus, it is probably a better idea to adapt the lighting class to the ambient luminosity in an absolute sense.

Using a simple categorization of luminosity levels, such as *shopping street = high, normal urban street = medium*, etc. as in the suggested method, is probably a good idea in order to make the parameter applicable.

It should be kept in mind that other vehicles will contribute to the ambient luminosity, which is related to the parameter "Traffic volume" in section 5.2.2.

Relevant: Yes.

Questions:

- What lighting class is needed in order to counteract the negative effects on visual performance caused by ambient luminosity?

5.2.8. Navigational task

Difficulty of navigational task: *the degree of effort necessary by the road user, as a result of the information presented, to select route and lane, and to maintain or change speed and position on the carriageway. Note: visual guidance provided by the road is part of this information.* (CEN/TR 13201-1).

Road lighting has been found to decrease the driver's level of workload (Assum, Bjornskau et al. 1999; Rudin-Brown & Jamson 2013). This implies that road lighting may enhance the driver's capacity to tackle a complex driving situation.

On Swedish roads, the navigational task is probably the most demanding in complex junctions, such as large interchanges with multiple lanes or urban intersections with mixed traffic compositions. There is some evidence that road lighting in intersections is beneficial from a safety perspective. In the meta-analysis by Elvik, Høye et al. (2013), it was found that road lighting reduces injury crashes in intersections both on urban and rural roads, and on motorway. However, the size of the effect is uncertain (Sasidharan & Donnell 2013), see also Section 5.1.1.

The reasons why lighting is beneficial in intersections are not well documented. Partly it may be explained by a study by Plainis and Murray (2002), where it was found that processing time (reaction time) increased as the luminance and contrast decreased. Furthermore, reaction time was increased in the near-periphery (compared to the central vision). In other studies, peripheral vision has been shown to be responsible for avoiding accidents (Kostic & Djokic 2012).

Thus, there is some support for using "Navigational task" as a criterion for selection of road lighting class, particularly in junctions. It is however not known whether the level of the lighting is of importance.

Another type of navigational task that may be of relevance is that of staying in the lane, which may be somewhat demanding in poor visual conditions, such as rural roads in rainy weather. Such conditions may be particularly difficult for older drivers and it is known from the literature that older drivers experience more problems with night-time driving that younger drivers, see e.g. Khan and Kline (2011). However, these problems seem to be mainly related to rural roads (Fors & Nygårdhs 2010), where it is not possible to use road lighting for economic and environmental reasons.

It should be emphasized that the navigational task can be assisted and supported by other measures than road lighting, such as road markings, signs and road geometry.

Relevant: Yes.

Questions:

- In what type of junctions is road lighting beneficial?
- Are there other navigational tasks than those related to junctions that are relevant as a road lighting criterion?

5.3. Criteria for lighting classes P

In this section, the suggested selection criteria for the P classes are discussed and where possible, linked to the scientific studies in section 5.1. An explanation of each parameter, as they are defined in CEN/TR 13201-1, is given in italics.

In Sweden, the P classes are applied only on footways and cycle tracks. The discussion below is thus limited to these types of paths.

5.3.1. Travel speed

***Travel speed:* -**

It is of importance for both pedestrians and cyclists to be able to detect obstacles and other road users in order to avoid them (Niska 2007; Fors & Nygårdhs 2010). The higher the speed the longer the distance for stopping. Travel speed may therefore be an aspect of importance for cyclists. Dark cycle tracks, where the perceived lighting has been inferior, has been mentioned as one contributing reason for accidents (Niska & Eriksson 2013).

Relevant: Maybe.

Questions:

5.3.2. Use intensity

***Use intensity:* -**

No literature that directly relates use intensity to the need for lighting has been found, and its relevance is thus speculative. A possible motive for the use of this parameter is that the more intense the use is of a cycle track and/or a footway is the more complex will the traffic situation be and there will be a limited capacity for action. This is probably more relevant for cycle tracks and for spaces shared by cyclists and pedestrians.

Also the absence of other road users might be a relevant factor, since absence of other people may increase the feeling of insecurity. In a British study (Painter 1996) it was found that improved street lighting can lead to reductions in crime and fear of crime, and increased pedestrian use after dark. On the other hand, using high lighting classes on sparsely used paths may not be justified for economic reasons.

Relevant: Maybe

Questions:

- How is use intensity related to the need for lighting?

5.3.3. Traffic composition

Traffic composition: *the distribution of vehicle types in the traffic stream, directional distribution of traffic, lane use distribution of traffic, and type of driver population on a given facility. In this report (CEN/TR 13201-1) simplified: mixed and motorized only.* (CEN/TR 13201-1).

In areas that both cyclist and pedestrians share there can be a substantial difference in travel speed among the road users, leading to a more complex traffic situation. Lighting can provide an increased possibility to detect other road users in order to avoid them (Niska 2007; Fors & Nygårdhs 2010).

<u>Relevant:</u> Maybe (related to travel speed and use intensity)

<u>Questions:</u>

- How does the traffic composition influence the need for lighting?

5.3.4. Parked vehicles

Parked vehicles: -

This criterion is not relevant on footways and cycle tracks.

<u>Relevant:</u> No.

<u>Questions:</u> **-**

5.3.5. Ambient luminosity

Ambient luminosity: *Assessed luminance levels of the surroundings.* (CEN/TR 13201-1).

As discussed in section 5.2.7, ambient luminosity may cause glare or increase the adaptation level so that the road/path appears dark. Being able to see the road is important in order to avoid falling, particularly for older road users (Fothergill, Odriscoll et al. 1995; Fors & Nygårdhs 2010) and for cyclists (Niska 2007). So, similarly to the M and C classes, ambient luminosity is probably an important parameter also for the P classes.

The *lack* of ambient luminosity may also be experienced as a problem, since it has been found to be related to perceived danger (Johansson, Rosén et al. 2011; Boomsma & Steg 2014). This can potentially, to some extent, be counteracted by illuminating the surroundings of the footpath.

<u>Relevant:</u> Yes.

<u>Questions:</u>

- What lighting class is needed in order to counteract the negative effects on visual performance caused by ambient luminosity?

- How much of the surroundings in dark environments should be lit in order for pedestrians and cyclists to feel safe?

5.3.6. Facial recognition

Facial recognition: *visual task of pedestrians consisting of a recognition of a face at certain distances that allows to take evasive or defensive action if thought necessary. Note: Generally facial recognition requires an overall minimum lighting value at a distance where the recognition of a face is possible. Note: An ideal facial recognition distance is 10 m – the point of transition between "close" and "not-close" phases.* (CEN/TR 13201-1).

Although often mentioned in publications on pedestrians and lighting, there is not much literature actually demonstrating the relevance of the parameter “facial recognition”. In Davoudian and Raynham (2012), the participants stated that recognising people was regarded as very important, however, the time actually spent looking at other people was limited. In two Swedish focus group studies (Niska 2007; Fors & Nygårdhs 2010), cyclists said it was important to be able to detect other road users (i.e. not just the face).

It may be reasonable to believe that facial recognition is more important in situations and places that are perceived as unsafe, such as lonely paths or in areas with high crime rates.

Obtaining good vertical illumination, which is needed in order to see faces, is challenging since the light must be directed downwards from the luminaires to avoid glare. In addition, the position of the luminaire in relation to the face will influence the possibilities to see the face and since the position varies as the pedestrian walks along a path, the light towards the face will vary. Thus, in order for the criterion “facial recognition” to be useful, some advice on how to arrange the lighting is probably needed.

Relevant: Maybe.

Questions:

- In what situations is facial recognition of importance?

6. Methods for evaluating road lighting

The aim of this chapter is to provide an overview of methods that are used to assess and evaluate road lighting. No judgements or ratings of the methods are made.

Objective	**Method, materials, procedure**	**References**
Accidents		
Accident rates	Before-after studies, cross-section studies, meta-analyses etc.	E.g. (Wanvik 2009b; Beyer & Ker 2010; Elvik, Høye et al. 2013)
Accident analysis	Analysis of inquest records of road traffic accidents, in order to identify contributory factors.	(Crilly 1998; Clarke, Ward et al. 2006)
Detectability, visibility, visual performance		
Drivers' detection distances to pedestrians	Subjects were moving towards a pedestrian, which they were told to look for, and were instructed to push a button when they were able to detect the pedestrian.	(Lundkvist & Nygårdhs 2012)
Detection distances to pedestrians	Subject was to indicate the detection threshold of a pedestrian walking towards. Both foveal and peripheral viewing were investigated.	(Eloholma, Ketomäki et al. 2004)
Pedestrians' detection of pavement obstacles	Two lab studies: 1) Subjects were asked to report whether a target was present or not, when looking through an aperture that was opened for 300 ms. Illuminance, target position and target height was varied. 2) Subjects were asked whether they could detect a 25 mm obstacle at distance of 2, 4, 6, 8 and 10 paces, in different illuminance levels.	(Fotios & Cheal 2013)
Drivers' detection of pedestrians and surrogate objects	Participants were placed at a fixed distance from a pedestrian crossing, while wearing occlusion glasses. The occlusion glasses cycled from opaque to clear and the number of cycles until the participant identified the location of an object (pedestrian or surrogate object) was use as a measure of detection performance.	(Gibbons & Hankey 2006)
Detection of a light signal	As criterion for visual performance was how often a light signal can be detected used. The subjects sat in a room and were asked to click every time they observed a light signal through a hole in a background screen.	(Lin, Chen et al. 2006)
Detection	Performed a target detection performance task to investigate the importance of work load. Real driving was conducted on an illuminated closed circuit road. The dependant variable was the detection distance and the study also compared driver and passenger conditions to see if there would be any differences.	(Mayeur, Bremond et al. 2010)
Detection and recognitions	Subjects were asked to react to a simulated road hazard and to say if the grating was horizontal or vertical, and to identify if the pedestrian was faced towards or away from the road.	(Lewis 1998; Lewis 1999)
Visual performance	Subjects were asked to notice a target, both on- and off-axis, and reaction time was used as indicator.	(He, Rea et al. 1997)

Objective	Method, materials, procedure	References
Drivers tracking task	Evaluate how a tracking task would affect target detection threshold in mesopic vision. Three phases was performed. 1: Target detection in peripheral vision, 2: Steering a tracking target, 3: Steering a tracking target and target detection in peripheral vision.	(Mayeur, Bremond et al. 2008)
Visual models		
Visibility level (VL)	The visibility level is the ratio of the actual contrast to the threshold contrast. The threshold contrast is the luminance contrast at which an object may be just detected. At the threshold contrast, an object has a probability of detection of 50%.	(Adrian 1989)
Small target visibility (STV)	The weighted average of the visibility levels of a number of flat, 18 cm side, square targets with diffuse reflectance of 0.5, placed vertically on the road surface.	(IESNA 2005)
Relative visual performance (RVP)	The RVP model is an empirical model of the reaction time for the detection of on-axis stimuli. The model includes a range of adaptation luminances, luminance contrasts and visual sizes.	(Rea & Ouellette 1991)
Gaze behaviour		
Pedestrians' gaze behaviour	Subjects were asked to walk different routes, when wearing an eye tracker, both in day time and at night.	(Davoudian & Raynham 2012)
Pedestrians' critical visual tasks	Registration of gaze behaviour (eye-tracking) and reaction time to audio stimuli. Critical times where the attention may be specifically focused on the task of walking is expected to result in longer reaction times.	(Fotios, Uttley et al. 2013)
Glare		
Dynamic discomfort glare	Measurement of muscle movements around the eyes when exposed to flickering lights.	(Murray, Carden et al. 2002)
Subjective experience: field studies		
Pedestrians' experience of a footpath	Questionnaire on visual accessibility, perceived danger and subjective lighting quality.	(Johansson, Rosén et al. 2011)
Subjective experience: movies/photos		
Pedestrian reassurance	Subjects were asked to photograph streets where they did and did not feel confident to walk at night. They were then interviewed about reassurance, and the photos were discussed.	(Fotios & Unwin 2013)
Perceived visibility of different lights	Web inquiry where subjects looked on photos of a person standing in different lighting (HPS and MH) and at different distances from the camera and told how they perceived the visibility of the person.	(Jägerbrand & Carlson 2011)
Pedestrians' perceived safety and acceptability of lighting policy	Ratings of perceived safety and acceptability of the lighting levels in virtual environments representing different levels of lighting and entrapment.	(Boomsma & Steg 2014)
Computer simulations		
Dominant contrast	Calculations of the metric dominant contrast, which is defined as the contrast of any part of the pedestrian that provides the highest visibility.	(Saraiji & Saju Oommen 2014)

Objective	Method, materials, procedure	References
Simulations of road lighting	Simulations based on photometrically accurate lighting software, where vehicle lighting and other stray light is taken into account. STV was used to evaluate visibility for various configurations (light level, location, age of observer etc.).	(Rea, Bullough et al. 2010)
Simulations of lighting at pedestrian crossings	Simulations based on photometrically accurate lighting software. Calculation of visual conditions in terms of relative visual performance (RVP) and unified glare rating.	(Bullough, Zhang et al. 2009)

7. Discussion, recommendations and conclusions

7.1. Guidelines and criteria for road lighting

In this study, guidelines and criteria for selection of road lighting levels have been reviewed, with the aim of identifying criteria that are scientifically grounded. The starting point of this work was the method for selection of lighting classes suggested in the technical report CEN/TR 13201-1, which was published recently. Our review shows no strong link between the selection criteria in CEN/TR 13201-1 and the scientific literature. This result is in line with previous studies, which have indicated a weak empirical basis of various criteria and recommendations for road lighting (see Chapter 1).

Common for all guidelines that were compiled in this study – the guidelines in CEN/TR 13201-1 as well as national guidelines – is that it was not possible to identify the origin of the guidelines. There are no references and few explanations to why certain criteria or recommendations are being used. Furthermore, there is limited support for the guidelines in the literature. On the other hand, no literature that contradicts current guidelines was found.

Road users' needs of road lighting in terms of safety and comfort are not well documented or, as with crash rate studies, there are studies, but the results are not consistent. In this discussion, it is important to distinguish between the need for road lighting on one hand, and the need for a certain lighting level on the other hand. Most studies about the effects of road lighting are focused on the first case, i.e. lighting versus no lighting. For example, there is little knowledge about what lighting levels are needed in order to detect vulnerable road users and what lighting levels are needed in order to counteract negative effects of glare from oncoming traffic.

In defence of present guidelines and practice, it should be emphasized that there are no indications that the guidelines and criteria used today are markedly poor. Most guidelines are probably reasonable from a road user perspective and they have probably been developed with the best intentions. Furthermore, it should be stressed that developing guidelines for road lighting is a difficult task. Not only is it difficult to demonstrate a relationship between road lighting and the potential effects of road lighting, in terms of e.g. crash rates, it is also difficult to handle the varying conditions that applies on roads. For example, if a study indicates that lighting is beneficial in crossings, does this apply to all kinds of crossings? Or, if a study shows that a certain lighting level is sufficient to detect obstacles on the roadway in good weather conditions, is this result valid also for worse weather conditions, such as rain or snow?

7.1.1. The need for scientifically grounded guidelines

Reducing greenhouse gas emissions is a global challenge which requires efforts within all systems and applications that uses energy. Reviewing current guidelines and practices for road lighting is thus important, and should be done in parallel with the achievements in lighting technology regarding development of energy-efficient light sources and lighting control systems.

Traditionally, guidelines for road lighting have been based on expected benefits in terms of traffic safety. In 1992, CIE stated that road lighting is assumed to reduce the number of crashes by about 30% (CIE 1992). In the meta-analysis by Elvik (1995) it was estimated that road lighting leads to a 65% reduction of fatal accidents. Such estimations (although not necessarily these particular figures) have been used in for example Finland and Norway, where the guidelines for when to use road lighting is based on calculations on the profitability, in terms of expected reduction in accidents (see also Appendix B). Similar calculations have been applied in Sweden previously. In such calculations, the electricity price will have an immediate influence on the decision on whether to illuminate or not. The benchmarking data in Chapter 3 (although somewhat uncertain) supports the hypothesis that the electricity price is a determining factor, and that there is a tendency that more lighting is being used in countries where the electricity price is relatively low. Although this approach – weighing the benefits of road lighting against the cost – is reasonable from a public economy perspective, there are obvious shortcomings which mainly origin from the fact that the available literature on the relationship between accidents and road lighting is inconsistent with respect to the size of the effects (see e.g. Boyce 2009, Beyer & Ker 2010, Sasidharan & Donnell 2013). A cost-benefit-model will thus not be very accurate, or it may even be misleading. In 2009, an attempt to identify accident reductions factors and update the British cost-benefit-model for road lighting failed, since no accident reduction due to lighting could be demonstrated (Crabb, Crinson et al. 2009).

Cost-benefit-analyses primarily consider the decision on whether to illuminate or not. When the decision to illuminate a road or street is made, a number of criteria such as *road type*, *traffic flow* and *presence of vulnerable road users* is usually applied to determine the lighting level. There are good reasons to believe that such an approach is beneficial, both from a safety perspective and from an energy use perspective, since the visual tasks and conditions, and thus the need for lighting, may vary a lot between different streets or roads. However, there is a risk that the lack of knowledge on how these parameters and criteria influence the needs and benefits of lighting results in guidelines where the recommended lighting levels are unnecessary high (according to the precautionary principle) or where the lighting is poorly adapted to the needs of the road users.

The advances in the development of lighting control systems and adaptive lighting systems provide a great potential to save energy by adapting the lighting level to the present conditions, for example with respect to traffic flow or the weather. In a British study (Fox 2009), it was estimated that a variable lighting system would save 2–18 tonnes of CO_2 per km of road and year, depending on road type and lighting class. The calculated saving included those for variable light levels, dimming to maintenance factor, dimming to reduce over lighting and saving made from using electronic instead of electromagnetic control gear (Fox 2009). However, in order to fully utilize this possibility, guidelines on how this adaptation should be done, is needed. This may include criteria that are not used in any present guidelines for road lighting with a static lighting level, for example presence of snow or temporary changes in traffic flow or traffic composition.

Another aspect that needs to be considered is the potential negative effects of lighting on wild life and ecosystems, and also on human beings. For example, it has been shown that night-time light pollutions have adverse effects on e.g. movements, foraging, communication, reproduction and mortality of various organisms (Gaston, Davies et al. 2012), that road lighting changes the composition of invertebrate communities (Davies, Bennie et al. 2012) and that artificial lighting, particularly broad spectrum light sources, may alter the balance of interspecific interactions among species that are dependent on detecting the spectral signature of light reflected from objects (Davies, Bennie et al. 2013). Minimizing such effects can only be achieved by increased knowledge.

Finally, the transportation system is constantly changing. From a situation where the car has been the main mode of transportation, the need of reducing CO_2 emissions has led to an increased share of e.g. cyclists and public transportation in many cities (City Ranking 2015). In addition, development in vehicle technology such as adaptive lighting, night vision systems, pedestrian detection systems and last but not least, automated and autonomous vehicles, may have an influence on vehicle driver's needs for road lighting. Thus, the traditional view where vehicle drivers have been the primary focus when designing and installing road lighting, which in the last few years has changed in many countries to include and emphasize the needs of vulnerable road users, may change even more in the coming years.

7.1.2. Development of new guidelines – what do we need to consider?

We suggest that the following factors should be considered when developing or modifying guidelines for road lighting:

- ***Road user needs***
  We think future guidelines for road lighting should have a greater focus on and a more solid basis in road user needs, in terms of for example detectability of pedestrians, visual guidance and visual comfort, when it comes to lighting level. Today's guidelines, in Sweden as well as in other countries, often include factors that are believed to be related to the needs and safety of road users, but as there is a lack of detailed knowledge on this, the present application of such criteria tend to be somewhat arbitrary.

- ***Energy use***
  In order to minimize the use of energy, dimming and adaptation systems should preferably be used in all new installations, and there should be guidelines on how to use them. Today, night-time reductions (or even switching off) of the lighting levels are applied in many places, but there is a potential to use more advances dimming schedules and for example adapt the lighting level to traffic flow or, which has been tested e.g. on a footpath in Stockholm (Kristoffersson 2013), let the light "follow" the road user. Another way of minimizing energy use is to always evaluate whether the road users' needs can be met by other means than lighting. On non-urban roads, such as roads in the outskirts of towns and cities, or crossings on rural roads, signs, road markings and delineator posts may eliminate the need for road lighting.

- ***Costs***
  The cost is a relevant factor in any publicly funded installations, but we think there are reasons to avoid using the traditional cost-benefit analyses that have their origin in accident statistics. In addition to the fact that such analyses probably are too inaccurate to provide a good basis for decisions (on whether to illuminate or not), they do not include other factors such as accessibility and security. For example, an unlit city would be very uncomfortable for pedestrians. In practice, many countries have a principle that states that urban areas should be lit and rural roads should be unlit, which is a reasonable principle for several reasons. The traffic environment becomes familiar and predictable from a road user perspective, urban areas and activities become accessible also at night, and light pollutions are, to some extent, limited to urban areas. However, in the end, the amount of money that can be spent on road lighting must be decided on by each road authority.

- ***Other factors***
  Although the primary aim of road lighting is to improve the visual conditions for road users at night, there are other factors that may be influenced by presence of road lighting, such as mobility, accessibility, security and crime (Painter 1996; Farrington & Welsh 2002; Johansson, Rosén et al. 2011). In addition, there are potential negative effects of lighting, such as light pollutions and disturbances in ecosystem. The relationships between these factors and road lighting are perhaps even more difficult to model and quantify than those between road lighting and the risk of accidents, but they are nevertheless important to consider and be aware of.

In addition to the factors listed above, we think that it is of great importance that guidelines and criteria for road lighting are easy to understand and apply. This was discussed in the workshop (see also Appendix B), where it was emphasized that words and concepts such as *small*, *large*, *complex* etc. should be avoided, as they give room for interpretations.

7.1.3. Methods and indicators to evaluate the effects of road lighting

Essential for the development or revision of road lighting guidelines is the possibilities to identify and evaluate the relevance of various parameters. Traditionally, two types of evaluations have been done:

accident analyses and visual task experiments such as *Small Target Visibility* (STV). The former has primarily been used to evaluate the effectiveness of lighting (versus no lighting), while the latter aims at investigating visual performance at different lighting levels. Both methods have been questioned (see Chapter 5.1.1 and 5.1.3) and there is thus a need to find alternative methods.

In Chapter 6, various evaluation methods reported in the literature are listed. These include drivers' detection distances to pedestrians (Eloholma, Ketomäki et al. 2004; Gibbons & Hankey 2006; Lundkvist & Nygårdhs 2012), pedestrians' gaze behaviour (Davoudian & Raynham 2012; Fotios, Uttley et al. 2013), glare (Murray, Carden et al. 2002), pedestrians' subjective experience of aspects such as visual accessibility and perceived safety (Johansson, Rosén et al. 2011; Jägerbrand & Carlson 2011; Fotios & Unwin 2013; Boomsma & Steg 2014). Based on this we suggest three potential ways of evaluating lighting:

- ***Visibility and detectability of pedestrians***
  Most knowledge on visibility of pedestrians is based on experiments were the driver has been asked to look for pedestrians. As expectancy will have an influence on the detection distances (Bhagavathula & Gibbons 2013), the result of such experiments may be hard to interpret in terms of driver needs. Developing methods to investigate the detectability of pedestrians *without* telling the driver what to look for is thus needed, in order to be able to investigate how lighting influences detectability in real traffic conditions. Eye tracking could perhaps be used for this purpose.

- ***Glare, visual discomfort and visual experience***
  Rating scales could be a possible way of evaluating the amount of glare and visual discomfort from oncoming traffic and ambient light sources, and the visual experience of the driving scene. Such an instrument could include existing and established scales such as the De Boer scale (De Boer 1967) but possibly also new scales or variables in order to cover other aspects of the visual conditions. Preferably, subjective methods should be combined with objective methods or models. A review of such models has been presented by Clear (2013).

- ***Subjective experience***
  Subjective experience may be most useful for the evaluation of lighting for pedestrians and cyclists. For example, ratings scales for various aspects of visual conditions and perceived safety could be used. An example of such a scale is the *Perceived outdoor lighting quality* (POLQ), which is an assessment tool for outdoor lighting in urban spaces (Johansson, Pedersen et al. 2014).

The methods suggested above are related to several of the parameters in CEN/TR 13201-1 that are assumed to be of relevance for selection of lighting class (Section 5.2 and 5.3), such as *traffic volume* and *traffic composition*.

Other possible ways of identifying needs and problems related to the visual conditions at night could be some sort of *road safety audit* i.e. a safety performance examination by an expert team, or in-depth case studies of night-time accidents. Such studies could potentially contribute to a better understanding of road lighting as a safety measure.

7.2. Recommendations regarding the use of CEN/TR 13201-1 in Sweden

There is no evidence that the method for selection of lighting classes presented in CEN/TR 13201-1 is better than the guidelines used in Sweden today, neither from a road user perspective nor from an energy use perspective. Thus, for the moment, we cannot recommend the introduction of this method.

If the road authorities still wish to introduce this method, for example in order to harmonize the guidelines with other European countries, we recommend the following:

- Careful selection of criteria, parameters and weighting values (see also below), preferably supplemented and supported by empirical studies.
- Extensive testing, both with respect to reasonableness of the results and with respect to the usability, reliability and repeatability of the method.

In the workshop where CEN/TR 13201-1 were discussed (Appendix B), some further remarks and recommendations were made:

- The selection of parameters and options will have a large impact on energy use, since an increase of one point (weighting value) corresponds to an increase of one lighting class.
- To make the method easy to use, there should be no more than two options per parameter. If there is a need for more than two, there have to be examples or definitions that describe the different options so the users can make correct choices. Some criteria also need to be clarified.
- It is important for lighting designers and engineers to get guidance on how to use the method. Predefined tables with recommended lighting classes for common road and street types can be helpful.

7.2.1. Criteria for the M and C classes

There is some support in the literature that *traffic volume*, *traffic composition*, *separation of carriageway*, *ambient luminosity* and *navigational task* are relevant parameters for selection of lighting class. These parameters were also regarded as relevant by the experts that participated in the workshop.

For all these parameters there is a need for more knowledge on how they are related to the road users' needs and safety. In addition, there are some considerations of how the parameters should be applied. For example, there are often large variations in traffic flow during day and night. Preferably, the lighting level should be adapted to the present traffic flow by using dimming schedules, but if this is not possible, which flow should determine the lighting level? CEN/TR 13201-1 suggests that traffic flow should be classified according to *percentage of maximum capacity*. This was questioned by the workshop participants, who thought there are better ways of expressing traffic flow.

Regarding the parameter traffic composition, some specifications are needed in order to make this parameter applicable. First of all, the use of the wording *high percentage of* is very non-specific and should thus be clarified. Secondly, the term *mixed* needs a clarification. Does it mean that different types of road users actually share the same space, such as at pedestrian crossings and streets where there is no dedicated cycle lane and cyclists thus have to cycle on the street, or does it mean that there are vulnerable road users in the proximity to the street (on pavements etc.)? Both cases might be relevant from a lighting level point of view, but for different reasons and accordingly with different recommendations for lighting design.

Similarly, the parameter navigational task would need some specifications. In Finland, the term *Driving task* is used instead, which includes control, guidance and navigation. When considering the parameter navigational task, it should be pointed out that there is other road equipment such as signs and road markings that may guide and assist the driver and thus reduce the need for lighting.

Design speed or speed limit is the first parameter in the CEN/TR 13201-1 table, and it has the widest range of weighting values. This implies that speed will have a great impact on the selection of lighting class (if the table is used in its original form). The experts that participated in the workshop considered speed as an important parameter at first, but after some discussions, the opinion changed a bit and the relevance was questioned. There is not much support in the literature that speed *per se* is a relevant parameter, however, if certain visual needs can be identified, such as the need to be able to detect and see pedestrians, speed will have an influence on the time available for detection and action.

Present guidelines in different countries for selection of lighting class include more or less the same criteria as CEN/TR 13201-1, i.e. traffic volume, traffic composition, separation of carriageway and complexity. Speed is also a commonly used parameter, as well as ambient luminosity. However, a difference between CEN/TR 13201-1 and national guidelines is that the latter often use road type (e.g. motorway, arterial road, local street etc.) as a selection criterion, which is not the case in CEN/TR 13201-1.

Other, minor, differences between present guidelines and CEN/TR 13201-1 is the parameter *parked vehicles*, which is not mentioned at all in six of the eight reviewed countries' guidelines, and parameters such as road width, number of lanes and presence of trackbound traffic, which are used in some national guidelines but not in CEN/TR 13201-1.

7.2.2. Criteria for the P classes

Regarding lighting class criteria for footways and cycle tracks, there is some evidence that *ambient luminosity* is of relevance, while the relevance of *travel speed*, *use intensity*, *traffic composition* and *facial recognition* is somewhat uncertain. There is not much literature that supports the use of these parameters and neither had the workshop participants a clear view on the relevance.

Factors related to perceived safety and security are not explicitly included in the parameters above, perhaps with the exception for the parameter facial recognition. Boomsma and Steg (2014), found that the acceptability of reduced lighting levels was related to perceived safety. Furthermore, perceived safety has been found to be linked to the built environment (Hong & Chen 2014). Thus, there might be reason to investigate whether there are other parameters than those suggested in CEN/TR 13201-1 that are of relevant for pedestrians and cyclists.

It is worth mentioning that technical committee within CIE (TC4-52) aimed at gathering evidence that can be used to set design criteria for pedestrian lighting, has recently been formed. The work includes compiling existing criteria in different countries, investigating visual tasks that are of importance for pedestrians, and considering cost-benefit factors.

7.3. Recommendations for further research

7.3.1. General recommendations

In order to increase knowledge on road users' needs and experiences in night-time traffic we suggest further research as follows:

- ***Exploration of road users' experiences and identification of needs***
  Feasible methods for this are various qualitative approaches, such as questionnaires, interviews and focus groups. It would probably be a good idea to carry out the assessment when road users are actually using the roads, for example interview them while driving or walking. Another interesting approach would be to carry out eye-tracking studies, in order to assess road user's visual behaviour in relation to the lighting conditions.

- ***Controlled studies***
  Based on the results from the qualitative studies, controlled experiments should be carried out to assess various aspects of user needs, such as detectability, visual comfort, adaptation levels and minimization of glare, or other factors that are regarded as important by the road users.

> The studies should aim at determining lighting levels for various situations were both road user needs and energy use is taken into account. In particular, parameters and criteria that may be the basis for how to apply dimming schedules and adaptive lighting should be investigated. A concrete proposal for a future study is to further investigate the suggestion in Crabb, Beaumont et al. (2005) that it may be safe to dim to 0.5 cd/m^2 during the quiet part of the night.

In a third step, the possibilities to carry out naturalistic driving studies (NDS) or similar should be investigated. There are probably some technical challenges with respect to vehicle instrumentation and lighting installations (for example, it would be interesting to be able to change the lighting level on some roads) that needs to be solved in order to accomplish such studies. However, naturalistic studies would be important in order to validate the results from the controlled experiments in real driving situations.

When carrying out studies on road lighting, the age of the participants should be considered. As visual performance tends to deteriorate with age (Khan et al. 2011), the needs of older road users are probably larger than that of younger drivers, and should thus form the basis when developing or revising road lighting guidelines.

Another suggestion for further research is to perform in-depth case studies of night-time accidents on roads with lighting in Sweden, in order to investigate whether there are factors related to the lighting and the visual conditions that may have contributed to the accidents. Of particular interest are accidents involving vulnerable road users, as they tend to be at an increased risk at night (Johansson, Wanvik et al. 2009).

It should be emphasized that further research should include investigations of criteria and guidelines for pedestrians and cyclists. Although there may be a "risk" that such investigations will come to the conclusion that pedestrians and cyclists would prefer to have higher lighting levels than today in order to feel safe and comfortable, which would increase the energy use of the lighting installations, this may still be beneficial from an energy perspective if it makes it more attractive to cycle or walk.

7.3.2. Recommendations for next phase in this project

The main motive for this project is to investigate whether energy can be saved by revising the guidelines for road lighting level. Based on the literature review, we think that the greatest potential in saving energy is found on roads where no vulnerable road users are present. For example, Johansson, Wanvik et al. (2009) showed that vulnerable road users in urban areas are at an increased risk of having an accident at night, while no such risk was seen for car occupants.

The third and last part of the present project, which aims at testing some method(s) for assessment of parameters and criteria that are of importance for road users and for energy use, and that can be used as selection criteria for road lighting class, will thus be focused on lighting for roads without vulnerable road users.

For roads where there are no vulnerable road users present, our hypothesis is that the most relevant parameter for selection of lighting level is traffic flow, which is related to visual comfort. Oncoming vehicles' lighting will increase the driver's adaptation level which will make the roadway appear dark, unless this effect is counteracted by road lighting. Thus, the research question the tested method should be able to answer is: *What lighting level is needed in relation to the traffic flow, including no or very low flow, for visually comfortable driving?*

7.4. Limitations

A limitation of the literature review in this report is that the literature search was limited to publications on road lighting. There is a possibility that results from other research areas would be of relevance for many of the topics discussed in the present report, such as research on visual performance, traffic safety and walkability.

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Appendix A. Terms and definitions

Below are definitions of words and concepts related to light, lighting or traffic engineering, in alphabetical order.

- **AADT**, **-** [-]. Annual average daily traffic.
- **Colour rendering index**, *CRI* [-]. A measure of the ability of a light source to show object colours faithfully compared to a reference source, which is either an incandescent lamp or daylight.
- **Colour temperature**, **-** [K]. A measure of light source colour appearance, applicable to nominally white sources.
- **Edge illuminance ratio**, *EIR* [-]. Average horizontal illuminance on a strip (with the width of one driving lane) just outside the edge of a carriageway in proportion to the average horizontal illuminance on a strip just inside the edge.
- **High pressure sodium, HPS.** High pressure sodium lamps are a type of gas discharge lamps, which provide a yellowish light with relatively poor colour rendering.
- **Illuminance**, E [lx]. The luminous flux per unit area at a point on a surface. The unit is lux. $E = \Phi_v / A$, where A is the area (m^2).
- **Light emitting diode, LED.** A light source.
- Three illuminance parameters are relevant for road lighting:
  - **Average illuminance**, $\overline{E}$ [lx]. Horizontal illuminance averaged over a road area.
  - **Minimum illuminance**, E_{min} [lx]. Lowest illuminance on a road area.
  - **Overall uniformity of the illuminance,** U_o, [-]. Ratio of the lowest illuminance to the average illuminance, i.e. $E_{min}/\overline{E}$.
- **Luminance**, L [cd/m^2]. Reflected luminous intensity per unit area. The unit is candela per square meter. $L = I/A$, where A is the area.
- Three luminance parameters are relevant for road lighting:
  - **Average luminance**, $\overline{L}$ [cd/m^2]. Average luminance of the road surface.
  - **Overall uniformity of luminance**, U_o [-]. Ratio of the lowest luminance to the average road surface luminance, i.e. $L_{min}/\overline{L}$.
  - **Longitudinal uniformity of luminance**, U_l [-]. Ratio of the minimum to the maximum luminance along a line parallel to the run of the road, i.e. L_{min}/L_{max}.
- **Luminous flux**, Φ_v [lm]. Radiant flux weighted by the spectral sensitivity of the eye, i.e. the amount of light that can be registered by the eye. The unit is lumen.

- **Luminous intensity**, *I* [cd]. The luminous flux emitted in a particular direction per unit solid angle. The unit is candela. $I = \Phi_v / \Omega$, where Ω is the solid angle (steradians).

- **Maintenance factor.** The luminous flux emitted from a light source decreases over time, due to lamp lumen depreciation and dirt on the luminaire. By including the maintenance factor in lighting calculations, this depreciation is accounted for. As a consequence, new lighting installations are usually gives more light than the lighting class prescribes.

- **Mesopic.** Refers to a mix of photopic and scotopic conditions. Corresponds approximately to luminances ≤ 10^{-1} cd/m^2.

- **Metal halide, MH.** Metal halide lamps are a type of gas discharge lamps, which provide white light.

- **Photopic.** Refers to daylight/colour vision. Corresponds approximately to luminances ≥ 10 cd/m^2.

- **Radiant flux**, Φ [W]. The total rate of flow of energy emitted by a source. The unit is watt.

- **Scotopic.** Refers to vision under low light conditions. Corresponds approximately to luminances in the range of 10^{-1}-10 cd/m^2.

- **Threshold increment**, *TI* [%]. Threshold increment is a measure of the disability glare from road lighting luminaires. It is defined as the percentage increase in the luminance difference needed to make an object visible in the presence of glare when it is just visible in the absence of glare. See also EN 13201-3

Appendix B. Workshop summary

A workshop was arranged at the Clarion Hotel Arlanda Airport the 25th to 26th of November 2014. The topic of the workshop was the national implementation of the technical report CEN/TR 13201-1 *Guidelines on selection of lighting classes*. The main question that was discussed concerned which criteria should be used for selection of lighting classes taking both the traffic and the energy perspective into consideration. In addition, a draft of the literature survey (i.e. this report) about scientific basis for the present criteria in CEN/TR 13201-1 was presented and there were discussions about knowledge gaps and research needs. The workshop was also an opportunity to start to co-operate in the work to revise road lighting guidelines in the Nordic countries and to exchange experiences and knowledge.

Experts on road lighting from Denmark, Finland, Norway and Sweden were invited. The participants were Pentti Hautala and Aleksanteri Ekrias (LiCon-AT Oy Finland, sponsored by Finnish Traffic Agency), Per Ole Wanvik (Statens Vegvesen, Norway), Petter Hafdell and Peter Aalto (Trafikverket, Sweden), Sara Nygårdhs, Carina Fors and Annelie Carlson (VTI, Sweden).

The programme for the workshop:

Tuesday 25th November

10:00 Introduction and presentations of the existing guidelines for road lighting in Finland, Norway and Sweden

11:00 Discussion about the existing guidelines and road lighting. Similarities?; Differences?; Where is there too much lighting?; Where is it too little lighting?

12:00 Lunch

13:00 Presentation of CEN/TR 13201-1

13:30 – 17:00 Discussion about the criteria in CEN/TR 13201-1. Which criteria are relevant?; Which criteria are not relevant?; Is there some criteria missing?

Wednesday 26th November

08:30 Presentation of the literature survey made by VTI

09:00-12:00 Discussion about criteria in CEN/TR 13201-1 and presentation of relevant and recent research.

12:00 Lunch

13:00 Discussion about criteria in CEN/TR 13201-1 and presentation of relevant and recent research.

14:45 Summary

15:00 Workshop ends

Similarities and differences in the Nordic countries regarding guidelines for road lighting.

National guidelines were presented by representatives from each country. The presentations were followed by a discussion about similarities and differences between the countries. Furthermore, the participants were asked about their view on the existing guidelines and whether they thought there are any particular road types or traffic environments that in general have too high or too low lighting levels.

Comparison of guidelines

The present guidelines in Norway, Sweden and Finland have a lot of similarities. The main difference is the recommendations for lighting of motorways. In Norway, the recommendation is that motorways should always be illuminated. In Finland and Sweden the guideline is that it should not be illuminated unless there is an identified need for it. The Norwegian recommendations are however under revision, since there is a view that there might have been an overconfidence in the benefits of illuminating motorways. The low energy prices in Norway may also have contributed to the decision to illuminate motorways. In 2008, the recommended lighting level for Norwegian motorways decreased from 2 cd/m^2 to 1 cd/m^2 without noticing any negative effect on traffic accidents. They are currently investigating if it is possible to decrease the levels further, studying results from US and Canada where the lighting levels are substantially lower than in Europe. Motorways with low traffic volumes will probably not be illuminated at all. Finland has also reduced the lighting levels on motorways from 2 cd/m^2 to 1 cd/m^2. The maximum value of 2 cd/m^2 is rarely used on some urban motorways. In practice values are 1.5 cd/m^2 (urban motorways) and 1 cd/m^2 (rural motorways). The required longitudinal uniformity is also lower, a ratio of 0.6.

In Finland, the decision of whether a road should be illuminated or not is based on the profitability, in terms of expected reduction in accidents. It is assumed that lighting will lead to an accident reduction of 20% on motorways, 25% on other road types with motorized traffic only and 30% on other road types with mixed traffic. Some road sections are lit regardless of average daily traffic volume (ADT), e.g. tunnels, urban motorways, major intersections, docks, frontiers and so on. Otherwise the average daily traffic volume is used to define whether or not the road shall be lit, Table 28.

Table 28. The Finnish criteria for whether a road shall be lit or not.

Road class		
Dual carriageway roads	ADT volume (veh/d)	
Motorway	40 000	
Dual carriageway, 2 + 2 lanes, intersections	20 000	
Dual carriageway , 2 + 2 lanes, guardrail	34 000	
Road with an overtaking lane, guardrail	23 000	
Single carriageway roads	Junction density (pcs/km) *	
	2	5
Main roads	7 000	3 000
Collectoral and local roads	2 500	1 500

A similar approach is applied in Norway. In Sweden, the basis of the recommendations is not well-documented but it is thought to originate from cost-benefit analyses on accessibility.

There was a discussion about the experience of reducing glare from oncoming traffic. In Sweden, the width of the central reserve of motorways has decreased and the problem with glare is increasing. 2+1 roads are also common, where the road is quite narrow and the carriageways are separated with a wire guardrail. In these types of roads glare may be a problem. In Finland they had a trial with using trees as a barrier between carriageways. However, the branches closest to the ground did not survive the environment of exhaust emissions, salt and wear particles. The trees ended up having no branches where it was needed, hence the glare reducing effect was lost. In Norway there is a requirement of shielding between carriageways in case there is no road lighting. They have had a similar test as Finland, with the difference of using shrubs instead of trees. The experience is that is seems to work.

There is also differences in the guidelines for illumination of roads in relation to cycle tracks and footways. In Norway and Finland, footways and cycle tracks are illuminated either with the road lighting of the main road or with separate lighting installation for pedestrians and pedal cyclists. Usually, when a footway or cycle track is adjacent to a main road, the main road illumination is adequate. In Norway, if the cycle track is illuminated the adjacent road is illuminated as well to facilitate the navigational task for drivers. In Sweden, there is the possibility to illuminate the cycle/pedestrian way but not the adjacent road.

In Sweden the lighting levels are the same for a combined cycle track and footway as it is for separated cycle track and footway. It should be higher at areas where the paths are combined. Also Norway concluded the need for more lighting on cycle tracks and footways.

Experiences from earlier revisions of guidelines for road lighting are that the work is much based on practices and experiences and that there are no concrete measures to base decisions on. There are no definitions of words and concepts such as *small*, *large*, *very complex* etc.

Lighting levels

It is speculated that the lighting levels might be too high on motorways. In both Norway and Finland the lighting levels on motorways have been reduced (see above).

In town and cities, the lighting levels are in general higher in Europe than in the US. There is no general view that the lighting levels in Nordic towns are either too high or too low. In Norwegian communities, the lighting levels tend to become very low due to the introduction of LED. The reason for the low levels is the notion of better vision with LED. However, it may be difficult to discover pedestrians and cyclists, particularly in bad weather conditions and in the presence of glare.

In Sweden, it has been noticed that there can be a spiralling effect of lighting levels in areas where new buildings are constructed. In the newly built areas, one often chooses to have high lighting levels. The surrounding areas, with lower lighting levels, are in comparison dark and one want them to also be as bright as the new one. Hence, the overall lighting levels may become too high.

The lighting levels at pedestrian crossings may be too low, especially in combinations of heavy traffic and glare. In Norway, there are positives experiences of having intense lighting at pedestrian crossings.

Adaptive lighting and dimming are being used in all three countries. In Norway, dimming is usually done by reducing the recommended lighting level by 50%, but not below 0.5 cd/m^2. When planning for a new installation, there must be an evaluation whether dimming should be applied. In Finland all new road lighting installations must be dimmable. Also, several schedules for dimming are being introduced, e.g. one which relates the lighting level to the variations in traffic volume during the day. In Sweden, there are no clear recommendations about dimming levels.

Complaints from the public about road lighting are reported when the lighting is not functioning, either not lit when it should or lit when it should not be. There is also complaints about poor lighting at pedestrian crossings. Complaints about lighting levels in general are rare.

When discussing lighting levels it should be kept in mind that there might be a discrepancy between the recommended levels and the actual levels. Measurements of lighting performance of new lighting installations are usually done in Finland, but very rarely in Norway and in Sweden. For existing installations, performance measurements are even rarer. In addition, the recommendations for road and street lighting provided by the road authorities in Finland, Norway and Sweden are not compulsory for the municipalities, where a majority of all lighting is located. This implies that there is limited knowledge on the actual lighting levels on the Nordic roads and streets.

Discussion about criteria for lighting class M

Pentti Hautala, who has been involved in the preparation of CEN/TR 13201-1 gave a presentation about the report. He emphasized that:

- *The criteria should be adapted to the specific needs and conditions in each country*
- *Classification of roads is not a part of the report because it is difficult to define classes that are applicable in all countries*
- *The report will probably be used in many European countries. Several countries are already using it.*

In Finland, a national adaptation of the CEN/TR 13201-1 criteria is currently under development. A new edition of Finnish national code of practice for road lighting will be published in the beginning of 2015. In Norway and Sweden, there is an interest in using CEN/TR 13201-1, but there have not yet been any activities aiming at incorporating the method in the national guidelines.

The parameters in CEN/TR 13201-1 were discussed, with focus on the M classes. The summary below reflects the spontaneous views and opinions of the participants at the workshop. It should not be interpreted as "the truth" or as the official view of the road authorities.

Design speed or speed limit

The participants thought that speed was a relevant parameter. The motives of having speed as a parameter were however not quite clear. One reason might be that the consequences of accidents are more severe in higher speeds. Another point that was brought up was that it is more strenuous to drive in darkness and lighting can relieve some of the strain. The vehicle headlamps will not give enough light for comfortable driving in high speeds.

There were a lot of discussions on how to divide speed into different options/intervals and how to relate those options to a weighting value. In the table of criteria and their proposed weighting value, speed has the largest interval of all criteria, ±2. This weighting value may be too high in relation to the importance of the criteria and it could probably be reduced. There are at the same time other criteria that are more important and which may have higher weighting values.

Some suggestions on options and weighting values:

- Maybe the option *Very high* can be skipped and only have *High*; *Moderate* and *Low* and decrease the weighting values to ±1.
- In the new edition of Finnish national code of practice for road lighting, the suggestion is to have five levels from -2 to 2, corresponding to speeds from 40 to 120 km/h, Table 29.
- Maybe the parameter speed and its options (speed limits) should be combined with other parameters.

Table 29. Parameters for the selection of lighting class M in Finland.

Parameter	Options	Description		Weighting Value V_W
Design speed or speed limit	Very high	120 km/h		2
	High	80, 100 km/h		1
	Moderate	60 km/h		0
	Low	50 km/h		-1
	Very low	30, 40 km/h		-2
Traffic volume	High	ADT ≥ 12 000		1
	Moderate	4 000 ≤ ADT < 12 000		0
	Low	ADT < 4000		-1
Traffic composition	Mixed with high percentage of non-motorised	Pedestrians, cyclists, parked vehicles		2
	Mixed			1
	Motorised only			0
Separation of carriageway	No			1
	Yes			0
Junction density		Intersections/km	Interchanges, distance between bridges, km	
	High	5	< 3	1
	Moderate	2	≥ 3	0
Ambient luminosity	High	Urban area		1
	Low	Rural area		0
Driving task	Difficult			1
	Normal			0

Speed was brought up for discussion again, at a later occasion. It was then speculated whether speed is a relevant criterion at all. The argument was that since drivers manage to drive fast without any road lighting at all (as on most motorways in e.g. Sweden), there might be no reason to have a *higher* lighting level on (lit) high speed roads than on roads with a lower speed limit.

Traffic volume

Traffic volume is used as a criterion in the present national guidelines in the three countries, both to decide whether to have lighting or not and to select lighting class. Finland has a connection between when lighting is profitable and AADT with regard to decreased level of accidents. Sweden has, for some years ago, used the EVA[8] model to estimate cost benefit with road lighting. However, for new roads Sweden do not estimate the impact road lighting may have on traffic accidents. The guidelines in Norway state that road lighting should be installed where it is socio-economically profitable with regards to traffic safety. Traffic volume is thus seen as a relevant criterion.

Comments on traffic volume as a criterion:

- There are probably better ways of expressing traffic volume than in percentage of maximum capacity.
- Traffic volume on streets are difficult to know since it is not registered.
- Dimming should be applied in relation to traffic volume.
- Traffic volume is something that has importance due to the presence of glare. A higher lighting level will counteract glare.

Traffic composition

Traffic composition is considered to be an important criterion, especially with regard to the presence of vulnerable road users. In a recently published American technical report on guidelines for implementation of reduced lighting on roadways there is a big emphasis on the vulnerable road users (Gibbons, Guo et al. 2014). The participants of the workshop agreed that this was good.

The suggestion on how to classify the traffic composition was discussed. Do “mixed” mean that there are vulnerable road users on the street or on separated ways (pavements) beside the street? Cyclists may use the street even though there is a path for pedestrians and cyclists. What do “a high percentage” mean? It was pointed out that it is very difficult to define different options, but nevertheless the options needs to be decided and explained in order to be applicable.

In Finland they are thinking about removing the option “high percentage of mixed”, in order to simplify the table. They have also removed the parameter “Parked vehicles” and added it as an option in the “Traffic composition” category (Table 29). A comment about the Finnish guidelines was that they seem to put a large emphasis on speed, while unprotected road users have a lower priority. It should be the other way around.

A suggestion was to include the share of heavy traffic since it will have an impact on the complexity of the traffic situation. Road lighting can in the circumstance with a large share of heavy vehicles improve the viewing distance which can make overtaking more secure. However, road lighting may also lead to false safety, where drivers will overtake in dangerous situations.

Separation of carriageway

Two motives for using *Separation of carriageway* as a parameter were identified: separated carriageways reduce the accident risks and the amount of glare. It might thus be a relevant criterion.

Junction density

Junction density was not much discussed. It was suggested to adapt the lighting level on the roads between the junctions to the lighting levels used in the junctions.

[8] EVA (Swedish: *Effekter vid väganalyser*) is a tool for cost-benefit analyses provided by the Swedish Transport Administration.

Parked vehicles

It is good to have lighting where people are getting in and out of their cars. This parameter may however be connected to traffic composition.

Ambient luminosity

Ambient luminosity is seen as an important parameter, particularly for urban areas where there might be commercial signs, highly lit sports fields and shopping centres close to the road. It is probably enough to have two options; *Normal* and *High* (0 and 1 as weighing value).

Navigational task

The definition and interpretation of *Navigational task* were discussed. In Finland, they use *Driving task* instead of *Navigational task*, which is similar to the US highway recommendations. *Driving task* includes control, guidance and navigation.

A suggestion was to change *Easy* to *Normal* and to delete *Very difficult* to make the interpretation easier. In that case there would be two options; *Normal* and *Difficult*. Difficult would be defined by having short distances between interchanges, several lanes, road markings that are difficult to see and short time to make decisions. It was emphasized that the various options must be clearly defined.

Having only two options is similar to the Finnish draft (Table 29), where *Driving task* have two levels of complexity. All agreed that this is a good solution.

A question was raised to whom one should dimension the road lighting for. Is it the drivers who seldom use the road or the ones who are often driving there?

The design and visibility of the road markings are important for the navigational task. It was speculated whether adaptive lighting could be used to enhance the visual conditions in case the road markings are of bad quality and/or difficult to see.

It was pointed out that navigational tasks often are related to conflict zones, where the C classes apply.

Other

It was pointed out that any modifications and adaptations of the table require extensive testing, i.e. one must make sure that the table gives reasonable results. It was also emphasized that the selection of parameters and options will have a large impact on energy use, since an increase of one point (weighting value) corresponds to an increase of one lighting class.

To make the table easy to use, it should be no more than two options per parameter. If there is a need for more than two, there have to be examples or definitions that describe the different options so the users can make correct choices. Some criteria also needs to be clarified.

It is important for lighting designers and engineers to get guidance on how to select lighting classes. Predefined tables with recommended lighting classes for common road and street types can be helpful. Some designers/engineers make calculations for every project whereas others do as they usually do. In Finland they have courses for designers, road authorities, municipalities, manufacturers and contractors to ensure they are all up to date and work with the same method. It is also important that the municipalities accept and use the tables. In Finland, Norway and Sweden the municipalities do not have to follow the guidelines. In Finland they follow the recommendations to a large extent.

The participants discussed the possibilities to have two different tables for M-classes: one for motorways and one for other roads including both rural and urban, Table 30. This would make the tables simpler to use and it may be possible to get a better compliance for what is needed. Simplifications are beneficial:

- More criteria → more insecurities

- Simplifications → more control

Table 30. Suggested criteria for selection of lighting classes for motorways and roads.

Motorway	**Road**
Design speed Traffic volume Junction density Glare blocking Ambient luminosity (?)	All suggested criteria are probably relevant. Presence of vulnerable road users is of particular importance.

An alternative suggestion was to use 1 cd/m^2 (M3) as a default value for all roads and then change to higher or lower lighting classes depending on the characteristics of the road. For instance, if there is a lot of traffic, disturbing glare or pedestrians and cyclists on the road, the lighting class should be of higher quality (M2). In conflict areas 15 lx (C3) could be used as a default value.

Yet another alternative was to just decide lighting classes for different road types and conflict areas, since this probably would be easier both for those who will develop the guidelines and for those who will use them. A drawback is that it might be difficult to cover all possible cases.

It was also suggested that the method for selection of lighting class should be able to answer if there should be lighting and in that case what lighting class to use. In Finland, this is done is a two stage approach: 1) Decision of whether to lit or not, based on expected profitability (Table 28), 2) Selection of lighting class (Table 29).

Road geometry and its relevance for road lighting was discussed. The need for lighting might be larger on old roads with a low standard and in curves with small radii. Road geometry is not explicitly included in CEN/TR 13201-1, but it might be included in the “Navigational task” parameter.

The colour of light has importance for vision, particularly for older people. Compared to young people, the transmission of light in older peoples’ eyes is reduced due to aging of the lens. The effect is larger for short wave lengths, i.e. blue-violet light. Bluish light is also perceived as more glaring. That has been a problem with LED, but the development of LED with a warm white colour has led to fewer complaints from road users.

A relevant question when developing guidelines for lighting is whom the lighting is designed for. Is it the average road user or those with the largest needs, such as older or disabled people?

It was discussed whether the table for selection of lighting classes can be used to select lighting levels for adaptive lighting (dimming). The conclusion was that it is probably better to not include adaptive lighting in the table. Dimming is mainly based on traffic volume.

The Finnish solution for how and when to use adaptive lighting gained interest. Two principles are used: 1) Dimming by traffic volume, 2) Dimming by time schedule. In both methods, dimming is done in two steps, reducing the lighting levels maximally by 50%, e.g. M3-M4-M5. In Finland there is a requirement that all new roads shall be equipped with road lighting that are possible to dim.

In Norway they are testing road lighting that “follows” the vehicles, i.e. the luminaires are lit some distance in front and behind of the car. They are also testing to dim the light to low levels, approximately 20%, during hours with no or very low traffic.

Weather may be an important criterion when deciding upon adaptive lighting. However, it is difficult to adapt the lighting to snowy or wet weather conditions because the conditions can be unstable. An argument for having good lighting in bad weather is that it is beneficial to be able to see for example snow and ice on the road.

Discussion about criteria for lighting class C

It was discussed whether a separate table for the C classes is needed. The participants discussed an alternative solution that should make is easy to choose lighting class for conflict areas. In junctions and roundabouts the lighting class should be one class higher (quality) or equal as it is on the adjoining roads. Equal if the intersection is simple and one higher if the intersection is complex. This approach is similar to what is suggested in CEN/TR 13201-1 for most conflict areas, i.e. to use a conversion table to convert the M classes on the connecting roads to a C class for the conflict area.

On rural roads, the intersections are more complicated since the adjoining roads most likely are not illuminated. The question is which lighting class one should choose in those circumstances. In Finland, if only the intersection is illuminated, lighting class M3 is used when the speed limit is ≥80 km/h, and M4 when the speed limit is ≤ 60 km/h.

There may be a need to have specific recommendations of lighting classes for some places, such as bus stops, quays and movable bridges. Pedestrian crossings should have their own requirements and should not be included in the M-, C- or P-classes.

Discussion about criteria for lighting class P

The P classes were only briefly discussed due to time constraints. The discussion were limited to lighting for footways and cycle tracks.

It was discussed how *Use intensity* should be applied. In the current Norwegian guidelines, only P2 and P4 are used on cycle tracks and footways. The number of users is the deciding factor for which of the classes that is used.

Lighting the surroundings of cycle tracks and footways can be important from a security perspective. LED lighting is not optimal from this point of view, since the amount of stray light is low.

Regarding traffic composition, it was believed that conflict situations mainly are dependent on the design of the street/path, and not that much related to lighting.

It was pointed out that modern headlamps for bikes can be very glaring, which may increase the need for high lighting levels on paths for pedestrians and cyclists. Besides, there are also many cyclists that do not have any headlamp at all, and they are difficult to detect in poor lighting conditions.

It might be relevant to include high speed cycle tracks (*Swedish: supercykelvägar*) as a parameter in the P classes. It is important to have good lighting on these paths.

Facial recognition and its relevance was discussed. It is difficult to know what is experienced as unsafe. Research indicates that light colour will have an influence on the possibilities to recognize faces.

Presentations of research

Per-Ole Wanvik presented a study by Ron Gibbons (Gibbons, Guo et al. 2014a) of traffic accidents and lighting levels in the US. The lowest night/day accident ratio happens at 15 lx and too high uniformity is not beneficial. A conclusion of the report is that there should be lower lighting class (quality) on motorways and higher on streets where there are unprotected road users present. It was suggested that 1 cd/m^2 is sufficient for motorways, while 1.5 cd/m^2 is recommended for streets.

Aleksanteri Ekrias presented the results of a small Belgian study (no publication available), where 14 lighting designers were asked to select lighting class for a few test cases based on the parameters given by CIE 115, which is similar to CEN/TR 13201-1. It was found that the interpretation of the parameters differed a lot among the designers and it was concluded that there is a need for guidelines on how to interpret and apply the criteria.

Field experiment and the need for research

The discussions regarding further research and the field experiment that will be performed later on in this project concerned the following topics:

- Adaptive lighting and visibility
- Light colour and the needs of older people
- Facial recognition
- Colour rendering. When is it beneficial? What are the recommendations?
- Mesopic models in practice
- Combination of road lighting and vehicle head lights in dense traffic
- Adaptation. How much light is needed to counteract glare?
- Older drivers and glare

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