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AN ADVANCED APPROACH TO ROAD LIGHTING DESIGN, MEASUREMENTS AND CALCULATIONS

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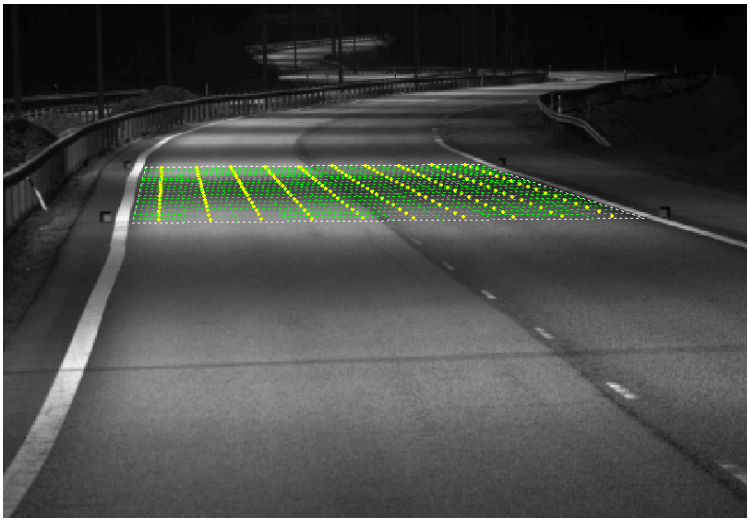

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Abstract

This research work has been carried out by Lighting Unit of Helsinki University of Technology during 2006-2008 as a part of a research project "ValOT”. The objective of the project is to develop the quality, safety and energy-efficiency of road lighting. The research project “ValOT” is funded by the Finnish Funding Agency for Technology and Innovation, Finnish lighting industry, and public authorities and municipalities.

This report focuses on the basics of road lighting design, measurements and calculations. Luminance design criteria and Small Target Visibility (STV) design criteria are introduced, based on the European and American standards. In this work also some fundamental problems of current road lighting design practice are discussed. Visual conditions and mesopic visual performance in night time driving are analyzed as well.

The paper introduces an advanced approach to road lighting calculations and measurements based on the use of an imaging luminance photometer and a computer program Road LumiMeter v2.0. The work also introduces a new method for road lighting luminance measurements and analysis.

Keywords: Road lighting design, measurements and calculations, visibility of targets, visual conditions, road lighting standards, imaging luminance photometer, road lighting calculation program

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1. Introduction

1.1 Background

The purpose of road lighting is to increase the safety, rapidity and comfort of road traffic. Road lighting should provide good visibility conditions by illuminating the road surface and its surroundings and by making targets on the road visible to the driver.

Road lighting could be considered to be among the most efficient traffic safety measures available. Studies have shown that the accident rate is 1.5 to 2 times higher during the night-time than in daylight. In the case of the fatal accidents the rate is three times higher in darkness as in daylight. In general, construction of road lighting is found to reduce night-time accidents by 20...40 %. Based on the several studies the mean accident reducing effect in darkness is found to be about 30 % for all injury accidents, 60 % for all fatal accidents, 45 % for pedestrian accidents, 35 % for injury accidents at rural junctions, and 50 % for injury accidents on motorways. The accident reducing effect is significantly lower during snowy and rainy weather conditions compared to dry weather conditions. There is found no significant correlation between lighting level or other road lighting quality parameters (overall and longitudinal luminance uniformities, disability glare, surround ratio) and accident rate. However, there are some indications that raised road luminance level reduces the accident risk for pedestrians, especially at pedestrian crossings. [Wanvik 2006]

Historically, two complementary measures of road lighting system performance have been employed: illuminance, or the amount of light from luminaires incident upon a given surface of interest, and luminance, or the amount of reflected light returned to the driver's eye from the surface of interest. Before about 1940, road lighting design criteria were based mainly upon lighting levels expressed in terms of illuminance units. The installations were designed on the basis of photometric data such as the luminous flux ϕ of the light sources and the light distribution of luminaires, and on the geometry of the installation (mounting height h, spacing s and road width w). Around 1940 this phase of photometry and geometry was followed by the phase of physiology. The design of lighting installation was shifted towards the inclusion of visible quantities: target luminance, road surface luminance, road surface luminance uniformities, and restriction of glare [de Boer 1982].

There have been a lot of studies and research looking into the basic concepts of vision in road lighting; probably the most comprehensive work was by Waldram [Waldram 1934], by Weston [Weston 1945] and by Blackwell [Blackwell 1959]. The work of Waldram defined the "silhouette principle" of road lighting: most targets on illuminated roads are seen as dark silhouettes against the bright road surface. The work of Blackwell and Weston studied visual performance and discovered that the ability to perform a given visual task was based on target size, target luminance and the luminance contrast of the target relative to its background. These basic ideas of visual performance have been the key to the development of the luminance concept of road lighting which is still used today. [Raynham 2004]

Early experiments in road lighting (1940s and 1950s) used Landolt rings and other stationary targets placed along the road surface as visual targets to evaluate the quality of the road lighting [de Boer 1967, van Bommel and de Boer 1980]. After various different visual tasks were tried out, the one adopted most widely by the road lighting research communities was a square target of 20 cm x 20 cm, having a contrast of 0.33 with respect to the road surface, and placed on the road 100 m in front of the driver. This visual task was used in the development of recommendations for the current road lighting levels [Raynham 2004].

After the Second World War road lighting research was no longer concentrating only on the visibility of targets on the illuminated streets, but started to include also visual comfort aspects. In the 1950s and 1960s, de Boer was one of the first researchers to add visual comfort to the pure visibility aspect of road lighting [de Boer 1967]. This was considered to be important in view of the fact that high-speed road users were making use of relatively comfortable motorways for relatively long drives. But it was also important due to traffic composition and density, which were changing dramatically already at that time. [CIE 2008]

In the 1960s, increases in the severity and frequency of traffic accidents led to attention in the statistical analysis of accident data. A lot of studies were made to find correlations between the number of accidents and road lighting quality. Probably the most comprehensive study of the effect of lighting on traffic accidents was carried out in the UK in the late 1970s by Green and Hargroves [Green and Hargroves 1979]. In the study, all the then-known road lighting quality parameters were taken into account. The parameter showing the strongest relationship with the night-time accident ratio was the average road surface luminance. [CIE 2008]

Due to the weak correlation between changes in road lighting quality parameter values and accident rates, the accident studies never played a deciding role in describing the quality parameters of road lighting (lighting level, luminance uniformities, disability glare). However, they played a role in decisions on whether or not to illuminate particular roads. In this context a comprehensive analysis of 62 studies from 15 countries published by CIE in 1992 [CIE 1992] has much relevance for whether or not to illuminate roads today. [CIE 2008]

Visibility factors have always been extremely important in the design of road lighting. Illuminance criteria have been proven to be inadequate predictors of the effectiveness of road lighting systems [de Boer 1982, van Bommel and de Boer 1980]. Although the visibility of targets is typically directly proportional to illuminance, there are too many intervening variables that determine the visual stimulus and the efficiency with which that stimulus is processed by the visual system.

In the 1970s, emphasis was placed on the anticipation possibilities of vehicle drivers. As a consequence, a more or less structural analysis of the driving task began to play an important role in research on road lighting. It was no longer sufficient to study only the visibility of targets located 100 m in front of the driver in the middle of the straight and more or less empty road. Many of the decisions a driver makes are based on the interpretation of the visual information available, such as road surroundings, the run of the road ahead, road surface markings, the presence of the other vehicles, pedestrians on road or on the roadside and, of course, possible targets on the road. Therefore, anticipation is important and supra-threshold visibility is required. [CIE 2008]

In 1970s Gallagher defined a measure for supra-threshold visibility, called the visibility index (VI), which can be defined from the lighting installation's photometric data [Gallagher 1976]. Since Gallagher's introduction of visibility index, many other researchers, especially in North America, have refined the concept. In the last 40 years a big effort has been made to add the visibility performance of the critical targets on the road in road lighting design, in order to provide more suitable solutions for real visibility conditions on the road. As a result Small Target Visibility (STV) concept was introduced in the Illuminating Engineering Society of North America document "American National Standard Practise for Roadway Lighting" ANSI/IESNA RP-8-00 [IESNA 2005] as one of the three criteria for designing continuous lighting systems for roads. However, in August 2006, the Roadway Lighting Committee (RLC) of the IESNA passed a motion to revise RP-8 by withdrawing the use of STV as a design metric. It was decided that the luminance criteria would be used for design of road lighting, illuminance criteria would be used for field or design verification, and STV criteria would only be used for comparison of systems that meet the luminance design criteria. The decision was initiated based on a continuing inability to correlate safety with the STV metric. [CIE 2008]

Until the late 1970s, road lighting was seen mostly in the context of motorised traffic. However, since the late 1970s, systematic approaches to the lighting of streets and reduction of the crime in night-time were made. One of the first systematic studies into the needs of residential areas and pedestrians, with the emphasis on personal security, was made by Caminada and van Bommel and published in 1980. [Caminada and van Bommel 1980]. The most important finding of the study was that the semicylindrical illuminance was the best suited measure for use in achieving a specified recognition distance in residential areas. Therefore, it is recommended that, if the security in streets is a potential problem, the semicylindrical illuminance should also be considered in addition to the conventional road lighting quality parameters. [CIE 2008]

Finally, in 1990s, increases in traffic congestion directed the research towards the evaluation on how road lighting could facilitate traffic flow. Facilitation of the traffic flow on the roads is however, dependent also on many other factors in addition to road lighting, for example road markings, traffic signs, traffic lights and so on. [CIE 2008]

Today, road lighting design, calculations and measurements in Europe follow the European standards EN 13201:2-4 [EN 13201-2 2003, EN 13201-3 2003, EN 13201-4 2003]. The European standard EN 13201-2 introduces ME/MEW-series of lighting classes for motorized traffic [EN 13201-2 2003]. ME/MEW classes are based on quality characteristics such as average luminance, overall and longitudinal luminance uniformities, disability glare and surround ratio. European Standard 13201-3 defines and describes the conventions and mathematical procedures to be adopted in calculating the photometric performance of road lighting installations designed in accordance with EN 13201-2 [EN 13201-3 2003]. EN 13201-4 specifies the procedures for making photometric and related measurements of road lighting installations [EN 13201-4 2003]. Standards EN 13201:2-4 are based on CIE publications No. 115 "Recommendations for the lighting of roads for motor and pedestrian traffic" published in 1995 [CIE 1995], No. 140 "Road Lighting Calculations" published in 2000 [CIE 2000] and No. 30-2 "Calculation and Measurement of Luminance and Illuminance in Road Lighting" published in 1982 [CIE 1982].

Illuminating Engineering Society of North America (IESNA) have proposed their own luminance design criteria in the American National Standard Practise for Roadway Lighting RP-8-00 (Reaffirmed 2005) [IESNA 2005].

1.2 Objectives of the work

The main objective of this work is to focus on the fundamentals of road lighting design, measurements and calculations. The work introduces the history of road lighting research and describes current road lighting design criteria. The work also concentrates on some fundamental problems of current road lighting design practice. Visual conditions and mesopic visual performance in night time driving are analyzed as well.

The other objective of the work is to introduce an advanced approach to road lighting calculations and measurements based on the use of an imaging luminance photometer and a computer program Road LumiMeter v2.0.

The quantity and the quality of road lighting can be analyzed and controlled with road lighting measurements. Road lighting measurements are conventionally done with spot luminance meters. The use of spot luminance meters, however, leads to long measurement periods and consequently requires the external conditions to remain stabile for several hours. The utilization of an imaging luminance photometer instead of a spot meter eases the luminance measurements and gives many new possibilities in analyzing the luminance distributions [Ekrias et al 2008a]. In Lighting Unit of Helsinki University of Technology a computer program Road LumiMeter v2.0 has been developed to be used along the imaging luminance photometers [Kolbe 2004, Ylinen 2007]. The main purpose of the program is to allow users to analyze data, measured with imaging luminance photometers, by using different road lighting standards and criteria and other optional calculation methods.

In this work the program Road LumiMeter v2.0 and the road lighting measurement results for seven different pilot locations are introduced. The pilot locations are measured and the road lighting quality parameters are calculated using different road lighting criteria (EN 13201:3-4, CIE No. 30-2, IESNA RP-8-00). The measurements are done with two different luminance photometers ProMetric 1400 and LMK Mobile Advanced. Also a new method for road lighting measurements is presented in the paper.

2 Road lighting design, measurements and calculations

2.1 Luminance design criteria

A surface and target are made visible by virtue of light being reflected from it and entering the eye of the observer. Thus, the illuminance on a road surface, which refers only to amount of light reaching that surface per unit of area, can give no indication of how strong the visual sensation will be and how bright the surface will appear to the driver [van Bommel and de Boer 1980]. The surface luminance depends on the amount of light radiated by the surface per unit of bright area and per unit of solid angle in the direction of the observer. This is the luminance (L) of the surface, which is given by

$$L = Eq \tag{1}$$

where E is the illuminance on the surface and q is its luminance coefficient, which is a measure of the amount of light reflected by the surface in the direction of the observer. Since brightness is finally determined not by illuminance but by luminance, the visual performance and visual comfort of a driver are directly influenced by the complex pattern of luminances existing in driver's view of the road ahead.

Road lighting for main roads is normally specified using the following parameters [EN 13201-2, IESNA 2005]:

- average road surface luminance (L_{av})
- overall road surface luminance uniformity (U_o)
- longitudinal road surface luminance uniformity (U_L)
- threshold increment ($TI\%$)
- surround ratio (SR)

The parameters all have a role in ensuring the lighting quality for the driver. Visual performance is governed by L_{av}, U_o. The ability to see a target on the road is a function of luminance on the darkest part of the road. The performance is also reduced by the disability glare characterized by TI.

A target may be seen because it differs from its background either in luminance or in colour: that is, there may be either a luminance contrast or a chromatic contrast. Both types of contrast depend on the reflectance properties of the scene and of the incident illumination and the illumination level. Luminance contrast between a target and its adjacent background is defined in Equation 2 [van Bommel and de Boer 1980].

$$C = \frac{L_t - L_b}{L_b} \tag{2}$$

where, C is contrast, L_t is luminance of the target and L_b is luminance of the background. If the target is darker than the background it will be seen in silhouette and its contrast is said to be negative. On the other hand if the target is seen brighter than the background its luminance contrast is said to be positive.

Several studies on visibility measures of realistic roadway tasks indicate that in road lighting conditions targets located on the road have mainly lower luminances than the background [Narisada and Karasawa 2007, Smith 1938, van Bommel 1970]. Thus, increasing the luminance of the background against which a target is viewed increases the chances of the target to be detected. It has been shown that under fixed road lighting conditions, visual performance improves with increase in road surface luminance and with decrease in vertical illuminance [de Boer 1967, van Bommel and de Boer 1980].

The difference between the average and the minimum road surface luminance should not be too high. This can be ensured by specifying a minimum for the ratio of minimum to average road surface luminance. This luminance ratio is called the overall uniformity U_o. The smaller the overall uniformity the worse will be the visual performance for targets seen against the low-luminance part of the road surface. Large luminance differences in the field of view also result in a lowering of the contrast sensitivity of the eye [de Boer 1967, van Bommel and de Boer 1980].

Threshold increment (*TI%*) is used to control disability glare. The concept behind it is the calculation of the veiling luminance due to the lighting installation and then the calculation of how much the light level should be increased to restore the visibility to the level it would have been in the absence of any disability glare [de Boer 1967, van Bommel and de Boer 1980].

The comfort of the driver is a function of L_{av} and U_L. The higher the road surface luminance, the easier it is to see targets, the less the eyestrain and thus, the greater the driver comfort. Higher road surface luminance also changes the adaptation of the driver's eyes and thus, the discomfort glare from the headlights of other traffic is reduced. Longitudinal uniformity is important for driver comfort as eyestrain may result from the continuously repeated sequence of alternate bright and dark transverse bands on the road surface ("zebra effect") as the driver travels down the road. The lighting parameter used to describe the severity of this effect is called longitudinal uniformity (U_L), which is defined as the ratio of the minimum road surface luminance to the maximum road surface luminance on a line parallel to the axis of the road and passing through the observer position. Discomfort glare from the luminaires can also cause a reduction of comfort to the driver [Raynham 2004].

Surround ratio (*SR*) is important to let drivers see vehicles, pedestrians and animals on the side of the road and thus take avoidance action if they come into their path. It did not arise as a result of the original studies of road lighting but has been later found useful on actual roads [Raynham 2004]. However, it can be argued that the current method of defining surround ratio is inadequate (Chapter 6.2).

The first recommendations of lighting for road traffic given by CIE have been published in publication No. 12 entitled "International Recommendations for the Lighting of Public Thoroughfares" (1965). Since this publication considerable progress has been made, in particular in such fields as:

- calculation and measurement of road surface luminance
- the evaluation of road surface luminance uniformity
- the description of the reflection characteristics of road surfaces
- the evaluation of glare and its limitation.

Nowadays road lighting design, calculations and measurements in Europe follow the European standards EN 13201:2-4 [EN 13201-2 2003, EN 13201-3 2003, EN 13201-4 2003]. Because road lighting calculations are made for optimising lighting conditions for drivers, the observation point is defined to be 1.5 m above the road surface (Figure 1). Measurement points are taken 60 m ahead of the observer so that the viewing angle lies between 0.5° and 1.5°. The longitudinal measuring area is taken from the first luminaire 60 m ahead to the following one on the same side of the road. The transverse measuring area is defined by borders of a carriageway [EN 13201-3 2003].

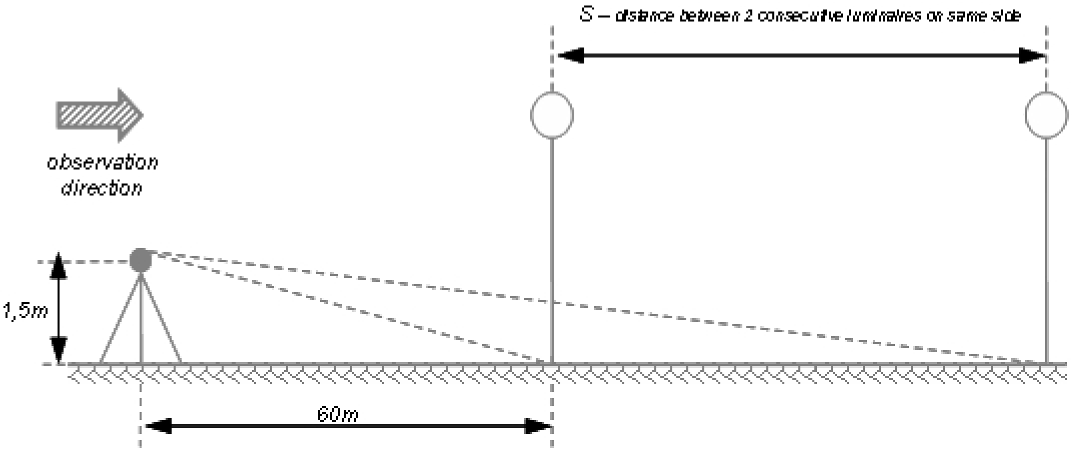


Fig. 1. Observation point of road lighting calculations and measurements [EN 13201-3 2003].

According to the European standard EN 13201-3 the luminance points should be evenly spaced in the measuring field and located as indicated in Figure 2 [EN 13201-3 2003]. The number of points to be concerned depends on the measurement area. The spacing of luminance points in the longitudinal direction is determined from the equation:

$$D = \frac{S}{N} \tag{3}$$

where D is the spacing between points in the longitudinal direction, S is the spacing between luminaires and N is the number of calculation points in the longitudinal direction with the following values: for $S \leq 30$ m, $N = 10$; for $S > 30$ m, the smallest integer giving $D \leq 3$ m.

In the transverse direction the spacing is determined from the equation

$$d = \frac{W_L}{3} \tag{4}$$

where d is the spacing between points in the transverse direction and W_L is the width of the driving lane. The spacing of points from the edges of the relevant area is $D/2$ in the longitudinal direction and $d/2$ in the transverse direction (Figure 2) [EN 13201-3 2003].

In the transverse direction the observation point is positioned in the centre of each lane in turn. The average road surface luminances as well as the overall and longitudinal road surface luminance uniformities are calculated from the measured values. Average road surface luminance L_{av} and overall road surface luminance uniformity U_o are calculated for the entire carriageway for each position of the observation point whereas longitudinal road surface luminance uniformity U_L is calculated for each lane separately. The operative values of quality characteristics are the lowest ones in each case. [EN 13201-3 2003].

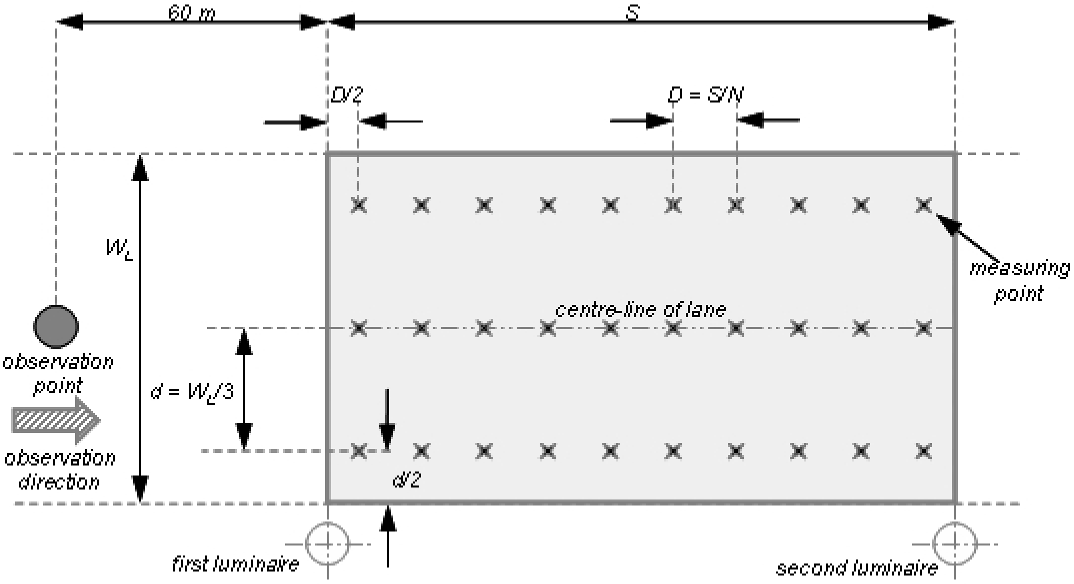


Fig. 2. Placement of measurement points of road luminance measurements [EN 13201-3 2003].

Illuminating Engineering Society of North America (IESNA) have proposed their luminance design criteria in the American National Standard Practise for Roadway Lighting RP-8-2000 (Reaffirmed 2005) [IESNA 2005]. The design criteria differ from the European standard but the fundamentals of both standards are the same. The measurement grid and the observer position of the American luminance design criteria are consistent to the STV design criteria introduced in the chapter 2.2.

2.2 Small Target Visibility design criteria

Considerable research has been performed over the past 40 years to investigate the relationship between alternative models of visibility provided by road lighting systems and alternative measures of driver performance and safety. The first successful attempt in developing a visibility criterion was the Visibility Index (VI) introduced in 1970s by Gallagher [Gallagher 1976]. The method was based upon the research of Blackwell [Blackwell 1946]. Gallagher used small grey cone-like targets on the road to measure the distances at which drivers took evasive action of some kind – changing speed, changing lanes, applying brakes, etc. He correlated this time-to-target with a visibility metric (VI) and for the first time found a strong correlation between driver performance and a lighting metric – visibility.

In 1977 Janoff et al studied the relationship between night accident rates and a wide variety of visual criteria, incuding horizontal illuminance, pavement surface luminance and visibility index (VI) [Janoff et al 1977]. Janoff et al. found only a weak inverse relationship between accidents and VI.

In 1989, Adrian proposed a new visibility criteria based upon the works of Blackwell (1946), Aulthorn (1964) and his own [Adrian 1989]. His Visibility Level (VL) was defined as simply the ratio of actual target luminance to threshold luminance (luminance contrast). The standard target proposed by Adrian is known nowadays as the Small Target (18 cm * 18 cm) and the visibility concept is recognized as Small Target Visibility (STV).

In the United States, a visibility concept Small Target Visibility (STV) was added as a design metric in ANSI/IESNA RP-8-1990, American National Standard Practise for Roadway Lighting. In RP-8-1990 the critical target, based on the STV concept was accepted to be an 18 cm x 18 cm flat square target with 20% reflectance. The size of the target corresponds roughly to the least clearance between the road surface and the body structure of normal cars. Thus the target represents a critical target which is the most difficult to perceive but still dangerous for a normal-sized vehicle [Güler and Onaygil 2003, Narisada and Karasawa 2007]. In RP-8-1990 the observer was defined to be 23 years old and the observation time was set to 0.2 s. In the ANSI/IESNA RP-8-2000 the reflectance of the critical target was changed to 50%. The observation time remained the same (0.2 s) but the observer age was changed to 60. [CIE 2008]

The visibility concept STV is based on an assumption that adequate road surface luminance as such does not mean that the target is visible to the driver. It is necessary to have a difference in luminance of target and target background for the target to be visible. This difference in luminance has to be above a certain minimum value for contrast visibility. This difference with respect to a threshold luminance value is termed Visibility Level (VL).

The STV concept, as defined in the ANSI/IESNA RP-8-2000 (Reaffirmed 2005) is a calculated measure of the visibility of a small two-dimensional target located on the road in front of the driver [IESNA 2005]. The VL is a metric used to combine effects of factors listed in RP-8 on a target of 18 cm x 18 cm with a diffuse reflectivity of 50%. The observer is located on a line that passes through the calculation points and which is parallel to the central axis of the road. With a 1° downward view from the horizontal, as the defined observation geometry, the fixation line meets the road at 83.07 m and at 1.45 m eye position from the road surface. The observer is an adult (60 years) with normal vision and the fixation time is 0.2 s. STV is calculated based on surface reflectivity and target orientations with respect to the observer. The results of the calculation are a contrast picture of the target with respect to the background.

The longitudinal road surface area for calculation is taken from the first luminaire to the following one on the same side of the road. The transverse road surface area for calculation is defined by the borders of a carriageway. As shown in Figure 3 there should be two grid lines per lane located on quarter (1/4) of the distance from the edge of each lane. In the longitudinal direction the distance between grid lines shall be one tenth (1/10) of the spacing between luminaires, or 5 meters, whichever is smaller. The starting point for grid lanes should not be located directly under the luminaire, but the grid should start at a point one half (1/2) of the grid cell size from the luminaire.

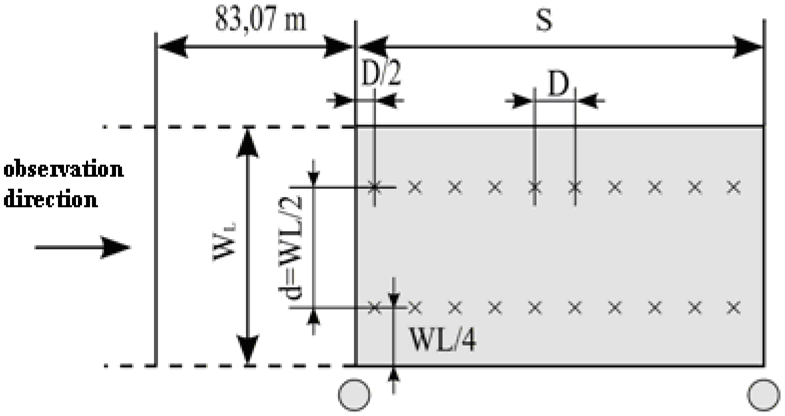


Fig. 3. Small Target location orientation [IESNA 2005].

In principle, the luminance design criteria (EN 13201:2-4, RP-8-2000) and the STV design criteria were developed based on the same basic fundamentals of visual performance. For the luminance method of design the idea was that the road surface luminance and the other parameters in road lighting (see ME/MEW classes in EN 13201-2), apart from Surround Ratio (SR), were set up so that they in general controlled the visibility of a particular target at 100 m from the observer [de Boer 1967, EN 13201-2 2003, Raynham 2004, van Bommel and de Boer 1980]. Thus, in general the various ME/MEW classes relate to different degrees of STV - classes. However, there are a few anomalies between these two methods, particularly if the impact of vehicle headlights and colour contrasts are also considered.

In general, an acceptable road lighting installation based on the luminance concept design is also acceptable when measured and calculated with the STV design criteria. When road lighting is designed with the STV criteria the quality requirements described in the luminance design criteria may not be fulfilled. The purpose of the STV criteria is to better optimize the design by accounting for the potential improvements in target detection provided by a certain level of non-uniformity of the luminance. A STV-based design would typically result in slightly greater pole spacing, which lowers the construction, maintenance and electric power consumption costs. However, one major problem of the STV concept is that it does not consider visual comfort at all. Thus, it is possible that a visibility measure shows adequate values while the longitudinal uniformity is extremely low for visual comfort. In addition, it can be argued that the driving task involves more than just avoiding targets lying on the road in front of the driver.

The STV concept was proposed in 2000 as the recommended design practice of the Illumination Engineering Society of North America (IESNA) as well as the American National Standard Institute (ANSI) [IESNA 2005]. However, in the meeting of the Roadway Lighting Committee (RLC), in August 2006, the committee voted to remove both the STV method and the illuminance method as design criteria for road lighting. The next revision of RP-8 will use the luminance method as the primary design metric for road lighting. There will be some instances, such as conflict lighting and field verification, where the use of illuminance design may still be necessary. The STV design may still be used as a means to select between installations that are identical in terms of the luminance based design criteria.

The main reason that the RLC decided to deprecate the STV method as a design metric is because there was no correlation found between STV design values and traffic safety. The STV method was originally advocated as a means to calculate the probability of detecting a small target on the road surface, while the luminance and the illuminance methods were "best practice" methods for a road lighting installations. Thus, the failure of the STV method to correlate to traffic safety is a more urgent problem than in case of the luminance design or the illuminance design. In addition, the STV method is very sensitive to the effects of headlights. If the illuminance on the target provided by headlights is added to the illuminance provided by the road lighting installation, the STV value may change substantially [Ekrias et al 2008b].

The STV method needs to be developed further based on the experimental investigation. In practice, there are a lot of parameters, which the theoretical calculation does not include. These parameters are also very difficult to plug in the theoretical equations.

At a minimum the STV design should include the impact on target visibility due to vehicle headlights. Another key issue is the impact of different targets instead of a single design target. For example, on many roads wildlife (elk, deer, reindeer etc) can pose a significant threat to the safety of the driver. Roads with high levels of pedestrian or bicycle traffic may also require different design parameters than motorways.

The STV design should also include the impact of off-axis targets (mesopic vision) and colour contrast on target visibility. Small Target Visibility concepts based on the assumptions needs to be verified. Relevant lacks of the method associated with the design procedures need to be investigated further to determine how such problems affect the design.

2.3 Revealing Power

A method of using given values of the lighting parameters to calculate the number of targets detectable at various positions on a road was first described 70 years ago by Waldram [Waldram 1938]. Waldram used as a basis for his calculations a relation known to exist between the contrast threshold and the background luminance. The set of targets was defined by the curve representing the probability of the occurrence of a reflection factor of pedestrian clothing not exceeding some given value. Waldram called the percentage of targets detectable at each location on the road the revealing power of the road lighting, a concept that was later to be used by other researchers [Harris and Christie 1951, Hentshel 1971, Lambert et al 1973, Narisada and Karasawa 2007, van Bommel 1979].

Revealing Power is expressed by a percentage value of targets revealed by the road lighting installation for the numbers of targets existing on the road. Revealing Power for the target darker than the background, is called the Negative Revealing Power, and for the target lighter than the background, the Positive Revealing Power. The sum of the absolute values of Negative and Positive Revealing Powers is called the Total Revealing Power. Based on the calculated Total Revealing Power at several grid points on the road surface, the Iso-Revealing Power curves for given percentage figures can be drawn [Harris and Christie 1951].

From the distribution of the Total Revealing Power, an Area Ratio of Revealing Power of each road lighting installation is calculated. The Area Ratio is defined as extend of the portion or portions of the road surface area which the Total Revealing Power is higher than a specified value [Narisada and Karasawa 2007, Harris and Christie 1951]. The Area Ratio expresses the general level of the Revealing Power under road lighting installation.

By changing, systematically, the photometric and the geometric parameters of road lighting installations, the relationships between Area Ratio and the photometric parameters (the average road surface luminance and the veiling luminance to be caused by the luminaires) and various geometric parameters, the layout configurations, the mounting height of and the spacing of the luminaires, can be calculated. It has been found that Area Ratio noticeably increases with increasing the average road surface luminance and the mounting height [Narisada and Karasawa 2007].

2.4 Some fundamental problems of current road lighting design practice

The way targets are seen against their background is critical for the performance of any visual task. In the development of road lighting design criteria it has been assumed that targets are visible to the driver only if they have adequate luminance contrast to their background [de Boer 1967, van Bommel and de Boer 1980]. However, it can be argued that also colour contrast can be effective at revealing a target from its background, especially in the case of road lighting installations with good colour rendering properties [Raynham 2004].

The visibility experiments made in Lighting Unit of Helsinki University of Technology suggest that colours have a major effect on target visibility if the road is illuminated with a light source with adequate colour rendering properties [Ekrias et al 2009]. The experiments indicate that in metal halide (MH) lamp illumination the target visibility is not only defined by luminance contrast but rather by the combination of colour contrast and luminance contrast. At the same time, under high pressure sodium (HPS) lamp illumination only red colour has an influence on the visibility of the target. The results suggest that all targets located on the road in road lighting environments can not be considered to be achromatic and that different colours affect target visibility differently in various road lighting conditions. Thus, in road lighting design it cannot always be assumed that targets on the road are visible to the driver only because of the adequate luminance contrast, but colour contrasts should also be considered in the development of road lighting design criteria.

In night-time driving conditions the purpose of road lighting is mainly to illuminate the road surface, while the headlights provide illumination to vertical surfaces, i.e. targets on the road. Several studies on visibility measures of realistic roadway tasks indicate that in road lighting conditions targets located on the road have usually lower luminances than the background [Narisada and Karasawa 2007, Smith 1938, van Bommel 1970]. If the target is darker than the road surface the vehicle headlights may result in decreasing the luminance contrast of the target and thus may have a negative effect on driving safety [Ekrias et al 2008b].

When considering recommendations for road lighting design criteria fundamental criticism can be made of the fact that the critical target used in the development of these criteria have been chosen simply on the basis of such commonsense considerations as that a stationary obstacle (20 cm x 20 cm or 18 cm x 18 cm) used in the experiments can be a danger for a driver and must therefore be seen in time. Too little is known, however, which targets are likely to appear on the road and which targets are critical for safety of the driver. [de Boer 1982].

It can be argued that, in practice, very few accidents are caused by targets that are only 20 cm x 20 cm in size. In driving, luminances of the target and the target background are also changing constantly and the target cannot be expected to be stationary. It is also quite obvious that in road lighting conditions visual targets are not completely diffuse (Lambertian). Visual targets like pedestrians may also have different clothes with different colouring and different reflection characteristics. Furthermore, in studies by Land it has been shown that drivers tend only to look at the section of road that they will cover in the next 2 s [Land and Lee 1994]. Even at 120 km/h it takes 3 s to cover 100 m. Besides, on some roads it is likely that it will be impossible for a driver to see the road surface more than 80 m away. [Raynham 2004]

Today the driving task involves more than just avoiding targets lying on the road. It can also be argued that due to increased traffic density, the target visibility requirement is not as relevant during periods of peak traffic. The requirement does become relevant, however, immediately after the traffic peak when the road surface is no longer “hidden” by all the vehicles, and when traffic speed again increases, making visibility at longer distances again important for safety. This, on the other hand, creates a good opportunity for use of flexible, adaptive road lighting. [CIE 2008]

One problem of current road lighting practice is that it is not known what kind of road lighting quantity and quality is needed to ensure good traffic safety in a given situation. Though road accident rates are a direct measure of traffic safety it seems that accident studies never played an important role in describing the quality parameters of road lighting. Road lighting standards define quality parameters for a static situation with fixed road lighting under static traffic, road and environmental conditions, while in reality the visibility conditions of the driver as well as the visibility tasks may vary a lot depending on many different factors. It also seems that road lighting recommendations to a great extent are based on knowledge, experiences and consensus among experts in international lighting communities and not so much on accident research. [Wanvik 2006]

3 Visual conditions in night time driving

3.1 Mesopic visual performance

In road lighting luminances usually fall in the mesopic region. It can be argued, that the light perceived by the eye at low light levels cannot be correctly defined with photopic photometry. At present, the photopic spectral luminous efficiency function *V(λ)* forms the basis of all road lighting calculations and photometry. The luminous flux (lumen) values and luminous efficacy (lm/W) values of lamps are based on *V(λ)*, as well as recommendations of luminance (cd/m^2) and illuminance (lx) values [Eloholma 2005]. Until today, there are no internationally accepted mesopic spectral sensitivity functions and consequently no accepted system of mesopic photometry [Viikari et al 2008].

The mesopic luminance region lies between the photopic region and the scotopic region. In mesopic vision both the rods and the cones are active and this causes changes in the spectral sensitivity of the human vision. The mesopic vision involves both foveal and peripheral vision, which is based on various receptor combinations on the retina. In developing basis for mesopic photometry a European research consortium MOVE adopted a visual performance based approach. In MOVE the task of night-time driving was divided into three visual subtasks, which are related to the detection of a visual target, the speed of detection, and the identification of the details of the target. Visibility data was generated simultaneously in five countries with 120 observers. The linear model as outcome of the MOVE work was recommended for practical mesopic photometry in, for example, road lighting applications. [Eloholma 2005]

The urgent need for a practical system of mesopic photometry has recently been acknowledged by the head organizations in the lighting field. Both CIE [Orreveteläinen et al 2007] and Illuminating Engineering Society of North America [IESNA 2006] have taken actions to reach the common objective of establishing a mesopic photometric system within the near future. Also, the lighting industry has encouraged the researchers in the lighting field to prompt actions towards a new international standard on mesopic photometry. [Viikari et al 2008]

The use of photopic photometry at the low light levels of road lighting favours HPS lamps because of their high output around the peak wavelength of the photopic V(λ). However, light sources with high output in the short wavelength region have frequently been acknowledged to be visually more effective in peripheral vision at the mesopic light levels [Akashi et al 2007, Eloholma 2005, Ketomäki 2006, Viikari et al 2008].

The proposed MOVE-model by MOVE consortium [Goodman et al 2007] and the X-model introduced by Rea et al in 2004 have both met criticism concerning especially the upper luminance limit of the mesopic region [Eloholma and Halonen 2006, Rea et al 2004, Rea and Bullough 2007]. The upper luminance limit of the

MOVE-model (10 cd/m^2) is claimed to unnecessarily complicate practical photometry and lighting specifications for "high" light levels, whereas the upper luminance limit proposed by the X-model (0.6 cd/m^2) would make the mesopic dimensioning concern only the roads in the lower lighting classes, which, at least in the European countries, are very few. The paper of Viikari et al (2008) proposed a new modified MOVE-model whose upper luminance limit is in between the limits of the previously proposed models [Viikari et al 2008]. The selection of upper luminance limit of the modified MOVE-model is based on road lighting luminance measurements in different weather conditions.

In the work of Viikari et al (2008) the proposed modified MOVE-model was examined along with the MOVE- and X-models using three independent experimental data sets provided by different European universities. The modified MOVE-model described the data best in nine situations out of 17. The MOVE-model was best in seven situations and X-model in one. The differences between the MOVE- and modified MOVE-model were small while X-model differed considerably from both the MOVE- and modified MOVE-models [Viikari at al 2008].

The CIE TC1-58 is currently working on an internationally accepted basis for mesopic photometry. The TC1-58 will complete its work in the near future and the outcome will be a model for the basis of visual performance based mesopic photometry.

3.2 Visual environment in driving

Driving is a complex task. The visual environment consists of several visual elements such as other vehicles, lane markings, signs, pedestrians, cyclists, and any unexpected targets appearing in the visual field. The basic visual task in driving a vehicle is to obtain sufficient information from the visual field to be able to get by in the environment [CIE 1992]. In order to trigger visual perception and to detect a target a certain luminance or colour difference between the target and its background is needed. In night-time driving conditions the contrasts of visual targets depend on the target reflectance properties, road surface reflectance properties, vehicle headlights, geometry of the lighting installation as well as on the location of the target in relation to the luminaries [Ekrias et al 2008b]. Also weather conditions have a major impact on the visual conditions of the driver.

In wet conditions the luminance distributions of road surfaces change significantly compared to dry conditions. Road surface areas with specular refection towards the observation point become very bright and may cause discomfort glare. On the other hand, the luminances of the darker areas of road surface decrease. This results in lower luminance uniformities and in worse driver's visibility conditions [Eloholma et al 2001, Ekrias et al 2007]. However, average luminances of wet road surfaces are usually higher compared to the dry conditions due to specular reflection [Ekrias et al 2007].

Luminances of snowy road surfaces are usually relatively high and can be multiple times higher than in dry road surface conditions. The overall and longitudinal luminance uniformities of snowy road surfaces are usually slightly lower than in dry conditions. [Ekrias et al 2007].

Night-time driving is a very complex situation also for the adaptation of the eye. The luminances in the visual field change constantly while the car is moving and the direction of view is changing. The luminances can be very low in the adjacent and surrounding areas of the road. There are also higher luminances in the visual field of the driver. These comprise, for example, traffic signs when illuminated and road luminaires. Also vehicle headlights have a major impact on the visual conditions of the driver. The effect of these areas with higher luminances to the adaptation luminance level is unknown. Traffic signs and the headlights of other cars usually remain only temporarily in the visual field. Fixed road luminaires are mostly located in the peripheral parts of the visual field, and their effect on the adaptation level may be quite small. The adaptation process becomes even more difficult to define at mesopic luminance levels, where the contribution of rods and cones to the visual performance changes with luminance level. This leads to a very complicated adaptation concept to model [Eloholma et al 2001].

A lot of research has been carried out over the years concerning the adaptation process of the eye. However, it is still uncertain which portion of the visual field determines the adaptation luminance [Eloholma et al 2001].

4. An advanced method for road lighting measurements and calculations

4.1 Road lighting measurements with an imaging luminance photometer

Road lighting measurements are conventionally done with spot luminance meters, which measure luminances of a small (usually 1^{o}) area at a time (Figure 4a). After selecting the adequate measurement area (one luminaire spacing) and placing the luminance spot meter, the road surface luminances can be measured. In the luminance design criteria the luminances are measured from several discrete points on the road surface and the average luminances as well as the overall and longitudinal luminance uniformities are calculated from the measured values [CIE 1982, CIE 2000, EN 13201-3 2003, IESNA 2005].

Measuring road surface luminances with conventional spot meters is very time consuming, because there are usually hundreds of luminance points to be measured. For example in the case of a highway with the luminaire spacing of 54 m and two traffic lanes in one direction, altogether 216 points have to be measured, only for one luminaire spacing and for one traffic direction. Another 216 points have to be measured to study the road surface luminances of the other side of the road.

The accuracy of the measurements made with spot luminance meters is also highly dependent on the weather and other external conditions as the measurement period can take several hours. During the measurements on roads, the traffic has to be directed elsewhere so that the measurements can be conducted. In using a spot luminance meter some details can also escape from the analysis or positional errors can easily appear. Furthermore, the measurement results do not give any information about road surface luminances located close to the measurement points and luminances on road surroundings.

The measurement of road lighting luminance data with an imaging luminance photometer is much faster compared to the luminance spot meters. The photometer captures the scene in few seconds and the captured image includes simultaneous data from the road surface and areas surrounding the road [Ekrias et al 2008a]. The utilization of an imaging luminance photometer instead of a spot meter is also more accurate and gives many new possibilities in analyzing the luminance distributions.

An imaging luminance photometer gives significantly more measurement information than a conventional spot luminance meter. In the luminance scene captured by the imaging photometer, not only the luminances of discrete points are given, but also luminances for the whole road surface area as well as those of the road surroundings and of any targets in the visual field. In evaluating the visual conditions of the driver, it is important that the luminances of the whole visual field are captured. [Ekrias et al 2008a]

A road luminance measurement system based on imaging luminance photometer allows new possibilities for analyzing the visual conditions of driving also in terms of visual targets in the field of view. The evaluation of target visibility levels over the roadway requires the measurement of the luminances of the target, its immediate surroundings and its background. The collection of luminance data point by point from a complex image with conventional spot meter requires carefulness and time. This can be solved by using imaging luminance photometer and calculation software [Ekrias et al 2008a].

In the Lighting Unit of Helsinki University of Technology two different imaging luminance photometers are used in road lighting measurements. The ProMetric 1400 shown in Figure 4b is a computer controlled CCD-based imaging photometer. The ProMetric 1400 is controlled by Radiant Imaging ProMetric software. The captured luminance image of ProMetric 1400 consists of 500(H) x 500(V) pixels and the system accuracy for luminance measurements is ± 3 % [Radiant Imaging 2001]. The imaging luminance photometer LMK Mobile Advanced, shown in Figure 4c, is based on the digital camera Canon EOS 350D. A CMOS Canon ASP-C is used as a sensor. The size of the luminance image is 1728(H) x 1152(V) and the software LMK 2000 is used to analyze the measured data. The system accuracy for luminance measurements is ± 8.2 % [TechnoTeam 2007].

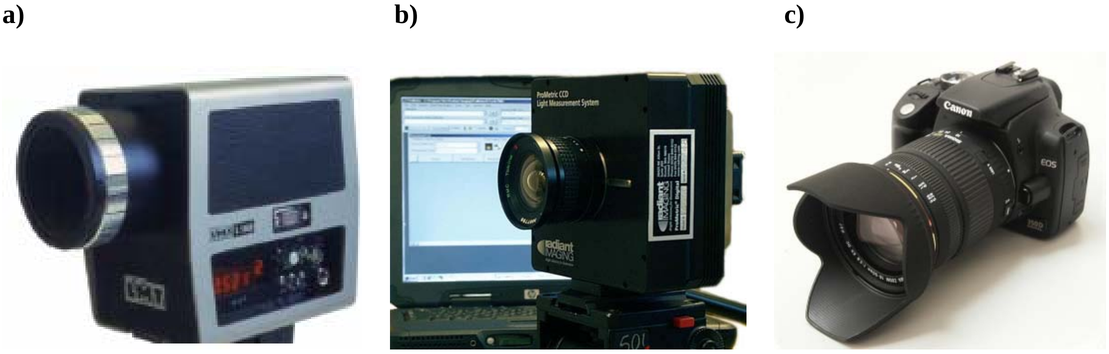
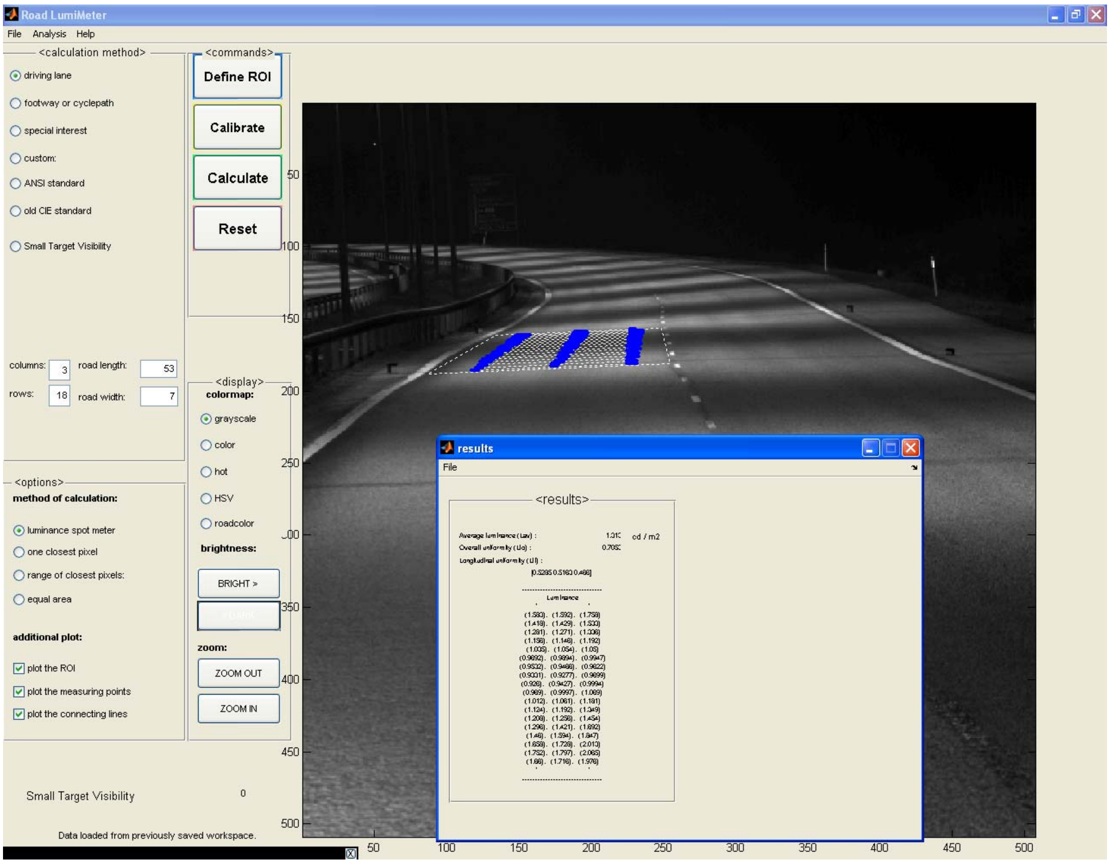


Fig. 4. a) Spot luminance meter LMT b) Imaging luminance photometer ProMetric 1400 c) Imaging luminance photometer LMK Mobile Advanced.

4.2 A new program for road lighting measurements and calculations

To be able to benefit from the use of an imaging luminance photometer in road lighting measurements, a Matlab-based computer program Road LumiMeter v2.0 has been developed at the Lighting Unit of Helsinki University of Technology [Kolbe 2004, Ylinen 2007]. The program calculates the road lighting quality parameters for different road lighting installations according to the different road lighting criteria (EN 13201:3-4, IESNA RP-8-00, CIE No. 30-2) and other custom methods. Figure 5 presents the main window of the program.

The Road LumiMeter v2.0 can be run as a standalone application or in the Matlab environment. Luminance images of the imaging luminance photometers are converted to numerical data files (text files) and imported to the Road LumiMeter v2.0. Figure 5 shows an example of a road luminance measurement made on highway VT1 from Helsinki to Turku. Figure 5 shows also the luminance measurement results for the left lane of a carriageway, calculated according to the standard EN 13201-3 [EN 13201-3 2003].



<calculation method>

- ● driving lane
- ○ footway or cyclepath
- ○ special interest
- ○ custom:
- ○ ANSI standard
- ○ old CIE standard
- ○ Small Target Visibility

columns: 3 road length: 53

rows: 18 road width: 7

<options>

method of calculation:

- ● luminance spot meter
- ○ one closest pixel
- ○ range of closest pixels:
- ○ equal area

additional plot:

- ☑ plot the ROI
- ☑ plot the measuring points
- ☑ plot the connecting lines

colormap:

- ● grayscale
- ○ color
- ○ hot
- ○ HSV
- ○ roadcolor

Small Target Visibility 0

Data loaded from previously saved workspace.

```
<results>

Average luminance (Lav) :          1.01   cd / m2
Overall uniformity (Uo) :          0.705
Longitudinal uniformity (Ul) :
            [0.5285 0.5163 0.488]

        -------------------------------
                  Luminance
             '                  '
        (1.583).  (1.592).  (1.758)
        (1.418).  (1.429).  (1.533)
        (1.281).  (1.271).  (1.336)
        (1.158).  (1.146).  (1.192)
         (1.035).  (1.054).  (1.05)
      (0.9892).  (0.9894).  (0.9947)
      (0.9532).  (0.9466).  (0.9822)
      (0.9301).  (0.9277).  (0.9899)
       (0.926).  (0.9427).  (0.9994)
       (0.969).  (0.9997).  (1.069)
        (1.012).  (1.061).  (1.181)
        (1.124).  (1.192).  (1.349)
        (1.208).  (1.258).  (1.454)
        (1.298).  (1.421).  (1.692)
         (1.46).  (1.594).  (1.847)
        (1.658).  (1.728).  (2.013)
        (1.752).  (1.797).  (2.065)
         (1.66).  (1.716).  (1.976)
             '                  '
        -------------------------------
```

Fig. 5. Main window of the computer program Road LumiMeter v2.0.

Table 1 lists the road lighting measurement and calculation methods which can be used in the Road LumiMeter v2.0 program for road lighting quality parameter calculations. In addition to three different luminance design criteria (EN 13201-3, IESNA RP-8-00, CIE No. 30-2), it is also possible to make road lighting calculations according to the Small Target Visibility design criteria [CIE 1982, EN 13201-3 2003, IESNA 2005]. When calculating the road lighting quality parameters with the program, it is assumed that the measurements made with imaging luminance photometers are made according to the set-ups described in the criteria. In the case of STV method the calculations are based on the measurements of small targets located on the road at certain positions as defined in the standard IESNA RP-8-00. The method also requires the veiling luminance levels of the road lighting installation to be known.

In the Road LumiMeter v2.0 also a custom method, in which the user specifies the number of measurement points in the transverse and longitudinal directions, is available for the road lighting calculations. Additionally, calculations for footways, cycleways and other road areas lying separately or along the carriageway of a traffic route, can be carried out.

TABLE 1. Road lighting calculation methods, which can be used in the program Road LumiMeter v2.0 for road lighting calculations.

Road lighting calculation methods
EN 13201-3
IESNA RP-8-00
CIE No. 30-2
Small Target Visibility (STV) (IESNA RP-8-00)
Custom method (user defined)

Table 2 shows various methods which can be used in the program for calculation of road surface luminance at each measurement point of the measurement area. In the case of the “*Luminance spot meter”* algorithm the program calculates the average luminance of the measurement point from the defined number of pixels based on the model of the realistic measurement set-up in which the road lighting measurements are made with luminance spot meter. For this option, certain geometry parameters of the carriageway and road lighting installation are required.

TABLE 2. Different methods for luminance calculation of a measurement point on road surface.

Calculation of luminance at each measurement point
Luminance spot meter
One closest pixel
Range of closest pixels
Equal area

In the case of the *“One closest pixel”* algorithm the program assumes that the value of luminance at certain measurement point is the luminance value of the closest pixel. The coordinates of the measurement point are rounded to retrieve luminance from a discrete pixel. In the case of the *“Range of closest pixels”* algorithm the program assumes that the value of luminance at certain measurement point is the average luminance value of a range of closest pixels. The user has to enter the range of pixels used in the calculation. In the case of the *“Equal area”* algorithm the program assumes that the value of luminance at certain point is the average luminance value of all pixels that are lying closest to the relevant measurement point. Basically, this divides the measurement area into rectangles with measurement points in the center. The main advantage of such method is that all road surface luminance values from the defined measurement area are included in the calculations. The number of the pixels taken into account for each measurement point depends on the distance of the measurement point from the camera objective.

In the Road LumiMeter v2.0 the luminance image can be displayed by using several different colour maps. The program has also brightness adjust and zooming functions. For luminance design criteria the program calculates the luminance of each measurement point, average road surface luminance L_{av}, overall luminance uniformity U_o and longitudinal luminance uniformity U_L. For the STV design criteria the visibility level for each target and the STV-value for a carriageway are calculated.

5. Road lighting measurements and calculations using various road lighting criteria

5.1 Case studies

In this work measurements and calculations were made for several various pilot locations, using different road lighting criteria (EN 13201:3-4, IESNA RP-8-00, CIE No. 30-2, STV) and other alternative methods. The main purpose of the study was to investigate how the quality characteristics of the same pilot locations vary in relation to the calculation methods used. The measurements and analysis were made using luminance photometers ProMetric 1400 and LMK Mobile Advanced and computer programs Radiant Imaging ProMetric, LMK 2000 and Road LumiMeter v2.0.

Road lighting measurements and calculations were made for seven different pilot locations. For each location road type and road lighting installation type are shown. The road lighting quality parameters for the same pilot locations and measurement areas were calculated according to different road lighting criteria and other alternative methods. Although the measurement areas (one luminaire spacing) and measurement conditions of the pilot locations were the same the measurement grids and the amount of measurement points varied according to the method used. The methods used for the calculations of each pilot location are shown in Table 3.

TABLE 3. Pilot locations of road lighting luminance measurements and calculations.

Test road	Lighting class	Lamp type	Road type	Calculation methods
VT1	AL3	HPS	Highway	EN 13201-3 (different variations), CIE No. 30-2, Custom 1, Custom 2, IESNA RP-8-00.
VT1	AL3	MH	Highway	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2, IESNA RP-8-00.
Ring Road III	AL2	HPS	Highway	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2 (point meter, equal area), IESNA RP-8-00, STV.
Leppälinnunrinne	AL4b	HPS	Local street	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2, IESNA RP-8-00.
Jakokunnantie	AL4b	HPS	Local street	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2 (point meter, equal area).
VT3	AL3	MH	Highway	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2 (point meter, equal area).
VT3, wet road surface	AL3	HPS	Highway	EN 13201-3 (point meter, equal area), CIE No. 30-2, Custom 1, Custom 2 (point meter, equal area).

Highway VT1 is the main route between the major cities of Helsinki and Turku in southern Finland. It consists of two carriageways separated by a central reservation. Each carriageway has two lanes. On VT1 new dimmable road lighting has been installed on road section from Kolmperä to Lohjaharju. The section is 17 km long and consists altogether of 762 luminaires (two luminaires/pole). The pole spacing is 53 m. The section consists of two different road lighting installations which are equipped with 250 W HPS lamps (15 km) and 250 W MH lamps (2 km). On VT1 the luminance measurements were made for both road lighting installations.

Ring Road III is an important highway in southern Finland. It is the outermost of the three beltways in the Helsinki region. It consists of two carriageways separated by central reservation and is mostly four lanes wide. On Ring Road III the luminance measurements were made on a recently built extension section which is not yet used by traffic. In this pilot location road lighting installation is new and consists of 250 W HPS lamps with pole spacing of 55 m. In this pilot location, in addition to other calculation methods, it was also possible to perform Small Target Visibility (STV) measurements and calculations, due to lack of traffic.

Leppälinnunrinne is a local street located in Leppäsilta, Espoo. It consists of two traffic lanes and is illuminated with HPS lamps. Jakokunnantie is a two lane local street located in Pakila, Helsinki. Like Leppälinnunrinne it has minor traffic volume and low driving speeds. Jakokunnantie is illuminated with HPS lamps.

Highway VT3 is a major road from Helsinki to Vaasa with very heavy traffic flow. It consists of two carriageways separated by a central reservation of five meters width. Each carriageway consists of two traffic lanes. On VT3 new road lighting has been installed on road section from Haaga to Ring Road III. It consists altogether of 442 luminaires of which 102 are equipped with metal halide lamps (MH 150 W) and 330 with high pressure sodium lamps (HPS 150 W). The pole height is 12 m and pole spacing 46 m. As in the case with VT1, on VT3 the luminance measurements were made in two different pilot locations, one illuminated with MH lamps and the other with HPS lamps. In the case of the pilot location illuminated with HPS lamps, the measurements and calculations were made with wet road surface conditions, while in the case with MH illumination the road surface was dry.

5.2 Results

Results of the road lighting luminance measurements and calculations are shown in Tables 4 - 11. For each pilot location and each method (except the STV method) the average luminance, overall uniformity and longitudinal uniformity were calculated. The methods, used for the measurements in situ and later for the calculations with the Road LumiMeter v2.0, are described below (Table 3):

EN 13201-3: The European standard, which is nowadays used for road lighting design, calculations and measurements in Europe (Chapter 2.1) [EN 13201-3 2003].

CIE No. 30-2: The CIE Technical report CIE No. 30-2 was published in 1982 and was used for road lighting design, calculations and measurements in Europe until it was replaced in 2000 by the Publication CIE 140-2000. In the CIE No. 30-2 the measurement grid and the amount of measurement points differ from the current standard EN 13201-3. There are also some slight differences between these two methods in defining the average road surface luminance and road surface luminance uniformities. [CIE 1982]

IESNA RP-8-00: The American National Standard Practice for Roadway Lighting, which is introduced by the IESNA, and is used for road lighting design, calculations and measurements in America [IESNA 2005]. The IESNA RP-8-00 describes three different road lighting design criteria which can be used for designing continuous lighting systems for roads. However, in the measurements and calculations presented in this chapter, the title IESNA RP-8-00 is used to represent specifically the luminance design criteria of the Publication.

The luminance criteria, described in the IESNA RP-8-00, differ significantly from the European standard EN 13201-3. The measurement set-up, the measurement grid and the amount of measurement points, all differ from the standard EN 13201-3. There are also some major differences between these two methods in defining the average road surface luminance and road surface luminance uniformities. In this work in the case of the method IESNA RP-8-00 the measurements were exceptionally made by using the same observation positions as in the standard EN 13201-3.

STV: Small Target Visibility is a calculated measure of the visibility of a small two-dimensional target located on the road in front of the driver. The STV method is introduced in the IESNA RP-8-00 [IESNA 2005]. The measurement set-up of STV method is introduced in the chapter 2.2.

Custom 1: The method Custom 1 is a variation of the methods EN 13201-3 and CIE No. 30-2. In the method Custom 1 the amount of measurement points in the longitudinal direction is the same as in the EN 13201-3 and the amount of measurement points in the transverse direction is the same as in the CIE No. 30-2. Thus instead of three points in the transverse direction five points are used for each lane. As in the CIE No. 30-2, the two outermost points are placed 1/10 of a lane width from the borderlines of the lane. At the same time the maximum spacing between points in the longitudinal direction is 3 m as defined in the EN 13201-3 and not 5 m as defined in the CIE No. 30-2. Also the positioning of the points in the longitudinal direction is consistent to the EN 13201-3. Basically the method Custom 1 can be considered to be a combination of the methods EN 13201-3 and CIE No. 30-2

(Figure 6).

Custom 2: The method Custom 2 is also a variation of the standard EN 13201-3. In the method Custom 2 the amount of measurement points in the longitudinal direction is reduced to 7 on major roads with pole spacing more than 30 m and to 5 on local roads with pole spacing less that 30 m. Thus, the total amount of measurement points is much lower compared to the standard EN 13201-3. The positioning of the points in the transverse direction is consistent to the standard EN 13201-3 (Figure 7).

In calculating the road lighting quality characteristics with EN 13201-3, CIE No. 30-2 and IESNA RP-8-00 the default calculation algorithm used was the "*Luminance spot meter"*. This means that the program calculated the average luminance of each measurement point from the certain amount of pixels based on the model of the realistic measurement set-up in which the road lighting measurements are made with luminance spot meter. The measurement cone of the spot meter was restricted to be 2' in the vertical plane and 20' in the horizontal plane. In this work the algorithm "*Luminance spot meter"* was assumed to be the default method of defining the luminances of the measurement points used for the calculation of road lighting performance.

In calculating the road lighting quality characteristics with the standard EN 13201-3 also *"Equal area"*, *"Single pixel"* and *"Range of pixels"* algorithms were used to study how the results vary in relation to the measurement area used for defining the luminance value of each measurement point.

In the methods Custom 1 and Custom 2 the luminances of the measurement points were defined by using the "*Equal area"* algorithm in which the value of luminance at certain measurement point is the average luminance value of all pixels that are lying closest to the relevant measurement point. In this way, all road surface luminance values from the defined area were included in the calculations while conventionally the road lighting design measurements and calculations are made by using only a certain part of road surface luminance data. In calculating the quality characteristics with the method Custom 2 also the "*Luminance spot meter"* algorithm was used.

Figure 6 shows the pilot location VT1 illuminated with HPS lamps and the measurement grid of the method Custom 1. The measurement area (one luminaire spacing) is divided into rectangles with the measurement points in the center. The measurement grid has 90 measurement points (5x18) per lane.

Table 4 shows the calculated results for the highway VT1 with HPS lamp illumination.The lighting class for VT1 is AL3 (L_{av} = 1,0 cd/m^2, U_o = 0,4, U_L = 0,6). [Tiehallinto 2006]. Compared to this, the measurements showed quite high average road surface luminance (2,55 cd/m^2), while the longitudinal luminance uniformity (0,45) was inadequate in relation to the lighting class requirements.

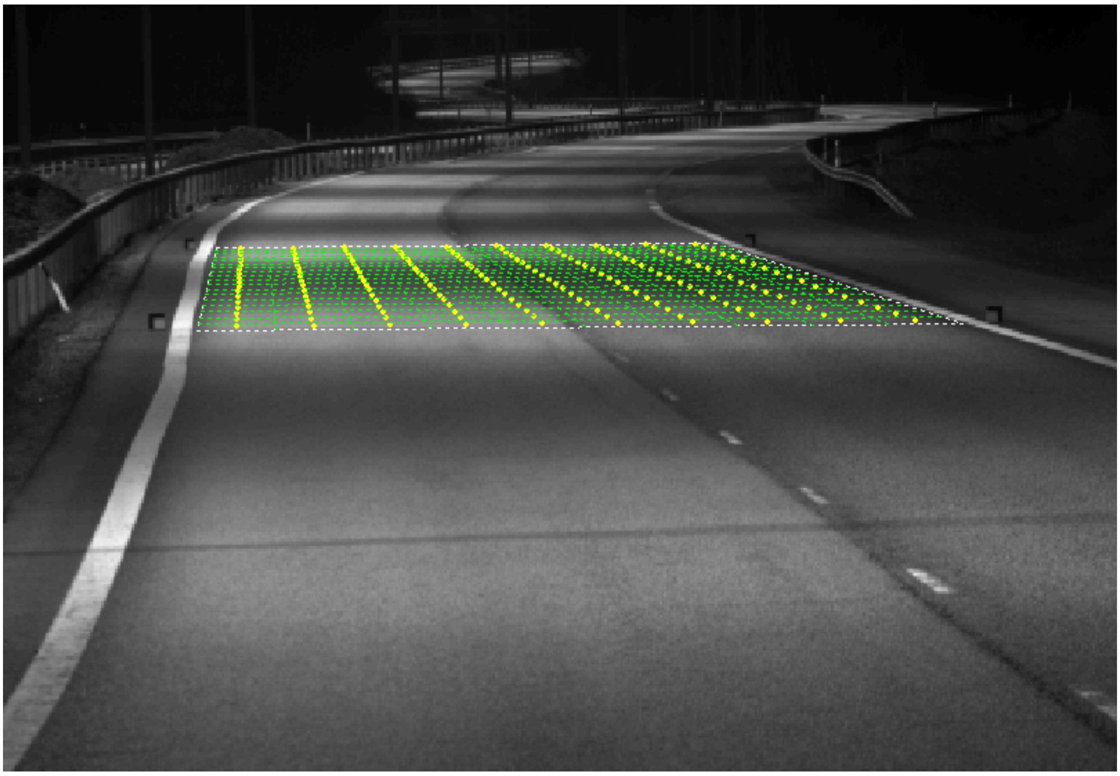


Fig. 6. Pilot location on VT1 illuminated with HPS lamps. Luminances of the pilot location are shown in gray scale map. The method Custom 1 is used for the calculation of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity. Each lane is divided to 90 measurement points; 5 points in the transverse direction and 18 points in the longitudinal direction. For each point the luminance value is calculated by using the average luminance value of all pixels that are located in the rectangle of the relevant point (Equal area).

TABLE 4. Calculation results for pilot location VT1 with HPS lamp illumination. The calculations were made with three different criteria (EN 13201-3, CIE No. 30-2 and IESNA RP-8-00) by using the "Luminance spot meter" algorithm and with two other methods (Custom 1 and Custom 2)) by using the "Equal area" algorithm. For each method average road surface luminance (L_{av}), overall luminance uniformity (U_o or L_{min}/L_{av}) and longitudinal luminance uniformity (U_L or L_{min}/L_{max}) were calculated.

Calculation method	L_{av} (cd/m^2)	U_o	U_L
EN 13201-3	2,552	0,476	0,45
CIE No. 30-2	2,400	0,468	0,4886
Custom 1	2,461	0,449	0,446
Custom 2	2,465	0.481	0,468
	L_{av} (cd/m^2)	L_{min}/L_{av}	L_{min}/L_{max}
IESNA RP-8-00	2,390	0,574	0,292

For the standard EN 13201-3 the average road surface luminance was 6 % higher and the longitudinal uniformity 9 % lower compared to the CIE No. 30-2 despite the fact that the measured road lighting installation, measurement conditions and the measurement area (pole spacing) were exactly the same. In the case of the method

Custom 1, the increase of measurement points reduced the overall and the longitudinal luminance uniformity values when compared to the EN 13201-3 and CIE No. 30-2. At the same time, including all the luminance values of the defined road surface area *("Equal area")* resulted in slightly decreased average road surface luminance compared to the EN 13201-3 and slightly increased average road surface luminance compared to the CIE No. 30-2.

In the case of the method Custom 2 the average road surface luminance value was close to the case with the method Custom 1. This was an expected result because both methods use the *"Equal area"* algorithm. Thus, in both cases the average road surface luminance was calculated by using all road surface luminance values of the measurement area. The only difference between these two methods was the number of measurement points used for the calculations and hence the size of the rectangular area (amount of pixels) of each measurement point.

The method Custom 2 resulted in slightly higher overall luminance uniformity value compared to the other methods. Also the longitudinal luminance uniformity was slightly higher compared to the standard EN 13201-3 and the method Custom 1. The differences were due to the significantly lower number of measurement points used for calculations. For example, on VT1, in the case of the standard EN 13201-3, 216 measurement points are needed to calculate the average road surface luminance of the carriageway. In the cases of the methods CIE No. 30-2 and Custom 1 the number of measurement points needed is 110 and 360. At the same time, in the case of the method Custom 2, the corresponding number of points is only 84.

The luminance values calculated with method IESNA RP-8-00 varied the most compared to the EN 13201-3. This was due to the fact that in the method IESNA RP-8-00 different number of measurement points and different measurement grid were used. There were also some major differences between these two methods in defining the road surface luminance uniformities. The biggest difference between the criteria EN 13201:2-4 and IESNA RP-8-00 is, however, the road surface luminance uniformity requirements for different road types. For example in the case of VT1 with HPS lamp illumination, the longitudinal uniformity is inadequate in relation to the EN 13201-2 lighting class ME3b requirements but at the same time it totally fulfills the requirements of the IESNA RP-8-00 (expressway) [EN 13201-2 2003, IESNA 2005]. Thus, it can be argued that the requirements of the IESNA RP-8-00 are not so strict concerning the luminance uniformities of the road lighting installation if compared to the European standard EN 13201-2. This, on the other hand, allows the use of greater pole spacing, which lowers the costs of the road lighting installation.

The calculation results presented in Table 4 show that different calculation methods resulted in slightly different average road surface luminance and luminance uniformity values depending on the method used for the calculations. Thus, the results indicate that absolutely the same road lighting installation may result in different road lighting quality parameter values depending on the method used for calculating the road lighting performance.

Table 5 shows the results for the pilot location VT1 with HPS lamp illumination calculated according to the standard EN 13201-3 by using different calculation algorithms. The results show that there were only slight variations in the calculated values when the algorithms *"Luminance spot meter"*, *"Single pixel"* and *"Range of pixels"* were used. The results indicate that, if the road surface is quite uniform and does not include very light or very dark irregular spots also the *"Single pixel"* algorithm may be used for road lighting calculations. This, however, should be avoided if possible.

The calculation results made with the calculation method *"Equal area"* varied significantly more from the results made with the algorithm *"Luminance spot meter"* than the other calculation methods. For the calculation method *"Equal area"* the average road surface luminance was 4 % lower, the overall luminance uniformity 3 % lower and the longitudinal luminance uniformity 2 % higher compared to the calculation method *"Luminance spot meter"*.

TABLE 5. Calculation results for pilot location VT1 with HPS lamp illumination. The calculations were made using the standard EN 13201-3 and the road lighting quality characteristics were calculated using four different calculation algorithms ("Luminance spot meter", "Single pixel", "Range of pixels" and "Equal area").

Calculation method	**L_{av}** (cd/m^2)	**U_o**	**U_L**
Luminance spot meter	2,552	0,476	0,448
Single pixel	2,592	0,482	0.440
Range of pixels (10)	2,565	0,479	0.443
Equal area	2,462	0,461	0,457

Figure 7 shows the pilot location VT1 illuminated with MH lamps and the measurement grid of the method Custom 2. As in the method Custom 1 the measurement area (one luminaire spacing) is divided into rectangles with the measurement points in the center. In this case, however, the measurement grid has only 21 measurement points (3x7) per lane.

Table 6 shows the calculation results for the highway VT1 with MH lamp illumination. Also in this case the longitudinal luminance uniformity U_L was inadequate (0,427) in relation to the lighting class AL3 requirements [Tiehallinto 2006]. For the MH lamp installation the average road surface luminance was significantly lower than in the case of the HPS lamp installation.

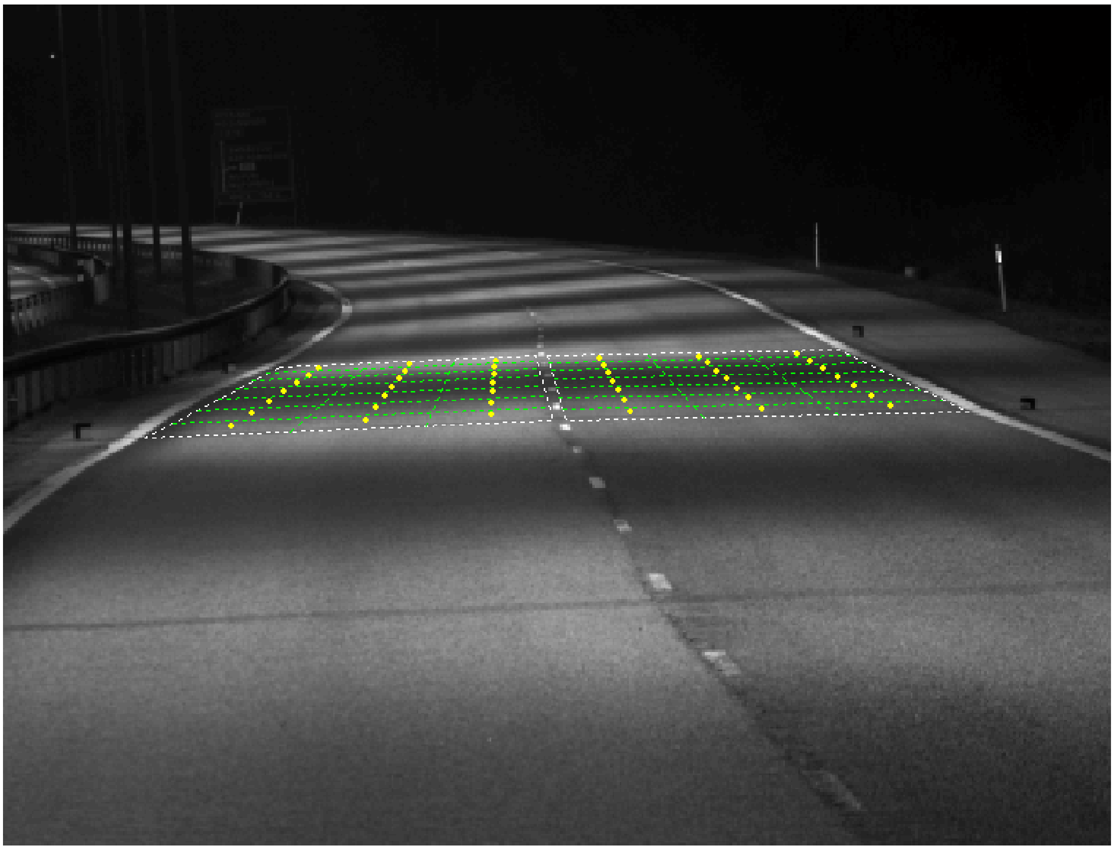


Fig. 7. Pilot location on VT1 illuminated with MH lamps. Luminances of the pilot location are shown in gray scale map. The Custom 2 method is used for the calculation of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity. Each lane is divided to 21 measurement points; 3 points in the transverse direction and 7 points in the longitudinal direction. For each point the luminance value is calculated by using the average luminance value of all pixels that are located in the rectangle of the relevant point ("Equal area").

TABLE 6. Calculation results for pilot location VT1 with MH lamp illumination. For the standard EN 13201-3 the calculations were made by using the "Luminance spot meter" and "Equal area" algorithms. For the methods CIE No. 30-2 and IESNA RP-8-00 the calculations were made with the "Luminance spot meter" algorithm and for two other methods (Custom 1 and Custom 2) the "Equal area" algorithm. For each method average road surface luminance (L_{av}), overall luminance uniformity (U_o or L_{min}/L_{av}) and longitudinal luminance uniformity (U_L or L_{min}/L_{max}) were calculated.

Calculation method	L_{av} (cd/m^2)	U_o	U_L
EN 13201-3, spot meter	1,190	0,545	0,427
EN 13201-3, equal area	1,110	0,513	0,409
CIE No. 30-2	1,150	0.532	0,442
Custom 1	1,108	0,507	0,407
Custom 2	1,108	0,531	0,439
	L_{av}	L_{min}/L_{av}	L_{min}/L_{max}
IESNA RP-8-00	1,230	0,520	0,388

In the case of the EN 13201-3 the calculation method *"Luminance spot meter"* resulted in 7 % higher average road surface luminance, in 6 % higher overall luminance uniformity and in 4 % higher longitudinal luminance uniformity compared to the calculation method *"Equal area"*. In the case of the method Custom 1, the road surface luminance uniformity values were the lowest. The average road surface luminance was 7 % lower, the overall luminance uniformity also 7 % lower and the longitudinal luminance uniformity 5 % lower compared to the standard EN 13201-3. All methods that used the algorithm *"Equal area"* for calculating the road lighting quality characteristics (EN 13201-3 (equal area), Custom 1 and Custom 2) resulted in about the same average road surface luminance values. However, the luminance uniformity values calculated with these methods varied in relation to the number of measurement points used for calculations.

In the case of the method IESNA RP-8-00 the average road surface luminance was 3 % higher compared to the standard EN 13201-3. Once again the luminance uniformity values (L_{av}/L_{min} = 1,992, L_{max}/L_{min} = 2,578) were within the requirements of the IESNA RP-8-00 (expressway) despite the fact that the longitudinal uniformity was significantly lower than the required value (AL3 (ME3b), U_L = 0,60) [EN 13201-2 2003, IESNA 2005, Tiehallinto 2006].

Also the results presented in Table 6 indicate, that some variations in measured and calculated quality parameter values may occur for the same road lighting installation, if different road lighting calculation methods are used for evaluation of the road lighting performance.

Figure 8 shows the pilot location on the highway Ring Road III, illuminated with 250 W HPS lamps. The lighting class for Ring Road III is AL2 (L_{av} = 1,5 cd/m^2, U_o = 0,4, U_L = 0,6). [Tiehallinto 2006]. In Figure 8 the method CIE No. 30-2 is used for the calculation of the road lighting quality characteristics and the measurement points in the measurement area are marked in blue (*"Luminance spot meter"* algorithm) [CIE 1982]. Table 7 shows the results for the Ring Road III calculated with eight different calculation methods.

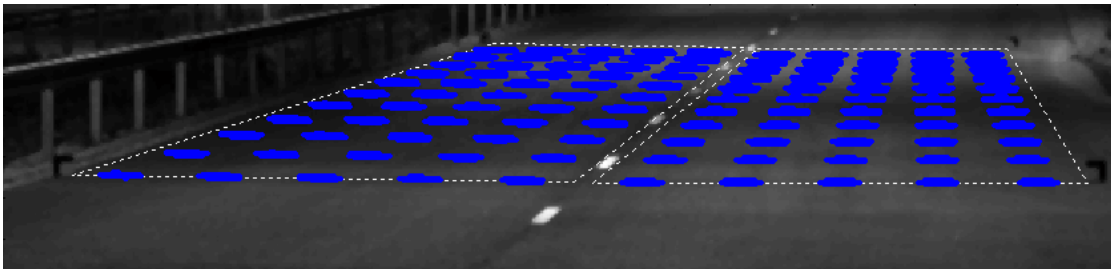


Fig. 8. Pilot location on Ring Road III illuminated with HPS lamps. The method CIE No. 30-2 is used for the calculation of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity. Each lane is divided to 55 measurement points; 5 points in the transverse direction and 11 points in the longitudinal direction. The algorithm "Luminance spot meter" is used for calculating the luminance values of the measurement points. The pixels included in the calculation of the luminance value of each point are shown in blue colour.

TABLE 7. Calculation results for Ring Road III with HPS lamp illumination. For each calculation method, except the STV method, average road surface luminance (L_{av}), overall luminance uniformity (U_o or L_{min}/L_{av}) and longitudinal luminance uniformity (U_L or L_{min}/L_{max}) were calculated. For the STV method the STV-value was calculated [IESNA 2005].

Calculation method	L_{av} (cd/m^2)	U_o	U_L
EN 13201-3, spot meter	1,685	0,482	0,450
EN 13201-3, equal area	1,666	0,466	0,442
CIE No. 30-2	1,64	0,460	0,513
Custom 1	1,670	0,446	0,449
Custom 2, spot meter	1,665	0,505	0,496
Custom 2, equal area	1,669	0,495	0,490
	L_{av}	L_{min}/L_{av}	L_{min}/L_{max}
IESNA RP-8-00	1,615	0,573	0,381
	STV		
Small Target Visibility	4,6		

For the pilot location Ring Road III the average road surface luminance values did not vary significantly when calculated with different methods. The method IESNA RP-8-00 resulted in lowest average luminance value, which was approximately 5 % lower compared to the standard EN 13201-3.

For Ring Road III there were some variations in overall and longitudinal luminance uniformity values between different standards and methods. The method CIE No. 30-2 resulted in highest longitudinal luminance uniformity, which was even 14 % higher compared to the EN 13201-3. Once again the method Custom 1 resulted in lowest luminance uniformity values compared to the other methods.

In the case of the method Custom 2 the calculation algorithm *"Luminance spot meter"* resulted in almost the same average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity compared to the calculation algorithm *"Equal area"*. When compared to the results calculated with the standard EN 13201-3 (spot meter) the method Custom 2 (spot meter) resulted in 1,2 % lower average road surface luminance, in 5 % higher overall luminance uniformity and in 10 % higher longitudinal luminance uniformity. The results indicate that decreasing the number of measurement points from 228 to 84 has no significant effect on the calculated average road surface luminance. However, decreasing the number of measurement points increases the overall luminance uniformity and the longitudinal luminance uniformity values to some extent.

For the pilot location Ring Road III the measured and calculated STV value (4,6) was lower than expected from the results of the method IESNA RP-8-00. For both methods the measured road lighting quality parameter values were adequate for the requirements [IESNA 2005].

Table 8 shows the measured and calculated results for the local street Leppälinninrinne illuminated with HPS lamps. The lighting class for Leppälinninrinne is AL4b (L_{av} = 0,75 cd/m^2, U_o = 0,4, U_L = 0,4). [Tiehallinto 2006]. In this pilot location every second luminaire was turned off after 11 pm for energy saving reasons.

TABLE 8. Calculated results for the local street Leppälinnunrinne, where every second luminaire was turned off to save electricity.

Calculation method	**L_{av}** (cd/m^2)	**U_o**	**U_L**
EN 13201-3, spot meter	0,666	0,239	0,146
EN 13201-3, equal area	0,670	0,241	0,147
CIE No. 30-2	0,692	0,244	0,147
Custom 1	0,671	0,235	0,147
Custom 2	0,674	0,255	0,162
	L_{av}	**L_{min}/L_{av}**	**L_{min}/L_{max}**
IESNA RP-8-00	0,636	0,253	0,153

As expected, the overall luminance uniformity and longitudinal luminance uniformity values were very low and did not fulfil the requirements of the lighting class AL4b. Despite the fact that every second luminaire was turned off the road lighting quality parameter values were adequate according to the IESNA RP-8-00 (local road class) [IESNA 2005].

In the case of the CIE No. 30-2 the average road surface luminance was 4 % higher compared to the EN 13201-3. There were no significant variations in the luminance uniformity values between these two methods. In the case of the method Custom 2, the road lighting parameter values were the highest. The average road surface luminance was 1,2 % higher, the overall luminance uniformity 7 % higher and the longitudinal luminance uniformity 11 % higher compared to the EN 13201-3.

Figure 9 shows the pilot location on the local street Jakokunnantie. The lighting class for Jakokunnantie is AL4b (L_{av} = 0,75 cd/m^2, U_o = 0,4, U_L = 0,4). [Tiehallinto 2006]. The measured luminances are presented in black-red-yellow-white non linear colour map. In Figure 9 the standard EN 13201-3 is used for the calculation of the road lighting quality characteristics [EN 13201-3 2003]. Table 9 shows the results for the Jakokunnantie calculated with six different calculation methods.

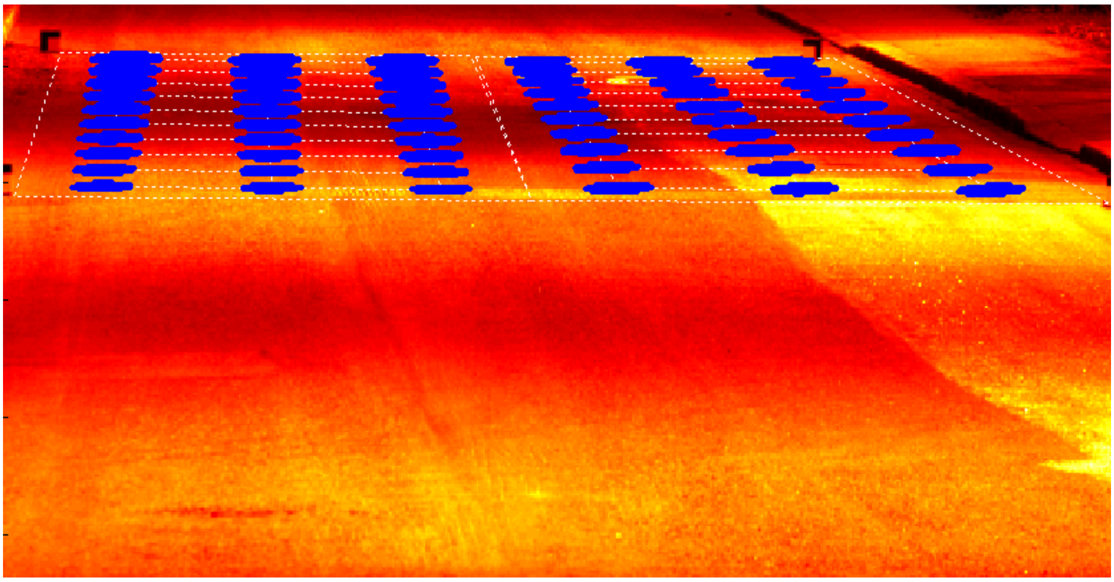


Fig. 9. Pilot location on the local street Jakokunnantie, in Helsinki, illuminated with HPS lamps. Luminances of the pilot location are shown in black-red-yellow-white non linear colour map with red dominance ("hot" colour map). Black colour represents very low luminance values and white colour very high luminance values. The standard EN 13201-3 is used for the calculation of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity. Each lane is divided to 30 measurement points; 3 points in the transverse direction and 10 points in the longitudinal direction. The algorithm "Luminance spot meter" is used for calculating the luminance values of the measurement points. The pixels included in the calculation of the luminance value of each point are shown in blue colour.

TABLE 9. Calculated results for the local street Jakokunnantie.

Calculation method	**L_{av} (cd/m²)**	**U_o**	**U_L**
EN 13201-3, spot meter	0,869	0,578	0,383
EN 13201-3, equal area	0,874	0,605	0,416
CIE No. 30-2	0,883	0,562	0,404
Custom 1	0,874	0,598	0,408
Custom 2, spot meter	0,885	0,616	0,454
Custom 2, equal area	0,875	0,608	0,465

In Jakokunnantie the average road surface luminance did not vary significantly when calculated with different methods. The highest difference was between the standard EN 13201-3 (*"Luminance spot meter"* algorithm) and the method Custom 2 (*"Luminance spot meter"* algorithm), but this difference was only 0,016 cd/m². The results show that decreasing the amount of measurement points by half has no significant effect on the average road surface luminance value.

Much higher variations between different methods were found when calculating the longitudinal luminance uniformity. For example in the case of the method Custom 2 and the algorithm *"Luminance spot meter"* the longitudinal luminance uniformity value was 19 % higher compared to the standard EN 13201-3 and the algorithm

"Luminance spot meter". In the case of the algorithm *"Equal area"* the corresponding difference between these methods was 12 %.

In the case of the method Custom 1 the calculated values were slightly higher compared to the standard EN 13201-3 and the algorithm *"Luminance spot meter"*. This was an unexpected result because usually the method Custom 1 results in lower average luminance and luminance uniformity values than the standard EN 13201-3, due to fact that method Custom 1 has more measurement points and takes also into account the dark areas close to the borders of a carriageway. The results indicate that in some cases the road lighting parameter values of the standard EN 13201-3 are dependent on the fact how the measurement points are positioned in relation to the bright and dark areas on the road surface. When the results of the method Custom 1 where compared to the standard EN 13201-3 and the calculation algorithm *"Equal area"*, the calculated average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity were lower than those calculated with the standard EN 13201-3.

Table 10 shows the results for the highway VT3 illuminated with MH lamps. Table 11 shows the results for the same highway but with the HPS lamp illumination and wet road surface. Wet road surface conditions were included in the studies to investigate if the road surface with very light and very dark areas and very low luminance uniformity would emphasize the differences between various measurement and calculation methods.

TABLE 10. Calculation results for the pilot location VT3 with MH lamp illumination and dry road surface. For each calculation method, average road surface luminance (L_{av}), overall luminance uniformity (U_o) and longitudinal luminance uniformity (U_L) were calculated.

Calculation method	L_{av} (cd/m^2)	U_o	U_L
EN 13201-3, spot meter	1,147	0,780	0,740
EN 13201-3, equal area	1,133	0,748	0,744
CIE No. 30-2	1,155	0,721	0,731
Custom 1	1,131	0,709	0,744
Custom 2, spot meter	1,150	0,792	0,741
Custom 2, equal area	1,131	0,802	0,786

The lighting class for VT3 is AL3 (L_{av} = 1,0 cd/m^2, U_o = 0,4, U_L = 0,6). [Tiehallinto 2006]. For wet road surface conditions the required minimum overall luminance uniformity value is 0.15. In dry conditions the overall and longitudinal luminance uniformities were very high and all the road lighting requirements were fulfilled (Table 10). Also for wet road surface conditions the overall luminance uniformity values were adequate in relation to the requirements (Table 11).

Despite the fact that in wet road surface conditions the overall and longitudinal luminance uniformities decreased significantly compared to the dry road surface conditions, the differences between the calculated values of different methods were still quite low. For example in the case of dry road surface conditions the variations for the average road surface luminance value were below ± 1,5 % when compared to the standard EN 13201-3. For wet road surface conditions the corresponding value was ± 1,6 %. Again, much higher variations between different methods were found when calculating the overall and longitudinal luminance uniformities for both pilot locations.

TABLE 11. Calculation results for the pilot location VT3 with HPS lamp illumination. During the measurements the road surface was wet. For each calculation method, average road surface luminance (L_{av}), overall luminance uniformity (U_o) and longitudinal luminance uniformity (U_L) were calculated.

Calculation method	L_{av} (cd/m²)	U_o	U_L
EN 13201-3, spot meter	5,057	0,192	0,320
EN 13201-3, equal area	5,041	0,200	0,315
CIE No. 30-2	5,086	0,186	0,362
Custom 1	5,039	0,182	0,319
Custom 2, spot meter	5,038	0,205	0,352
Custom 2, equal area	5,137	0,189	0,367

In the case of VT3 with MH lamp illumination the method Custom 1 resulted in lowest overall luminance uniformity. The overall luminance uniformity was 10 % lower compared to the value calculated according to the standard EN 13201-3 (spot meter). In the case of the standard EN 13201-3 the calculation method *“Luminance spot meter”* resulted in 1,2 % higher average road surface luminance, in 4 % higher overall luminance uniformity and in approximately the same longitudinal luminance uniformity compared to the calculation method *“Equal area”*.

The method Custom 2 (spot meter) resulted in almost the same average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity compared to the standard EN 13201-3 (spot meter) despite the fact that in the case of the method Custom 2 the amount of measurement points was reduced from 192 to 84. When compared to the results calculated with the method Custom 1, the method Custom 2 (*“Equal area”*) resulted in the same average road surface luminance, in 13 % higher overall luminance uniformity and in 6 % higher longitudinal luminance uniformity. The results indicate that the number of measurement points has no significant effect on the average road surface luminance as long as the number of points used in calculations is not very small. However, the amount of points used has an impact on the overall luminance uniformity and the longitudinal luminance uniformity.

Also for the pilot location VT3 with the HPS lamp illumination, the method Custom 1 resulted in lowest overall luminance uniformity and longitudinal luminance uniformity value. In the case of the CIE No. 30-2 the average road surface luminance was 1 % higher, the overall luminance uniformity 3 % lower and the longitudinal luminance 13 % higher compared to the standard EN 13201-3. There were also some slight variations found in calculated values between different calculation algorithms of the same method.

Due to the wet road surface and low luminance uniformities, some unexpected results were found in the calculated results of the pilot location VT3 with HPS lamp illumination. The methods that use the algorithm *"Equal area"* for calculating the road lighting quality characteristics (EN 13201-3, Custom 1 and Custom 2) resulted in slightly different average road surface luminance values, while usually the differences between these calculated values are very marginal. The method Custom 2 (equal area) resulted in 6 % lower overall luminance uniformity compared to the standard EN 13201-3 (*"Equal area"*), while usually the uniformity value calculated with the method Custom 2 is higher than the one calculated with the standard EN 13201-3. Still, the variations of the calculated values between different methods were not significantly higher compared to the variations in normal, dry road surface conditions.

The results of this work show that different calculation methods may result in slightly different average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity values. Thus, the results indicate that the same road lighting installation may result in different road lighting quality parameter values depending on the method used for calculating the road lighting performance. Much higher variations between different methods were found when calculating the overall luminance uniformities and longitudinal luminance uniformities of the road lighting installation than in the case of the average road surface luminance.

The method CIE No. 30-2 usually resulted in lower overall luminance uniformity and higher longitudinal luminance uniformity values compared to the standard EN 13201-3. This was due to the fact that in the calculations made with the CIE No. 30-2 more measurement points were included in the transverse direction but, usually, less points in the longitudinal direction, compared to the use of the EN 13201-3. The luminance values calculated with method IESNA RP-8-00 varied the most compared to the EN 13201-3.

The method Custom 1 resulted in lowest overall luminance uniformity and longitudinal luminance uniformity values compared to the other methods. This was due to fact, that in using the method Custom 1 more measurement points are included, than in the other methods. At the same time, the method Custom 2 usually resulted in highest overall luminance uniformity and longitudinal luminance uniformity values compared to the other methods due to the small number of measurement points used for calculations.

The results show that there were only slight variations in the calculated values when the algorithms *"Luminance spot meter"*, *"Single pixel"* and *"Range of pixels"* were used. Only the calculation results made with the calculation method *"Equal area"* varied from the results made with the algorithm *"Luminance spot meter"*.

The method Custom 2 resulted in very similar average road surface luminance values compared to the standard EN 13201-3 despite the fact that in the case of the method

Custom 2 the number of measurement points was much lower than in the case of the standard EN 13201-3. The results indicate that the number of measurement points has no significant effect on the calculated average road surface luminance value as long as the number of points used in calculations is more than 21 measurement points per lane. However, the number of points used in the measurement and calculations has an impact on the overall luminance uniformity and the longitudinal luminance uniformity values. In general, it can be argued that the higher the number of measurement points in the longitudinal direction, the lower the resultant longitudinal uniformity value. At the same time, the higher the number of total measurement points, the lower the overall luminance uniformity value.

6. Discussion

6.1 Road lighting measurements and calculations

According to the current European standard EN 13201-3 in road lighting design, measurements and calculations three calculation or measurement points are used in the transverse direction in each driving lane. The two outermost points are placed 1/6 of a lane width from the borderlines of the lane and the third one in the middle of the lane. If assumed that the lane width is 3,5 m, the outermost points are placed 1,17 m from the central line. At the same time, the width of a common vehicle is about 1,6 m and if the vehicle is located in the middle of the lane the tyres are located 0,8 m from the central line. In practice, this means that the central line of the measurement points is located between the wheel tracks in the middle of the lane and the other two lines are located on the outer edges of the wheel tracks. In Finland, due to the use of studded tyres during winter time, the wheel tracks are usually lighter that the borders and the central area of the driving lanes. The borders and the central area of the lane are also usually dirtier than the wheel tracks due to dirt, gravel, oil and rubber. Thus, if the road lighting measurements are made, depending on the road, either all of the measurement points are measured from the darker part of the road surface, or 2/3 of the measurement points are measured from the light road surface and 1/3 of the measurement points are measured from the dark road surface. Also the road surface deformation may affect the measurement results due to the fact that 2/3 of the measurement points are located on the outer edges of the wheel tracks.

Figure 10 shows an example of the situation, in which the locations of the measurement points dominate the calculated results of the road lighting installation. As shown in Figure 10, on a road section of Ring Road I, only wheel tracks of the right lane have been paved due to the high weariness and deformation of the road surface caused by very heavy traffic flow and studded tyres. The new pavement strips are darker than the old pavement but, because of the high specular reflection of the new pavement, the luminances of the new pavement are higher compared to the luminances of the old pavement. As shown in Figure 10, in the case of the standard EN 13201-3, 2/3 of the measurement points are located on the edges of the new pavement, while 1/3 of measurement points (the central line) are located on the old pavement.

Figure 11 shows the same measurement area calculated according to the Publication CIE No. 30-2 and the calculation algorithm *"Luminance spot meter"* and Figure 12 the same area calculated according to the standard EN 13201-3 and the calculation algorithm *"Equal area"* (Chapter 4.2, p. 21). Table 12 presents the calculation results for one driving lane made according to the criteria EN 13201-3, CIE No. 30-2, IESNA RP-8-00 and the methods Custom1 and Custom 2. The pilot location on Ring Road I is illuminated with HPS lamps. The lighting class for Ring Road I is AL2 (L_{av} = 1,5 cd/m^2, U_o = 0,4, U_L = 0,6). [Tiehallinto 2006].

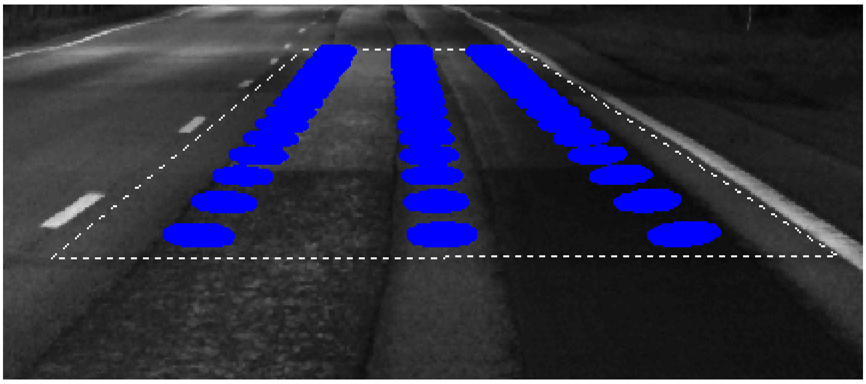


Fig. 10. Pilot location on Ring Road I illuminated with HPS lamps. On a road section of Ring Road I only wheel tracks of the right lane have been paved due to the weariness of the road caused by the heavy traffic flow. The standard EN 13201-3 ("Luminance spot meter") is used for the calculation of road lighting parameters.

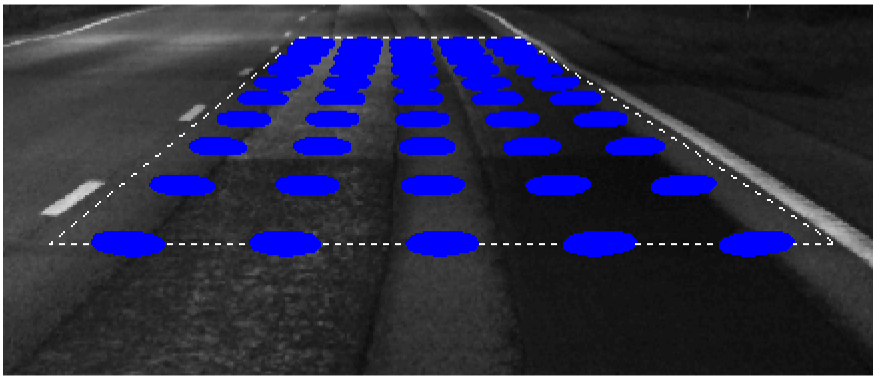


Fig. 11. Pilot location on Ring Road I illuminated with HPS lamps. The method CIE No. 30-2 is used for the calculation of road lighting parameters.

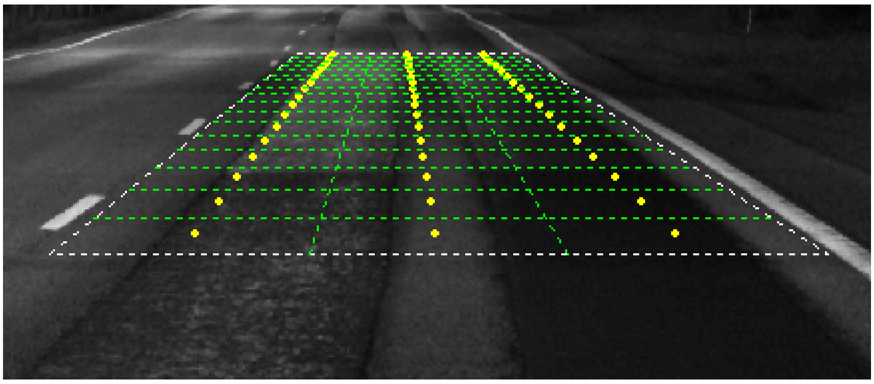


Fig. 12. Pilot location on Ring Road I illuminated with HPS lamps. The calculation method "Equal area" is used for the calculation of road lighting parameters.

As can be seen from Figures 10 and 11 in the case of the CIE No. 30-2 the measurement points are distributed more equally between the new and the old pavement areas. This has an apparent effect on the calculated results. In the case of the IESNA RP-8-00 all of the measurement points are located on the wheel tracks (new pavement).

TABLE 12. Calculated results for the pilot location Ring Road I with HPS lamp illumination.

Calculation method	L_{av} (cd/m^2)	U_o	U_L
EN 13201-3, spot meter	1,050	0,275	0,530
EN 13201-3, equal area	0,886	0,472	0,540
CIE No. 30-2	0,991	0,360	0,515
Custom 1	0,895	0,433	0,59
Custom 2, spot meter	1,029	0,287	0,565
	L_{av}	L_{min}/L_{av}	L_{min}/L_{max}
IESNA RP-8-00	1,209	0,294	0,182

Unlike the previous case studies of the paper, in this pilot location high variations were found between the calculated results of different methods. Especially the overall luminance uniformity varied significantly in relation to the method used. In the case of the standard EN 13201-3 the calculation algorithm *"Luminance spot meter"* resulted in 19 % higher average road surface luminance, in 72 % lower overall luminance uniformity and in 2 % lower longitudinal luminance uniformity compared to the calculation algorithm *"Equal area"*. The difference in overall luminance uniformity values was very high considering the fact that the measured road lighting installation, measurement conditions, measurement area (pole spacing) and the standard used for the calculations were exactly the same. For the CIE No. 30-2 the average road surface luminance was 6 % lower, the overall luminance uniformity 31 % higher and the longitudinal uniformity 3 % lower compared to the EN 13201-3. In the case of the IESNA RP-8-00 the average road surface luminance was 15 % higher compared to the EN 13201-3. Also the luminance uniformity values calculated according to the IESNA RP-8-00 were quite low when compared to the other methods.

The results indicate that according to the standard EN 13201-3 three quite narrow measurement lines are used to define the road surface luminance properties for the whole lane. At the design stage of the road lighting installation this may not be a problem but, in the road lighting measurements this may cause some inaccuracy in the results. One solution may be the use of the calculation method which is similar to the method *"Equal area"* introduced in this work. Nowadays the road lighting design is mostly done with the calculation and visualization programs and thus, it would be easy to include all luminance values of the defined area of road surface into calculations. At the same time, the use of imaging luminance photometers is becoming more and more common which enables the use of such calculation methods also in the road lighting measurements.

Of course it can be questioned if all luminance information from the defined road surface area is really needed. For example, are the luminance values close to the borders of the measurement area relevant from the driver's point of view? If a target is positioned close to the border of the carriageway it is usually seen against the road surroundings (forest, bushes, barriers, buildings and so on) and not against the road surface. On the other hand, if the same target is located closer to the driver and the vehicle, the areas close to the borders of the carriageway may be important in forming the luminance contrast needed to perceive the target on the road. So should different measurement areas, from the one restricted by borders of a carriageway, be used for defining the road lighting quality parameters? Which road surface and road surrounding areas should a driver see well and are all the measured and calculated data relevant for the safety of the driver? These fundamental questions need to be considered and investigated in the further development of the road lighting standards and recommendations.

The measurement cone of a spot luminance meter as defined in the standard EN13201-4 is restricted to be 2’ in the vertical plane and 20’ in the horizontal plane [EN 13201-4 2003]. However, for example in the case of road lighting installation with pole spacing of 55 m, with such regulations the measurement areas for the furthest measurement points are over 5 m in length and about 0,6 m in width. There again, the standard EN 13201-4 recommends that the measuring area of a single point on the road should not be greater than 0,5 m transversely and 2,5 m longitudinally. This, on the other hand, means that with the same pole spacing of 55 m, for the furthest measurement points, the measurement cone of the spot meter is restricted to be about 1’ in the vertical plane and 15’ in the horizontal plane. For most spot luminance meters the measurement area is, however, circular, which means that in order to perform the longitudinal measurements according to the requirements, the areas measured in the transverse direction, have to be kept small.

So, in reality, if the measurements are made according to the standards EN 13201:3-4 and the observation distance is set to 60 m, certain parts of the road surface area are measured twice or even multiple times depending on the luminance meter used. There again, if the measurement cone of the spot meter is decreased, the measurement areas in the transverse direction are very small. In both cases three quite narrow strips of the road surface are measured very precisely, while the areas between the measurement lines and the areas close to the borderlines of the lane are not measured at all.

Furthermore, it can be argued that a driver sees the road ahead of him/her in perspective and gives weight to a luminance according to the apparent size of the area concerned: the closer the area is to him/her, the larger it will appear and the more influence it will have in comparison with other areas of equal real size farther away. In road surface luminance measurements with luminance spot meters, the individual luminance values are not weighted according to the apparent size of the areas concerned, that is to say too little weight is given to the areas close to the driver (also smaller areas measured) and too much to those further away.

6.2 Surround ratio

Surround Ratio (SR) value introduced in the European standard EN 13201-3 defines the road lighting illumination levels on the roadside [EN 13201-3 2003]. The Surround Ratio (SR) value is based on the horizontal illuminance at certain points on the surface close to the carriageway. The SR value is calculated from the average horizontal illuminance on the two longitudinal strips each adjacent to the two edges of the carriageway, and lying off the carriageway, divided by the average horizontal illuminance on the two longitudinal strips each adjacent to the two edges of the carriageway, but lying on the carriageway. The width of all four strips shall be the same, and equal to 5 m, or half of the width of the carriageway, whichever is the least. The SR value is defined by using the equation:

$$SR = \frac{E_{S1} + E_{S2}}{E_{R1} + E_{R2}} \tag{5}$$

where, E_{S1} and E_{S2} are the average illuminances of the strips lying off the carriageway and E_{R1} and E_{R2} are the average illuminances of the strips lying on the carriageway [EN 13201-3 2003].

However, it can be argued that such method of defining the illumination of the road immediate surroundings is inadequate when considering the visibility of targets located on the roadside and being a potential threat to a driver. This is mostly because in such case the target is seen against the road surroundings and not against the road surface. The road surroundings are usually substantially darker than the illuminated road surface and thus, the luminance contrast of the target is significantly different than in the case when the same target is located on the road, in front of the vehicle. At the same time, the luminance provided by luminaires on the vertical surfaces of the target, located on the roadside, is inadequate to form sufficient positive contrast needed for the perception of the target due to the fact that the purpose of road lighting is mainly to illuminate the road surface. This may result in a situation, in which the slightly illuminated dark target is seen against the dark road surroundings. In such case the target has similar luminance as the background and may not be visible to the driver.

One solution for this problem could be the use of vertical or semicylindrical illuminances in addition to the horizontal illuminances. The requirements for the vertical or semicylindrical illuminances should be defined based on the idea of the target having adequate luminance contrast due to illumination of road lighting and vehicle headlights. In that way the SR-value would also consider the visibility of targets, which may appear on the roadside.

The reflection characteristics of the roadside surfaces can vary a lot depending on the road. The illuminance values measured close to the carriageway do not indicate the real luminance levels of the strips lying off the carriageway. Hence, if the target is located on the road, and is seen partly against the strips area close to the carriageway, it is not really known how the strip affects the visibility of the target. Thus, it can be argued, that instead of illuminance values, luminance values should be used in defining the SR value and the quality of road lighting installation.

The SR value (Equation 5) described in the standard EN 13201-3 is dependent on the sum of two average illuminance values, which means that if one strip is illuminated well and the other is not, the SR value can be the same as in the case with two slightly illuminated strips. In such case both installations fulfil the requirements, but the situation is totally different considering the visibility of targets on the road or roadside.

7. Conclusions

The primary function of road and street lighting is to keep the safety of the people and increase the rapidity and comfort of road traffic. Road and street lighting should provide good visibility conditions and reduce potential hazards by illuminating the road surface and its surroundings and by making targets on the road visible to the driver. Luminance measurements of road and street lighting are needed to get data from the field and to analyse the luminous environments from the drivers' point of view. The luminance measurements are also a good way to control and secure the quality of road lighting. The advantages of an imaging luminance photometer are the speed of measurement and the possibility to gather simultaneous luminance information from a large visual scene. The utilization of an imaging luminance photometer instead of a spot meter eases the luminance measurements and gives many new possibilities in analyzing the luminance distributions [Eloholma 2004].

While the theory on which road lighting design, measurements and calculations are based is well established, it is possible to argue that it is imperfect and thus, gives rise to problems and inconsistencies in current road lighting practice. Road lighting for drivers was developed using the task of viewing of a small flat square target at a distance of 100 m, however, the relevance of this task to actual driving conditions can be questioned. In the development of road lighting design criteria it has been assumed that targets are visible to the driver only if they have adequate luminance contrast to their background and, thus, any potential advantage from colour contrast is not considered. Furthermore, in the development of road lighting the impacts of vehicle headlights on targets visibility should be taken into account.

The road lighting measurements and calculations of this work show that the same road lighting installation may result in different road lighting quality parameter values depending on the calculation method used for calculating the road lighting performance. Much higher variations between different methods were found when calculating the overall luminance uniformities and longitudinal luminance uniformities of the road lighting installation than in the case of the average road surface luminance.

At the moment, in road lighting design, measurements and calculations only a part of the luminance data is used for defining the road lighting quality. With development of computer programs and with imaging luminance photometers becoming more common, it can be questioned if it is better to use a calculation method, which includes all road surface luminance values from the defined road surface area of interest.

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